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Measurement of the NOx emission of light diesel vehicles in real road driving by PEMS

Deng-Siang Jhang*, and Jau-Huai Lu

Department of Mechanical Engineering, National Chung Hsing University, Taichung, Taiwan

* Corresponding Author: E-mail: shane0316@hotmail.com

Abstract. The exhaust emissions generated by diesel vehicles have great impacts to local air pollution. The most damaging pollutants of diesel vehicles are nitrogen oxides(NOx) and particulate matter(PM). PM has been classified by WTO as a carcinogen, and nitrogen oxides are also classified as potentially carcinogenic. The emission of diesel vehicles has been regulated by EPA since 1987 in Taiwan. The emission standard at the present time is equivalent to EU 5. However, the emission test is carried out in a well controlled laboratory with a specified driving cycle. It has been criticized that the test does not reflect the real emissions on the road. The real road condition is much more complicated and harsh. The emission generated on the real road might be quite different from that in the laboratory. This paper presents the emission measurement of light diesel vehicles on real roads. A portable vehicle measurement system (PEMS) was used to measure the concentration of pollutants in the tailpipe. The instantaneous exhaust flow rate was also recorded with a pitot tube. The real emission was accumulated by integration of the measured concentration variations. Three different driving modes were arranged in each test, including urban, rural, and highway. Several light diesel vehicles that meet EU 5 and EU6 standard were tested. Results of test showed that highway mode has the highest emission rate while urban mode emits the least pollutants.

1. Introduction

In recent years, the problem of air pollution has gained more and more public attention. One of the major causes of air pollution is the pollutants generated by the vehicle on the road, especially nitrogen oxides and particulate matter produced in the exhaust gas of the diesel vehicles. Nitrogen oxides have been classified by WTO as carcinogens. It may cause nerve damage on the human body. Long-term inhalation can cause cerebral palsy, hand and foot atrophy and other hazards. NOx decompose rapidly in the atmosphere and react with common chemicals in the air. Under the sunlight, the reaction products of nitrogen dioxide and other chemicals form nitric acid, which is the main component of acid rain. In addition to nitric acid, ozone is also a major product of NOx reaction. Ozone exposure of pregnant women may cause increase in neonatal interpalpebral narrow incidence and teratogenicity. NOx emissions from diesel vehicles account for 44% of all mobile sources in Taiwan, making diesel exhaust control more urgent and crucial for the reduction of NOx production.

The traditional way to measure the NOx emission of diesel vehicles is to conduct a test in a well controlled laboratory in which vehicle is mounted on top of a dynamometer and follows a driving cycle that simulates a real traffic pattern in some specific areas. The exhaust gases are collected with a constant volume system and then are analyzed with gas analyzers. Since the environment of the laboratory is well controlled and the driving pattern is fixed, it is not surprising that the measured emission factors are lower than those collected on real roads. It has been reported that the diesel vehicle NOx emissions data on real roads are significantly higher than the regulatory pollution emission standards [1]. As a result, EU began to plan to conduct real driving test for light diesel vehicle as part of the regulatory testing procedures from 2011 onwards.

The Taiwan EPA also considers to adopt the real driving test as part of the regulatory testing procedure in the near future. However, the traffic pattern as well as the road conditions in Taiwan are quite different from that of European countries, a series of studies on the feasibility of real road testing were carried out in advance to the enforcement the regulation. This paper presents the results of light duty diesel vehicles on real roads in the middle part of Taiwan.

This study follows the RDE (Real Driving Emissions) protocol defined in EURO VI regulations, including the boundary conditions and testing procedure. A PEMS (Portable Emission Measurement systems) was used to collect the instantaneous emission data on real roads.

2. TEST METHOD

2.1. *program*

According to the RDE regulations [2], the whole trip is divided into three parts by vehicle speed, namely, urban, rural and motorway. The emission in the whole process should be continuously sampled. Table 1 shows the details of each part. The average vehicle speed in the urban area must be 15-40 km/hr. Temporary stop (idling) is required in urban area. Temporary stop is defined as vehicle speed less than 1 km/hr. The time duration for each stop should be 10 seconds or more. The total time duration of temporary stop should be 6-30% of the whole time duration in urban area. However, if one stop exceeds 180 seconds, this trip should be discarded.

