Proceedings Paper:
Wang, X, Thomas, D, Ge, Y et al. (14 more authors) (2018) Proceedings of Real Driving Emission (RDE) Measurement in China. In: SAE Technical Papers. WCX World Congress Experience, 10 Apr 2018 SAE International .

https://doi.org/10.4271/2018-01-0653

2018-01-0653

Proceedings of Real Driving Emission (RDE) Measurement in China

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Abstract

Light-duty China-6, which is among the most stringent vehicle exhaust emission standards globally, mandates the monitoring and reporting of real driving emissions (RDE) from July, 2023. In the process of regulation promulgation and verification, more than 300 RDE tests have been performed on over 50 China-5 and China-6 certified models. This technical paper endeavors to summarize the experience of RDE practice in China, and discuss the impacts of some boundary conditions (including vehicle dynamic parameters, data processing methods, hybrid propulsion and testing altitude) on the result of RDE measurement. In general, gasoline passenger cars confront few challenges to meet the upcoming RDE NO_x requirement, but some China-5 certified samples, even powered by naturally-aspirated engines may have PN issues. PN emissions from some GDI-hybrid powertrain systems also need further reduction to meet China-6 RDE requirements. Vehicle dynamic parameters, both $v.a_{pos}$-[95] and RPA, have been confirmed to have strong impacts on RDE NO_x and PN emissions. Data processing methods, namely moving average windows (MAW) and power-binning (BIN), output quite similar emission factors if engine-stop, warm-up and idle are excluded from the calculation. Testing altitude up to 2400m shows evident influence on RDE measurement, however, no clear correlation between altitude and RDE emissions can be concluded so far.

Introduction

With ever increasing concerns over in-use emissions from passenger cars, as a new type-approval content, real driving emission (RDE) has become a mandated test in the upcoming Euro-6d and China-6 regulations. The employment of RDE is expected to restrain the overly narrow calibration of engine map and prevent cheating, it also encourages the development and application of advanced emission control technologies [1,2].

However, the RDE test has an intrinsic drawback; it is non-reproducible. Since any individual RDE test is performed randomly on-road, a number of variables, such as driving behavior, weather and altitude, could have varying influence on the results. Although the present regulations have set a series of limitations for the above boundary conditions, these can only reduce variability, not eliminate it. Hence, in order to account for the non-repeatability of RDE tests and determine more appropriate limit values, or conformity factors [3], there is a necessity to carefully investigate the impacts of those boundary conditions on RDE results.

Many papers have previously conducted vehicle on-board emission measurement using PEMS, but the majority of them have been confined to non-legislated real-world tests.

Merkisz et al. [4] conducted an extensive study, testing 150 different Euro-4 to Euro-5 certified cars in accordance with RDE, and then comparing results to corresponding laboratory NEDC and WLTC results. It should be stated that the protocol used in this study was the one being considered for EU RDE legislation at the time but varies from that currently in legislation, which sets different speed delineations between modes and is engine-start and idle inclusive. This paper found that both RDE CO and NO_x emission were about 80% of their respective type-I limit values, while WLTC CO and NO_x emissions were 31% and 60% of their corresponding limits. The NEDC test gave far lower NO_x emissions than the WLTC in this study, while the CO gave approximately equal values.

Merkisz et al. [5] also extracted the engine operating conditions during on-road measurement and conducted an analysis into the impact of dynamic behavior on emission factors. They found that peaks of CO emission appeared in both acceleration and deceleration conditions, and CO emission in real-world clearly increased with higher levels of acceleration. With respect to NO_x emissions, peaks were noticed at speeds of 4 - 12 m/s with -0.6 - +1.8 m/s^2 acceleration, and 10 - 26 m/s with -0.2 - +1 m/s^2 acceleration. Based on comparison of the distance-specific emission factors between individual on-road test portions and equivalent NEDC portions, this study concluded that acceleration and vehicle speed for these sections are the most influential factors on CO and NO_x emissions.

Few other papers have gone in-depth regarding the engine operating conditions during real-world measurement and their correlations with exhaust emissions. Similarly, few other studies have looked into how the vehicle dynamic parameters affect the regulated emissions.

In view of this, using the data we accumulated during the making of China-6 RDE regulation, this technical paper endeavors to summarize the results we obtained and elucidate the influences of some boundary conditions on RDE emissions.

China RDE regulation, equipment and vehicles

Learning from EU, China-6 also adopts RDE using PEMS as the new Type II type-approval test to replace the former idle emission test. The requirements of China-6 RDE are in general the same as EU's, but some differences still exist.

A valid RDE trip can range from 90 to 120 minutes and must consist of three separate driving conditions, namely urban, rural and motorway driving. For each driving condition, a range of at least 16km must be traversed. Ideally, the percentages of urban, rural and motorway driving in a valid RDE trip are 34%, 33% and 33% respectively, but a variation of ±10% is permissible. The definition of each driving condition depends on vehicle speed; 60km/h and 90km/h are the boundaries to distinguish urban from rural driving and rural from motorway driving respectively. A valid RDE trip shall also satisfy vehicle dynamic parameter criteria, to ensure the testing can represent routine driving.

In addition to trip composition, there are other boundary conditions to be met for a valid RDE test, so as to produce reliable and comparable test results:

1. Ambient temperature when performing tests shall be within 0 to 30°C, and temperatures down to -7°C or up to 35°C are also acceptable, but coefficient for "extended temperature" shall be applied.
2. A valid test shall be conducted at an altitude no higher than 700m, or an "extended altitude" less than or equal to 1300m. Since in China millions of vehicles are operating at much higher altitudes, there regulates a so-called "further extended altitude" condition. This allows RDE testing at an altitude up to 2400m, with the "further extended altitude" coefficient applied here.