The speed in rural area is 60-90 km/hr. In motorway, the speed range is 90-145km/hr and there should be at least five minutes that the speed exceeds 100km/hr. The entire trip should be between 90-120 minutes and each trip shares about 1/3 of the whole time duration with 10% tolerance. The altitude difference between the start and the end is no more than 100 meters. The slope of the route should be less than 1200m/100km. Each trip should be no less than 16 km.

Table 1. RDE test standard

	urban	rural	motorway
speed	<60 km/hr average speed 15-40km/hr	60-90 km/hr	>90 km/hr No more than 145km/hr exceeds 100km/hr for at least five minutes
Total trip ratio	34%±10% (No less than 29%)	33%±10%	33%±10%
idle	6-30% A single stop should not exceed 180s	--	--
trip	No less than 16 km	No less than 16 km	No less than 16 km
1.Total time 90-120 mins 2. altitude difference between the start and the end is not more than 100 meters ， The height of the path should be less than 1200m / 100km			

The PEMS equipments used in this study are installed safely in the vehicle, as suggested by the EU RDE protocol. The fuel used in the test is commercial diesel fuel with sulphur content less than 10 ppm. Engine was started at first to reach the working temperature before the vehicle was on the way. Then, the test was conducted according to the rout planned in advance and the emission data were collected with the PEMS.

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2.2. Devices

Before performing the EU RDE test, the PEMS equipments were installed on the vehicle at first, as shown in Figure 1. The sensors, including the exhaust flow meter, OBD, and GPS, were confirmed to be normally functioned. Mainly for the measurement of vehicle emissions, it can detect CO_2, CO, and NOx concentrations in the exhaust. A chemiluminescent analyser was used to measure the NOx variations in the exhaust flow. The NDIR detector was used to measure the CO_2 and CO concentrations. The tail pipe diameter and length must meet the requirements of RDE specifications to ensure that the flow in the exhaust pipe is stable and uniform. The instantaneous exhaust flow was determined by a Pitot tube which was installed on an extended pipe connected to the original tail pipe, as shown in Figure 2. The exhaust gas was sampled through the sampling hole which is located at the rear part of the extended pipe. Sampling time delay should be considered because the sampling tube is quite long. The delay time in the whole process is corrected for the instrument before the test. It was about 1-2 seconds, depending on the engine running condition. The exhaust density was corrected to a temperature of 20 degrees.