Another difference in China-6 RDE regulation relates to the data processing method. Only Moving Average Window (MAW) method is acceptable according to China's Measurement Law. Since the promulgation of China-6 RDE regulation is prior to EU's Package 4, the following data acquired during testing is excluded from the final calculation:

1. Engine-start and warm-up, when engine coolant temperature has not yet reached 70 °C (it is worth arguing that warm-up effects may remain even after this temperature, particularly for those hybrid models, whose catalyst temperatures have weaker linkage with coolant temperature)
2. Idle – durations with vehicle speeds under 1 km/h
3. Engine-stop – durations where the vehicle engine is switched off

China RDE regulation also differs from the EU's in terms of the acceptance of using ±50% secondary tolerance for "normality check". Currently only +50% is acceptable in Europe. The purpose of accepting negative secondary tolerance is in part to balance the impact of "further extended altitude". Due to decreased air density and thus aerodynamic drag at elevated altitude, and fuel consumption becomes lower.

Table 1. Specifications of the PEMSs used for RDE testing in China

Model	HORIBA OBS-ONE	AVL M.O.V.E	Sensors LDV
CO	Non-dispersive Infrared (NDIR)		
CO_2	Non-dispersive Infrared (NDIR)		
NO_x	Chemiluminescence (CLD)	Non-dispersive Ultraviolet (NDUV)	
PN	Condensation Particle Counter (CPC)	Diffusion Charger (DC)	Condensation Particle Counter (CPC)
Exhaust flow rate	Pitot flow meter		

In China, the most commonly used RDE PEMSs are HORIBA OBS-ONE, AVL M.O.V.E and Sensors LDV. All the PEMS makers claimed that their equipment can operate at 2400 m. In this paper, instruments from all three of these manufacturers were used. Table 1 lists the main specifications, while Figure 1 shows the installations of all the three PEMS devices on-board.

All the vehicles discussed in this paper are China-5 or China-6a certified. If needed, specifications of the test vehicles will be mentioned along with discussion. In order to evaluate RDE emissions, all the test vehicles performed two or three WLTC tests in laboratory, and then were shipped to various cities at different altitudes for RDE testing. RDE tests were conducted strictly according to the protocol regulated in China-6. For each vehicle, the RDE test was repeated 1 to 3 times in a given city.

Figure 1. Pictures of test equipment installed on typical test vehicles

Conformity Factors

For a certain kind of tailpipe emission, the conformity factor (CF) discussed in this section is defined as the quotient of RDE emission factor divided by laboratory WLTC result in the same metric. For the convenience of result evaluation and comparison with other studies, tailpipe emission limits of China-5 and China-6 are given in Table 2.

Table 2. Tailpipe emission limits of China-5, China-6a and China-6b

	CO	THC	NO_x	NMHC	N_2O	PM	PN
China-5 (gasoline)	1000	100	60	68	n.a.	4.5	n.a.
China-5 (diesel)	500	n.a.	180	n.a.	n.a	4.5	6E11
China-6a	700	100	60	68	20	4.5	6E11
China-6b	500	50	35	35	20	3.0	6E11

Figure 2 illustrates the conformity factors of CO, NO_x and PN emissions of eighteen China-5 (point 1 to 18 from left to right) and twenty-one China-6 certified gasoline vehicles. Engine displacement of the eighteen China-5 certified vehicles ranged from 1.2 to 3.7 liters. The test vehicles are all powered by GDI engines, except for Car 1, 3, 10, 12, 15, 16 and 17. In terms of China-6 models, engine sizes are within 1.0 and 3.7 liter. Engines of Car 19, 22, 24, 29, 30, 34, 35, 37 are port-fuel injection, and the rest are GDI.

It should be clarified that in China RDE regulation, CO emission is a mandatory pollutant to be monitored, but unlike NO_x and PN, no conformity factor has been set to restrain real-world CO emission.

It can be seen in Figure 2 that the majority of the test vehicles have conformity factors approximately equal to or smaller than 1, which implies that for gasoline vehicles, CO emission discharged in real driving conditions seldom exceeds that measured in laboratory over WLTC. Such a result accords well with Merkisz et al, who compared free driving emissions with laboratory emissions over NEDC [4].

Except for one China-5 certified model powered by a down-sized, turbocharged gasoline engine, conformity factors of NO_x are even smaller than CO. Over 80% of the test vehicles have conformity factors smaller than 0.5, indicating that unlike diesel, RDE NO_x emissions from gasoline vehicles are of less concern in China. Alternatively, the WLTC might be a little too aggressive to represent normal Chinese driving behavior.

Conformity factors of only three vehicles, a China-5 naturally-aspirated, a China-5 GDI-hybrid and a China-6 GDI, exceed the China-6 CF_{PN} limit of 2.1. Compared to NO_x, the conformity factors of PN are larger on average, demonstrating that PN control can be more challenging, and more work is needed in the future. It is worth noting that in Figure 2, some PFI models also produce high PN emission, i.e. Car 3 and 12. In this case, we suggest that PN emissions from PFI models should be regulated as well, with the application of PN limit extended from GDI-only to every gasoline model.

Among the 39 test vehicles, only one vehicle has an installed GPF system (Car 34), whose CF_{PN} has been maintained under 0.1. Given that the rest test vehicles could also control real driving emissions at satisfied levels, GPF seems not the only technical route to meet the upcoming China-6a.