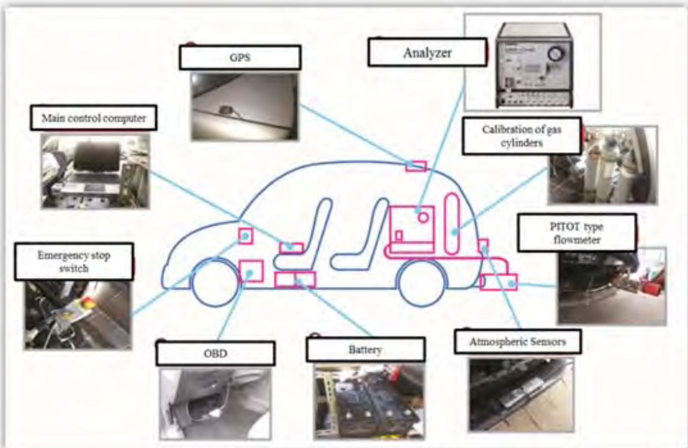


Figure 1 The PEMS equipment that conforms to the EU standard

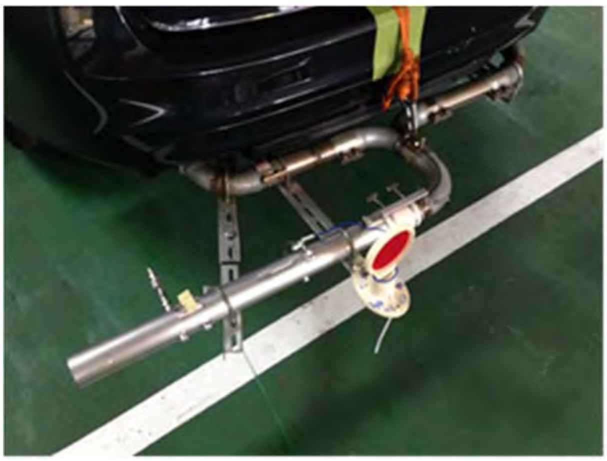
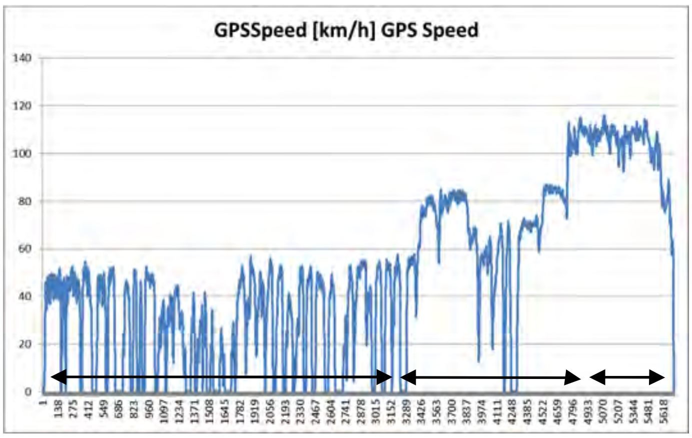


Figure 2 PEMS equipment of sampling tube

According to the EU RDE protocol, the vehicle speed and the associated acceleration information should be provided by the GPS (Global Positioning System) rather than the on board OBD system. The GPS used in this study has the characteristics of fast positioning and high precision, and can measure the vehicle speed, altitude and driving route at that time.
A total of 21 light diesel vehicles were selected in this investigation, ranging from 1600c.c. passenger car to 3200c.c. pickup. The selection principle includes high market share, high representation, and in the warranty within the vehicle. All the test vehicles in this study are equipped with a set of diagnostic devices (On-Board Diagnostics, OBD), which can be used to collect a complete record of vehicles or engine parameters, such as engine speed, exhaust temperature, intake manifold pressure.

3. Measurement results and discussion

We take the data of a vehicle as an example to show the variations in vehicle speed, NOx concentration, and exhaust flow rates during the test, as shown in Figure 3 to Figure 5. The entire trip took 95.43 minutes. Figure 3 shows the vehicle speed variations in the entire trip. The test started from the urban road. We can see that the vehicle stops and goes quite often in this mode. The average speed in this mode was 29km/hr. In a substantial part of this test, the road speed was only 20km/hr, and the maximum speed was no more than 50km/hr. About 55 minutes after the start, the vehicle left the urban area, and ran into the rural area. We can see that the vehicle was going more smoothly in this area because part of the road in this mode is express way and there was less traffic lights. The vehicle speed varies between 60 km/hr and 80 km/hr with an average speed of 76 km/hr and a maximum speed of 90 km/hr. At 79 minutes after the test started, the car went into the third mode, the motorway. The vehicle speed is quite stable. It remains at 110 km/hr for most of the time. Besides, acceleration and deceleration are quite rare.



urban rural motorway

Figure 3 GPS vehicle speed variations during the test

Figure 4 shows the variations in NOx concentration. It can be found that normally the concentration of NOx in the urban area is very low. However, peaks of NOx concentration occur occasionally. The NOx concentration in the rural mode is significantly higher than that in the urban area. This is because increasing vehicle speed would enhance combustion temperature within the cylinder, leading to instantaneous NOx concentration rise. The same trend can be found in the motorway mode. The NOx concentration in this mode is even higher because of the high vehicle speed.