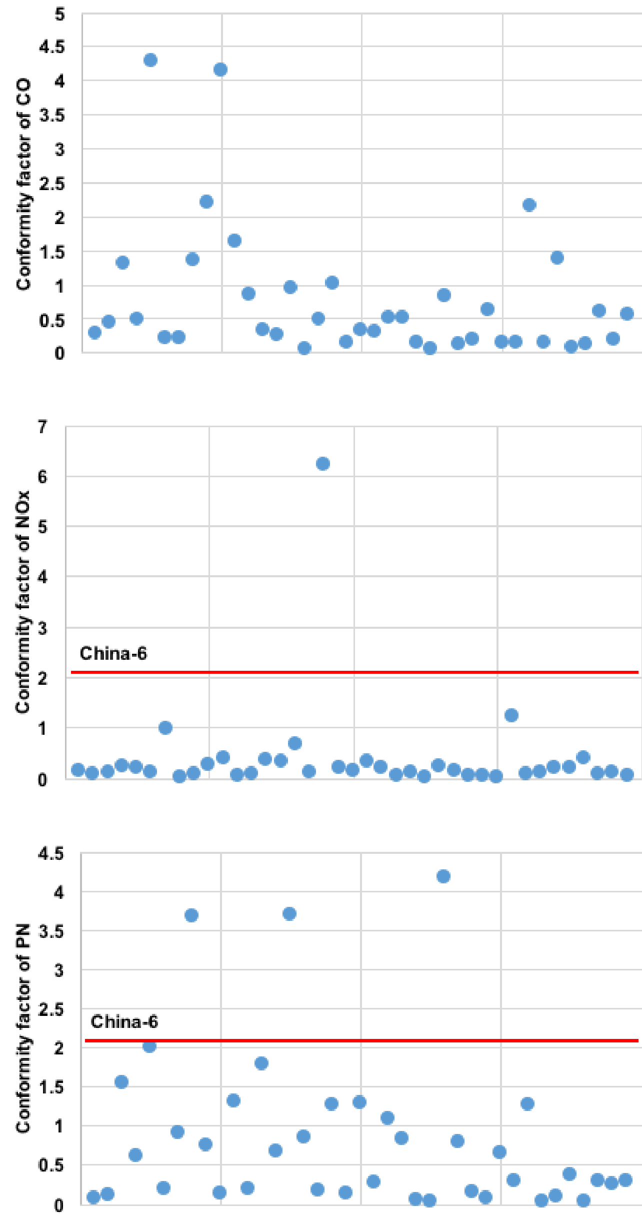

Figure 2. Conformity factors of tested China-5 and China-6 certified vehicles

Hybrid Propulsion

Driven by ever-decreasing CO_2 limits, hybrid propulsion is expected to prevail in the next decade. This section looks into the influence of hybrid technology on RDE.

Figure 3 compares RDE emissions from three pairs of vehicles, these 6 vehicles are selected from the aforementioned 39 vehicles. To promote the comparability, hybrid and ICE-only vehicles in each pair of vehicles come from the same car manufacturer, and share similar engine specifications and reference mass. All the vehicles tested in this section are China-5 certified. Car A to Car D are powered by 1.5 to 1.8 liter naturally-aspirated engines while Car E and Car F employ 1.6 liter GDI engines.

It can be seen in the figure that, for all the six samples, CO emission creates no challenge to meet China-6 except that laboratory CO emission from Car D shall be at least halved to meet the requirement of China-6a.

A plausible reason for much higher laboratory CO emission than RDE CO emission from Car D may be attributed to the aggressive driving style of WLTC and the small engine on-board. Car D is a popular economy-class model equipped with a 1.5L engine, meaning there is more chance for the engine to be run in wide open throttle and fuel-rich conditions so as to track the acceleration/speed targets of WLTC.

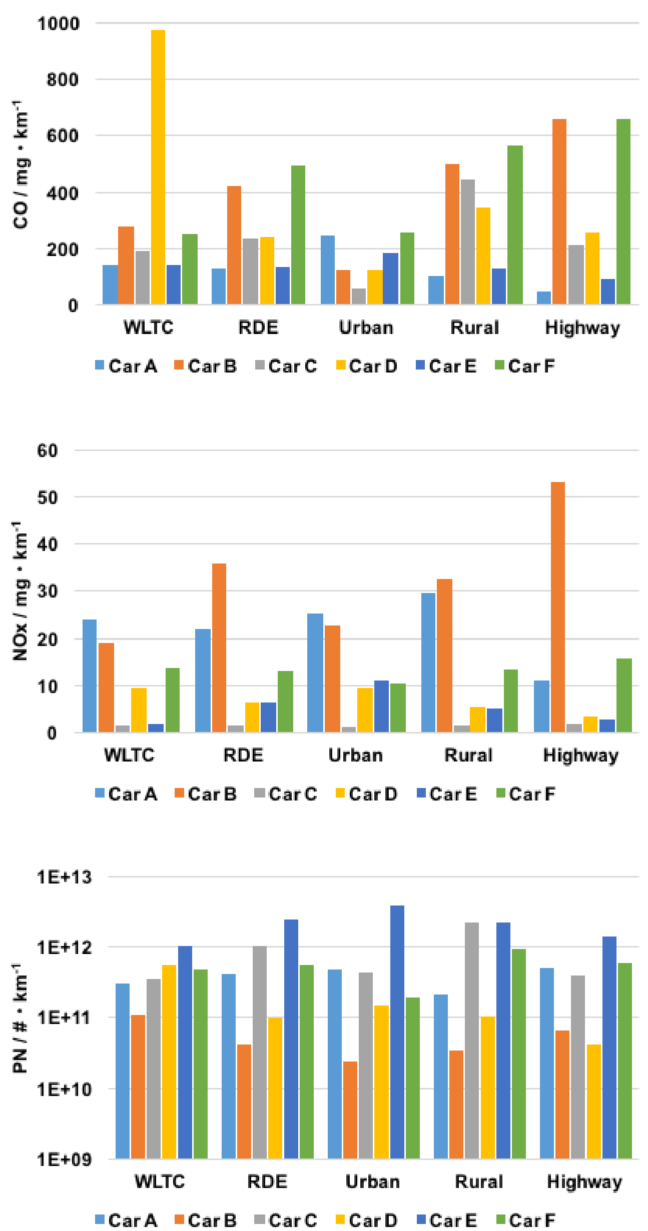

Figure 3. A comparison of RDE emissions from purely ICE-powered and hybrid models (Car A, Car C and Car E are hybrid models with comparable vehicle weight, engine displacement and technologies of their counterparts).

Additionally, almost all the China-5 models are calibrated according to NEDC, so switching to WLTC may let the operating points of the engine go beyond the “emission-control area” and cause increased CO emission. As shown in Figure 3, this hypothesis can be partially supported by increased NO_x and PN emissions measured in laboratory.

NO_x emissions are also of less concern, as shown in Figure 3, particularly for the hybrid models. However, it is worth noting that Car B produces almost two times the laboratory NO_x emissions in the RDE test. It is on the boarder of failing RDE test if we inappropriately introduce China-6’s CF here, which is now 2.1, much more tolerant than present EU’s 1.5.

With respect to PN emission, both hybrid model Car C and Car E emit more particles in the RDE tests than the standard limit. Such a result warns that for hybrid vehicles, in particular GDI-hybrid models, RDE PN emission can be a risk.

Looking at the patterns of different driving modes excessive PN emission is mainly discharged in urban and/or rural driving stages. It is deduced that increased PN may be a consequence of frequent stop-and-go in urban driving and sudden acceleration/deceleration in rural and motorway driving. Both behaviors can result in very short periods of fuel-rich combustion in-cylinder, which provides more favorable conditions for the generation of particles. However, this hypothesized reason is insufficient to explain the mixed PN results found in Figure 3. A more detailed analysis based on OBD data may help better understand the underlying reasons.

For hybrid vehicles, another challenge for NO_x and PN control is the matter of catalyst temperature. In order to maintain good fuel economy, engines on hybrid models only operate for very short periods of time in urban driving. Thus, it is very difficult to guarantee high enough catalyst temperature and conversion efficiency. Carmakers are now developing electrical heating systems to alleviate this issue.

Vehicle Dynamic Parameters

Both EU and China RDE regulations mandate a verification of vehicle dynamic parameters before data processing, in order to guarantee that the trip is representative enough – being neither too aggressive nor too gentle – to reflect the emission levels in routine operations. In this process, two parameters, namely $v.a_{pos}$-[95] and RPA, are defined and verified. $v.a_{pos}$-[95], which is the 95th percentile of positive products of vehicle velocity and acceleration, is an indicator to prevent over-aggressive driving. Conversely, the aim of setting RPA, which is short for Relative Positive Acceleration, is to prevent surreally gentle driving from giving low emission results. As shown in Eq. (1), to calculate RPA, one should first pick out data points with vehicle acceleration ratios larger than 0.1 $m \cdot s^{-2}$, and using vehicle speed to multiply acceleration and time step (1 s) then divided by distance traveled in this corresponding second.

$$RPA = \frac{\sum_{i=1}^{n} a_i v_i \Delta t}{s} \quad (1)$$

$v \cdot a_{pos}$-[95]

Figure 4 and Figure 5 show the impacts of $v.a_{pos}$-[95] on RDE CO, NO_x and PN emissions during urban driving stage and rural combined with highway driving stages, respectively. In each figure, a tendency line is also sketched by using linear regression, regression function and coefficient of determination. (R^2) are given in the upper left corner of the figure.

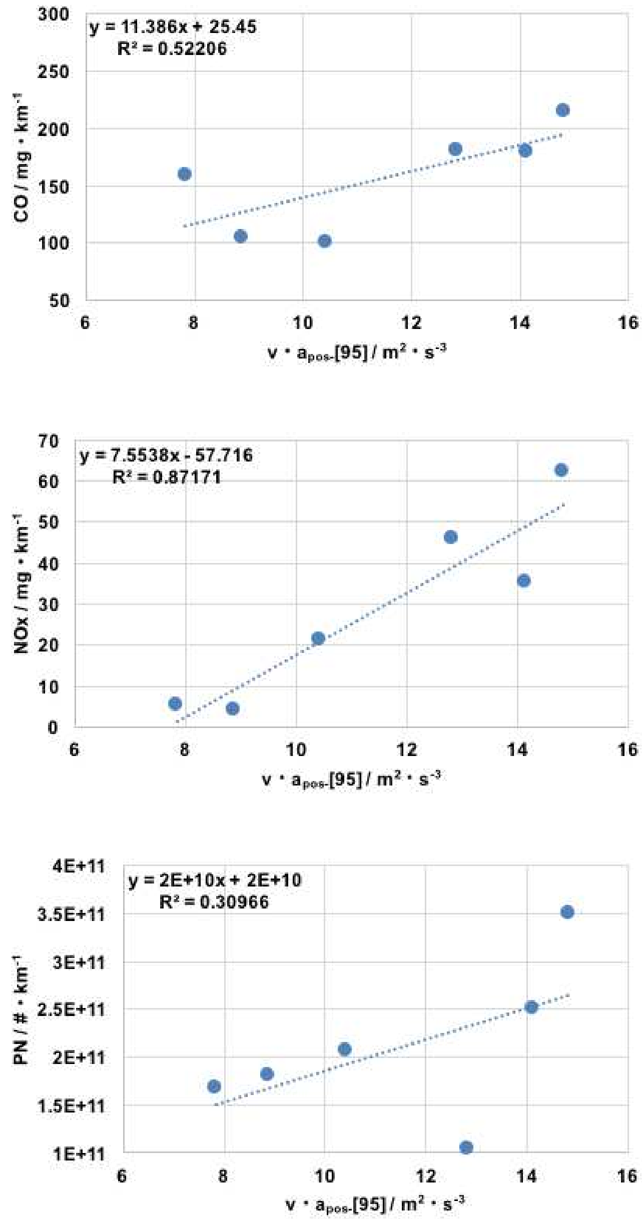

Figure 4. Influences of $v \cdot a_{pos}$-[95] on urban CO, NO_x and PN emissions.