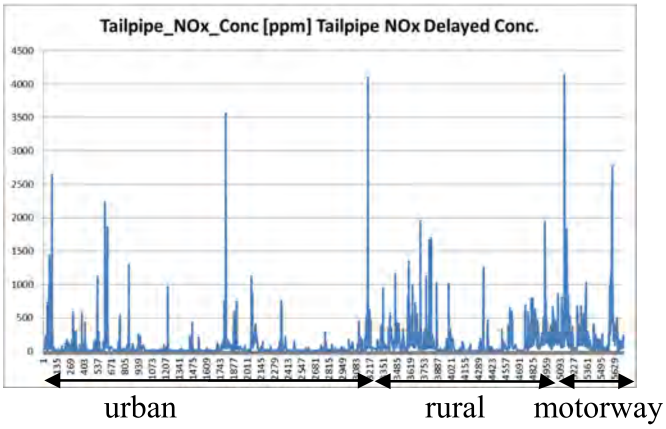


Figure 4 NOx concentration variations during the test

Figure 5 shows the exhaust flow rate variations. Exhaust flow rate is a good indicator of engine load. In the urban area, the exhaust flow rates vary around $1m^3/min$, with instantaneous peak values up to $3m^3/min$. Comparing Figure 3 and Figure 5, we can see that the instantaneous increase in flow rate occurs when the vehicle accelerates. The exhaust flow rate increases when the vehicle speeds up. The NOx concentration also followed. The exhaust flow rate increased in the rural mode. But the degree of change is not as obvious as the urban area. While in the motorway, the exhaust flow rate was significantly higher than $1m^3/min$. It became $3m^3/min$ normally with peaks at 5 m^3/min.

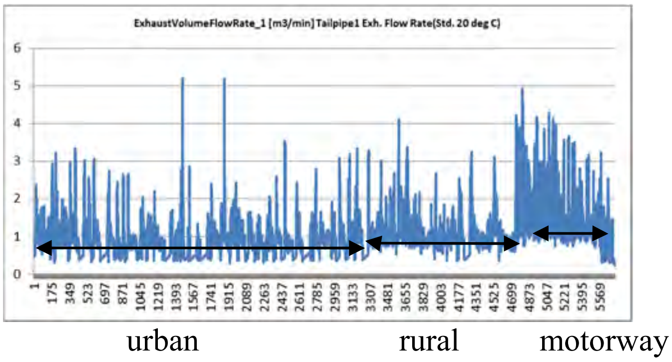


Figure 5 Exhaust flow rate variations during the test

In this study, the data were taken once per second, and the measured speed was used to calculate acceleration every second. The formula of calculation is as follows:

$$An=(Vn+1-Vn-1)/2 \qquad (1)$$

And then multiply the acceleration and speed to get the power of the moment, the formula is as follows:

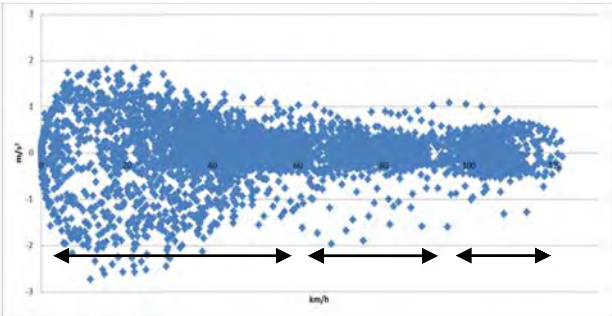
$$P=Vn*An \qquad (2)$$

And convert the NOx concentration (ppm) to the emission (g / sec), as follows:

$$\dot{m} = C \times \dot{Q} \times \rho$$

Where C is the concentration, Q is the exhaust flow under standard conditions, and ρ is the density of the gas under standard conditions.

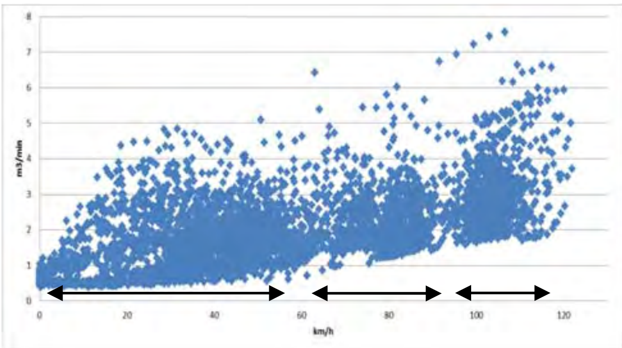
Figure 6 shows the acceleration and velocity distribution of the vehicle in the whole test. The vehicle speed in the urban area varies between 0 to 50 km / hr. The speed in the rural area is about 60 km/hr to 80 km/hr. The speed in the motorway is between 90km/hr and 115km/hr. In the urban area, acceleration and deceleration occur frequently, and their magnitudes vary in a broad range, about -3m/sec^2 ~ +2m/sec^2. In the rural area, the magnitudes of acceleration and deceleration are relatively narrow, -0.3 m/sec^2 to + 0.5 m/sec^2. In the motorway road sections, acceleration and deceleration variations are about the same as that in rural area, -0.5m / sec^2 ~ +0.8 m / sec^2.