As shown in Figure 4, RDE CO emission measured in the urban driving stage positively correlates with increased $v.a_{pos}$-[95] despite some discrepancies corresponding to lower $v.a_{pos}$-[95] running. Since the R^2 value of this fitting line is 0.52, further conclusion on a linear correlation cannot be made reliably. The tendency established between CO and $v.a_{pos}$-[95] under urban driving conditions inverts during rural and highway driving in Figure 5. RDE CO emission generally decreases with increased $v.a_{pos}$-[95], but because of the existence of several singular points, the R^2 value in Figure 5 is only 0.30. When $v \cdot a_{pos}$-[95] increases from 12 to 24 $m^{-2} \cdot s^{-3}$, RDE CO emission decreases by about one third, a much smaller margin than that during urban driving.

In the urban driving stage, a good linear correlation between RDE NO_x emission and increased $v \cdot a_{pos}$-[95] can be established, with R^2 being as high as 0.87. As shown in Figure 4, RDE NO_x emissions are very sensitive to a change in $v \cdot a_{pos}$-[95], when $v \cdot a_{pos}$-[95] increases from 8 to 15, NO_x emissions increases almost ten-fold. While, the linear correlation between RDE NO_x emissions and increased $v \cdot a_{pos}$-[95] is no longer so strong or sensitive in rural and highway driving stages. There are many data deviations from the trend line, and the R^2 is only 0.39. On average, RDE NO_x emissions increase by around 200% when $v \cdot a_{pos}$-[95] ascends from 12 to 26 $m^{-2} \cdot s^{-3}$. Even so, a positive trend between RDE NO_x emission and $v \cdot a_{pos}$-[95] can still be clearly seen and concluded from Figure 5.

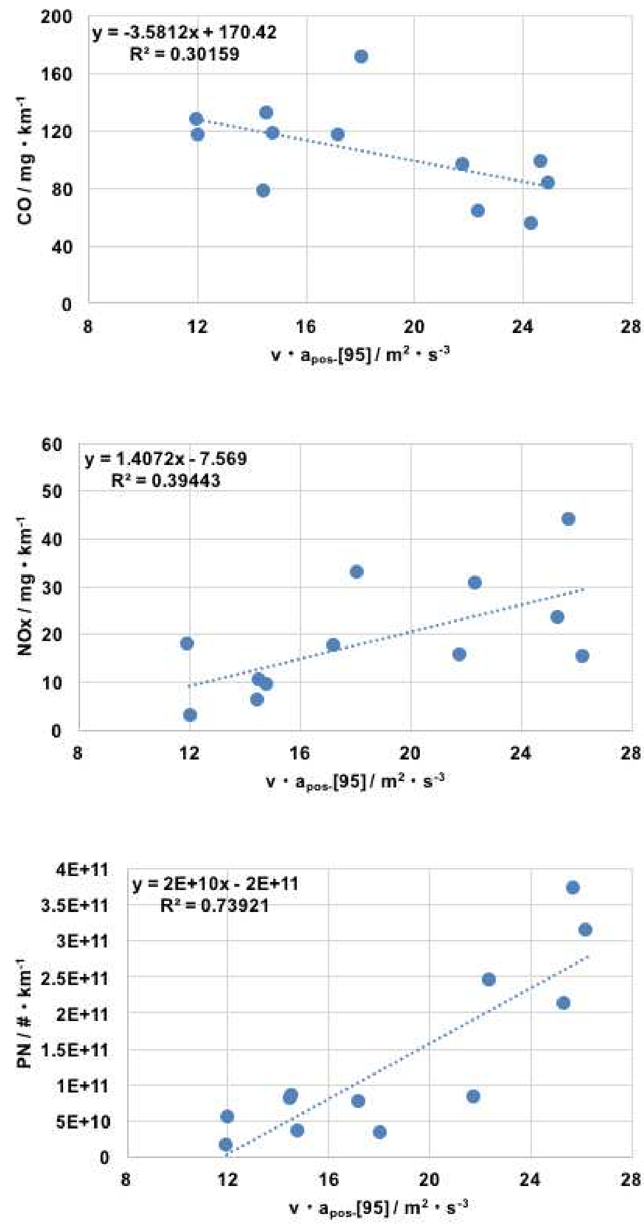

Figure 5. Influences of v·a_{pos}-[95] on rural and highway CO, NO_x and PN emissions.

Excluding the two singular points on the right-hand side of Figure 4, which render the R^2 for urban PN- v·a_{pos}-[95] regression low at 0.31, RDE PN emission fits a positive linear correlation with v·a_{pos}-[95] well. When v·a_{pos}-[95] rises from 8 to 15 $m^{-2}·s^{-3}$, an increase of 60% in RDE PN emission from the baseline is noticed. In rural and highway driving stages, the positive linear correlation between RDE PN emission and v·a_{pos}-[95] becomes stronger, and RDE PN emission seems more sensitive to a change in v·a_{pos}-[95]. As illustrated in Figure 5, RDE PN emission increases by about an order of magnitude when v·a_{pos}-[95] doubles.

RPA

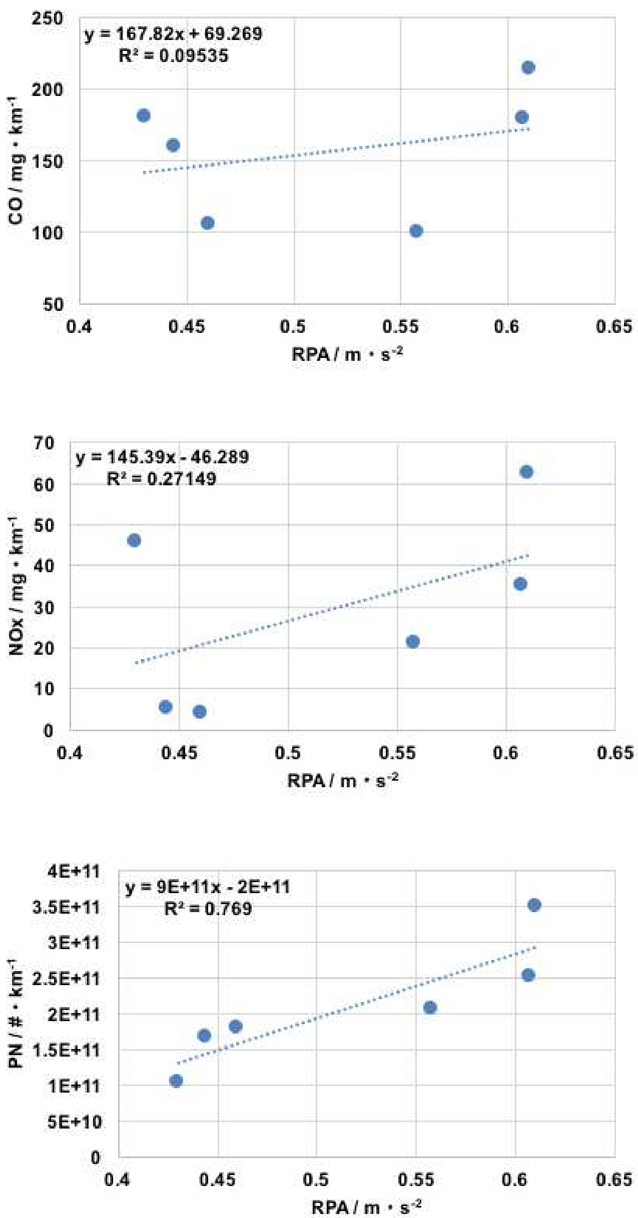

Figure 6. Influences of RPA on urban CO, NO_x and PN emissions.

Figure 6 depicts the influences of RPA on RDE emissions during urban driving. And Figure 7 illustrates the impacts of RPA on RDE emissions during rural driving combined with highway driving.

Unlike v·a_{pos}-[95], both in urban and rural plus highway driving stages, RDE CO emission can be poorly correlated to increased RPA. The R^2 values in urban and rural plus highway durations are only 0.095 and 0.08. Either during urban or rural plus highway driving, the regression line in Figure 6 and Figure 7 seems rather flat. The difference between RDE CO emissions measured and the minimum and maximum RPAs in each figure is on average no higher than 30%.

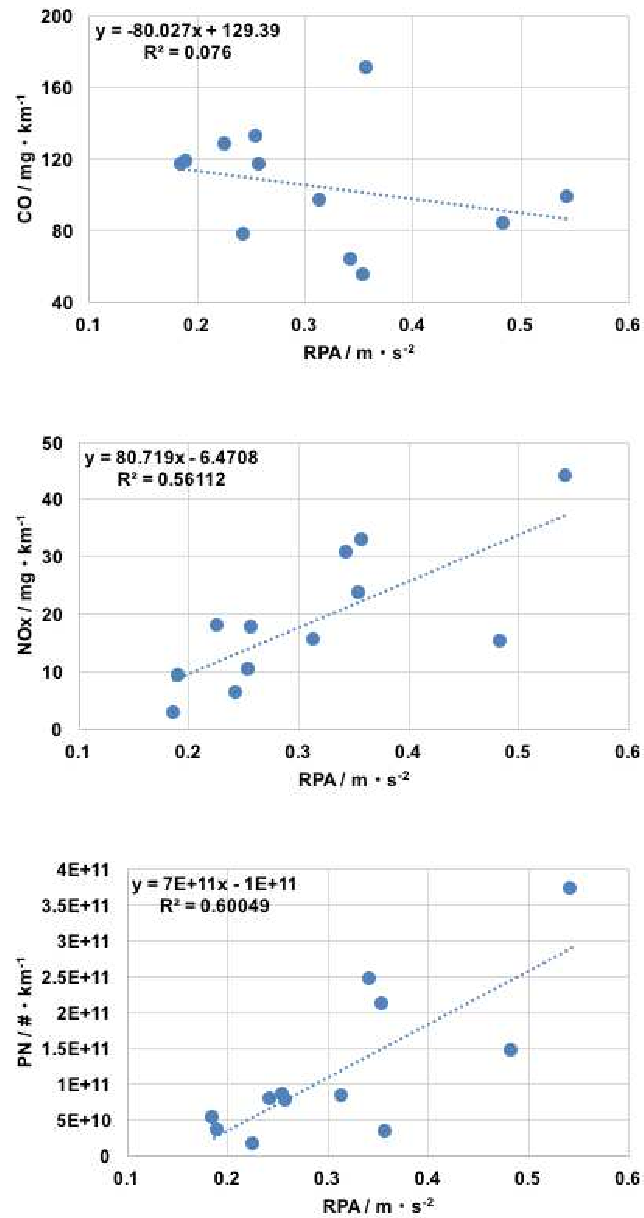

Figure 7. Influences of RPA on rural and highway CO, NO_x and PN emissions.

In urban driving stages, it is quite hard to create a linear correlation between RDE NO_x emissions and RPA since almost all the data points deviate from the regression function in Figure 6 and the R^2 is an unreliable 0.27. Apart from the two singular points on the left and right sides of the figure, RDE NO_x emissions linearly increase with increasing RPA. When RPA increases from 0.45 to 0.6 $m \cdot s^{-2}$, RDE NO_x emissions increased nearly six-fold.

A much better positive linear correlation between RDE NO_x emissions and increased RPA is observed in rural and highway driving in Figure 7. Similar to $v \cdot a_{pos}$-[95], RDE NO_x emissions in rural and highway stages are not as sensitive as during urban driving. NO_x emissions rise approximately 3.5 times once RPA increases from 0.2 to 0.6 $m \cdot s^{-2}$.