urban rural motorway

Figure 6 Acceleration and velocity distribution

Figure 7 shows the relationship between exhaust flow rate and vehicle speed. In the urban area, the flow rate varies 0.5 ~ 3m^3/min. In the rural area, the flow rate is between 1.2 ~ 4m^3/min. And in the motorway, most of the exhaust flow rate was 1.5m^3/min or more. In view of the trend, the faster the vehicle speed, the greater the exhaust flow, the trend is the same as the vehicle in Figure 5.



urban rural motorway

Figure 7 Speed and exhaust flow

Figure 8 shows the relationship between the vehicle acceleration and NOx emissions which is expressed as g/sec. When the vehicle speeds down rapidly, the deceleration is less than -0.5 m/s^2, we can see that NOx emissions are very low. It makes sense that engine emits low concentration of NOx when it is at low load and the driver does not step on the throttle. However, in the positive acceleration region, the relationship between the vehicle acceleration and NOx emissions is not clear. There is no clear trend to show how and when NOx emissions will increase as vehicle speeds up. This is because acceleration is only one of the indicators of vehicle load, not the only indicator.

Figure 9 shows that a non linear relationship exits between NOx emissions and vehicle load during vehicle testing, where vehicle load is defined as equation (2). It can be seen from the figure that as the vehicle power increases, the NOx emissions increase too. If engine is doing negative work, the emissions of NOx is almost zero.

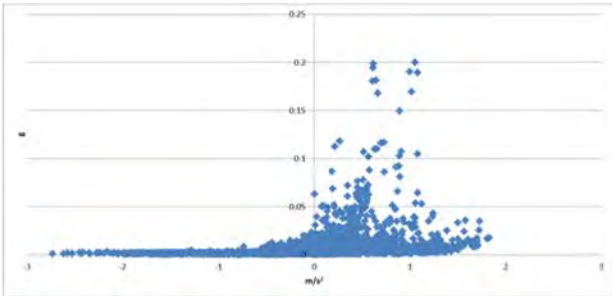


Figure 8 Acceleration of NOx emissions distribution

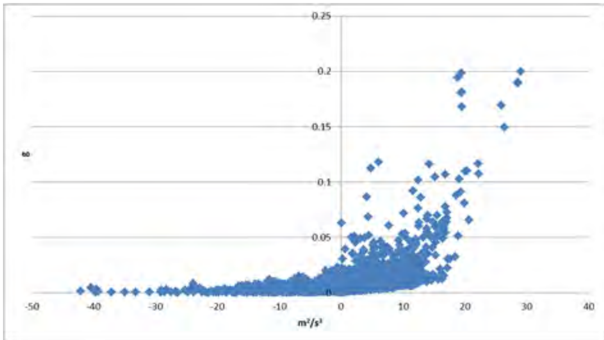


Figure 9 Relationship between NOx Emissions and Vehicle Load

The details of NOx emission in each mode is summarized in Table 2. The urban mode has the longest driving time, and accounts for 43.27% of all NOx emission. The emission factor for urban mode is also the highest. But in terms of emission rate, motorway mode has the highest value.

Table 2. Comparison of NOx Emissions from Different Roads

	urban	rural	motorway
Trip time (min)	64.5	18	14
Distance (km)	31.9	23.1	24.4
Average speed (km/hr)	30	77	104
Emission amount (g)	16.27	9.06	12.27
Emission rate (g/min)	0.252	0.503	0.876
Emission factor (g/km)	0.510	0.392	0.503
Emission ratio (%)	43.27	24.10	32.63

A total of 21 vehicles were tested in this investigation. Figure 10 shows the results of test. Most of the tested vehicles emit less than 1g/km of NOx on the road. It is noted that three vehicles emit more than 1g/km of NOx in urban area, two vehicles emit more than 1g/km of NOx in aural area, and only one vehicle emits more than 1g/km of NOx in motorway. It is interesting to note that the emission in different mode is not necessary consistent. Figure 10 shows that one vehicle has high NOx emission in all three modes. However, another one vehicle has high NOx emission in urban mode only. Its emission in motorway is comparatively low.