As shown in Figure 6 and Figure 7, RDE PN emission also correlates well with RPA in both urban and rural plus highway driving stages. The R^2 values for the two stages are 0.77 and 0.6 respectively. During urban driving, RDE PN emission increases slightly faster with RPA than that with $v \cdot a_{pos}$-[95]. RDE PN emission increases two-fold when RPA increases from 0.45 to 0.6 $m \cdot s^{-2}$. Like $v \cdot a_{pos}$-[95], RDE PN emission corresponds more markedly to changed RPA in rural and highway driving stages. RDE PN emission nearly increases by an order of magnitude when RPA increase from 0.2 to 0.55 $m \cdot s^{-2}$.

Data Processing Methods

In EU regulation, there are two methods available for RDE data processing, namely moving average windows (MAW) and power-binning (BIN). However, in China RDE regulation, only MAW method is acceptable since the BIN method disobeys "The Metrology Law" of the People's Republic of China.

In the early stage of RDE promulgation, there were voices arguing the discrepancy between MAW and BIN methods. Figure 8 compares the emission factors calculated by using both methods. It can be seen that for the same trip, all the pollutants except for NO_x from Car C outputted with BIN method are to various degrees (from 10% to 490%) larger than those outputted with the MAW method. CO and NO_x emissions seem more sensitive to the data processing method than CO_2 and PN emissions.

By comparing the guidelines for both processing methods, it is noticed that only the MAW method requires an exclusion of engine-stop, warm-up and idle. Hence, it is reasonable to suppose that this is where the discrepancy originates. In order to verify this hypothesis, we use BIN method to re-calculate the test data without engine-stop, warm-up and idle and make comparisons with MAW method, as the yellow bars shown in Figure 8.

It is not amazing to see that the results yielded from MAW and BIN with exclusion methods agree well with each other, particularly PN emission, so it is concluded that the gap exists between MAW and BIN is caused by different treatment of engine-stop, warm-up and idle conditions. Future revisions of the RDE regulation shall equal the methods of data exclusion, with engine-stop, warm-up and idle – which have been ubiquitously deemed as high-pollution conditions – not being excluded from calculation, just like what the EU has legislated.

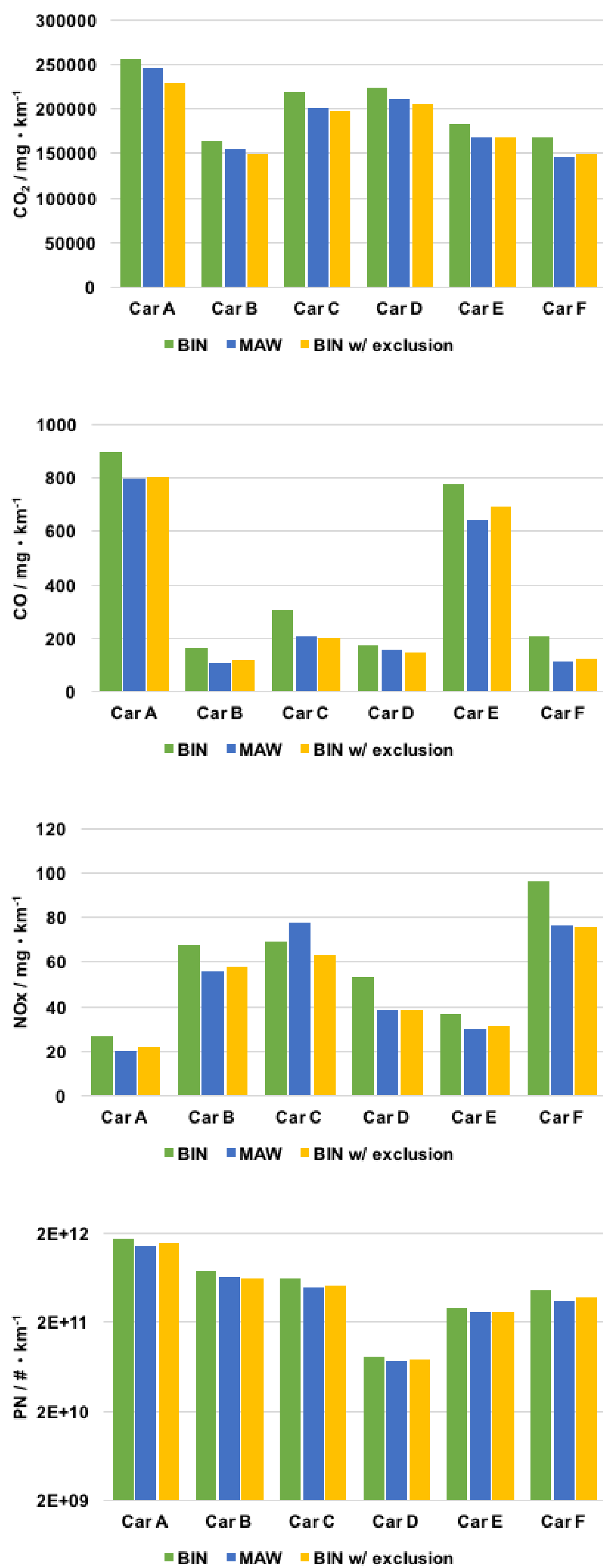

Figure 8. RDE emission factors yielded using different data processing methods (BIN w/ exclusion denotes BIN method with engine-stop, warm-up and idle excluded from the calculation).

Testing Altitude

As introduced in former sections, China RDE regulation differs from EU's in allowing further altitude extension to 2400m because millions of in-use vehicles are operating at such a height in China. Figure 9 illustrates the influences of testing altitude on the result of RDE tests. All the data listed here is collected from China-6 certified vehicles.

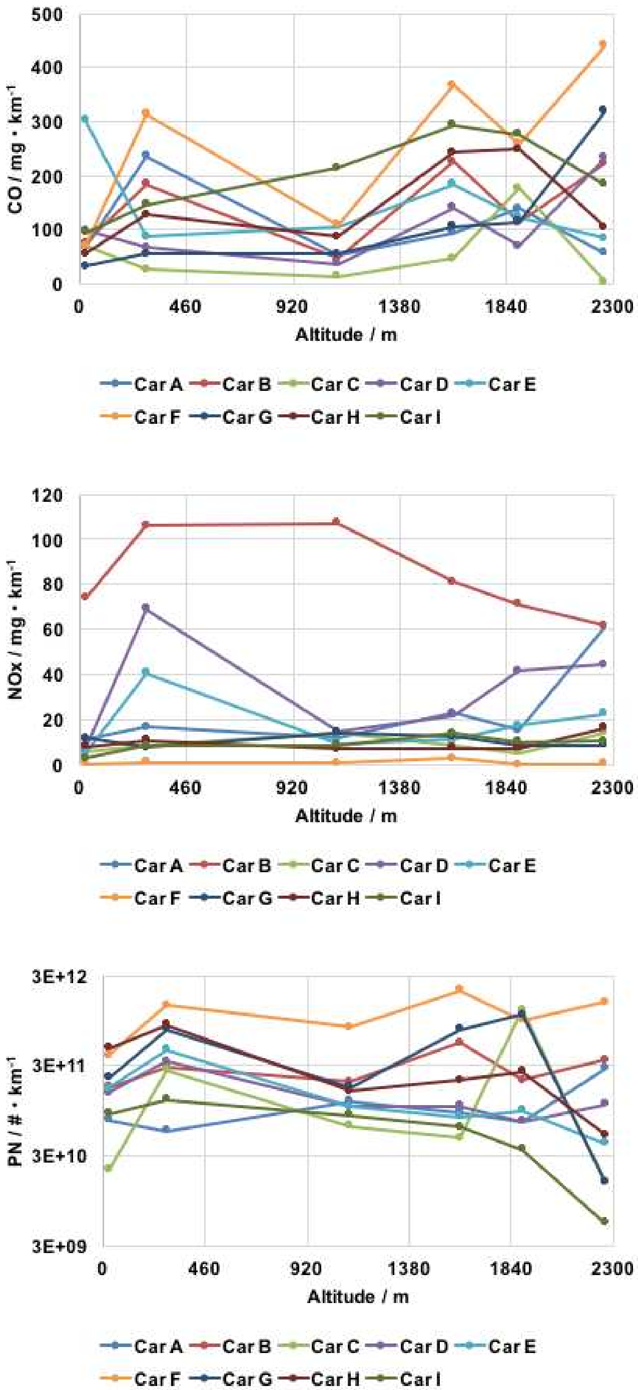

Figure 9. Influences of testing altitude on the result of RDE tests

As depicted in the figure, all the test vehicles are able to meet China-6 with a legislative conformity factor of 2.1, which means at high altitude, exhaust emissions from modern vehicles are not much worsened and can still meet the requirement of regulation, even with no high-altitude extension coefficient.

However, the correlation between each pollutant and ascending altitude is highly mixed, differing from vehicle to vehicle. Many of the test vehicles discharge more CO and NO_x at 2400m, whereas the rest yield equal or lower emission factors. NO_x and PN emissions from some test vehicles seem insensitive to the change in altitude, yet PN emission from one vehicle drops almost an order of magnitude when it runs from sea level to 2400m.

A plausible explanation to the mixed correlation between exhaust emissions and testing altitude could be that changing altitude may always be accompanied by changed traffic, e.g. average speed, frequency of stop-and-go, and weather conditions (e.g. temperature, atmospheric pressure and humidity) so it is very difficult to perform single-variable comparison. The influence of testing altitude being investigated here is only nominal, as in fact, it is a combination of several boundary conditions.

Summary/Conclusions

Based on the experience of China RDE practice, this technical paper endeavors to summarize the influences of some boundary conditions on the result of RDE measurement, so as to provide supporting information and implications for the next-stage EU and China RDE regulation promulgations.

Conformity factors. The majority of test vehicles have CF_{NOx} smaller than 1, implying WLTC might be a little too aggressive to reflect Chinese driving behaviors. Some of test vehicles powered by PFI engines also give high PN emission, suggesting that a PN limit should be applicable for all gasoline vehicles instead of GDI-only.

Hybrid propulsion. RDE PN emission from some models employing GDI-hybrid systems can also be problematic, requiring special attention in urban and rural driving stages.

Vehicle dynamic parameters. RDE CO emission roughly increases with $v \cdot a_{pos}$-[95] in the urban driving stage, but this correlation inverts during rural and highway driving. There is no clear correlation between RDE CO emission and RPA that can be concluded in all driving stages. Both $v \cdot a_{pos}$-[95] and RPA show quite strong impacts on RDE NO_x and PN emissions. In all driving stages, increased $v \cdot a_{pos}$-[95] results in marked increases in RDE NO_x emission. A similar tendency is noticed with increased RPA in rural and highway driving stages. Both increased $v \cdot a_{pos}$-[95] and increased RPA yield increased RDE PN emissions in the urban driving stage. Notably, in rural and highway driving stages, RDE PN emission is more sensitive to the change in vehicle dynamic parameters, PN increases by nearly an order of magnitude once $v \cdot a_{pos}$-[95] or RPA doubles.

Data processing methods. Currently, with engine-stop, warm-up and idle included in the calculation, the BIN method always outputs larger emission factors for all the pollutants. An exclusion of the aforementioned data successively narrows the gap between the two methods to 10%.

Testing altitude. Extra high altitude beyond the EU suggested 1300m does have influence on RDE emissions, but no clear correlation between testing altitude and RDE emissions can be concluded thus far.

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Acknowledgments

The work reported in this technical paper is financially supported by Supporting Plan for Talented Postdoctoral Researchers and National Natural Science Foundation of China (Grant No. 51476012). The authors would like to give thanks to CATARC, VETC and VECC for their kind assistance throughout the research.