The average NOx emitted in each mode were calculated as shown in Figure 11. It is 0.51 g/km in the urban area, 0.44 g/km in the rural area, and 0.48 g/km in the motorway. The averaged emission factor is 0.48 g/km for the whole trip. The tested vehicles emit the highest NOx per kilometer in the urban area. It is interesting to note that the NOx concentration in the exhaust pipe is the lowest in urban area, as shown in Figure 4. Its emission factor is the highest. The reason that the lowest concentration would

produce the highest amount per kilometer is that the vehicle speed in urban area is low. The time elapsed per kilometre is long such that NOx accumulation is high.
The current emission standard for NOx of light diesel vehicle is 0.18 g/km. The regulatory driving cycle is the new European Driving Cycle (NEDC). All the 21 vehicles were tested with NEDC in this study and the averaged emission factor is 0.13 g/km, much less than the regulation value. As a result, the real road emission factor of NOx is 3.7 times higher than the results of laboratory test.
In addition, the study of 21 vehicles for World Light Vehicles Test Cycles (WLTP) were carried out in this study. The averaged emission factor of NOx for WLTP is 0.284g/km, about 60% of the real road value. It is noted that the emission factor of WLTP is higher than that of NEDC, and is closer to the real road value.

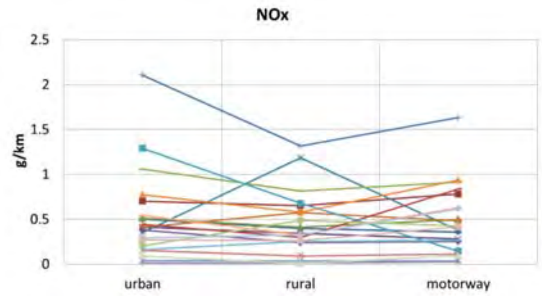


Figure 10 The NOx emission factor in each vehicle of 21 vehicles.

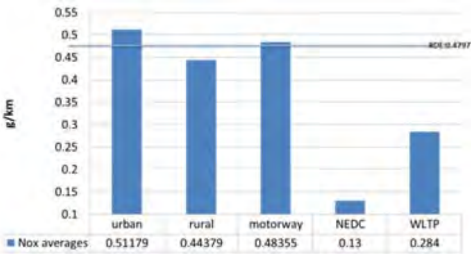


Figure 11 Averaged NOx emission factor for 21 vehicles

Table 3. Comparison of Emission factors for different driving condition

<table>
<tr><td>NEDC</td><td>WLTP</td><td>urban</td><td>rural</td><td>motorway</td></tr>
<tr><td rowspan="2">0.130</td><td rowspan="2">0.284</td><td>0.512</td><td>0.444</td><td>0.484</td></tr>
<tr><td colspan="3">0.480</td></tr>
<tr><td colspan="5">Regulatory standards：0.18 g/km (NEDC)</td></tr>
</table>

Table 3 shows the results of emission factors for different test condition. It can be seen that no matter what kind of condition on real roads, the real emission factor is always higher than the NEDC emission factor. The maximum speed in NEDC is 120km/h, about the same as that in real motorway shown in Figure 3. However, the time duration of maximum speed in NEDC is less than one minute, much lower than that in real motorway. Furthermore, the acceleration and deceleration in NEDC is also much more gentle. The maximum speed in WLTP is 131.3km/h, which is higher than that in real motorway because the speed limit of highway is 110 km/hr in Taiwan. The high speed duration (defined as more than 100 km/hr) in WLTP is around 6 minutes. Besides, the acceleration and deceleration rates in WLTP are much wilder than that in NEDC. That is the reason WLTP has more than twice the emission factor of NEDC. However, the real road has even wilder acceleration and deceleration rates such that the real emission factor is 70% more than that of WLTP.

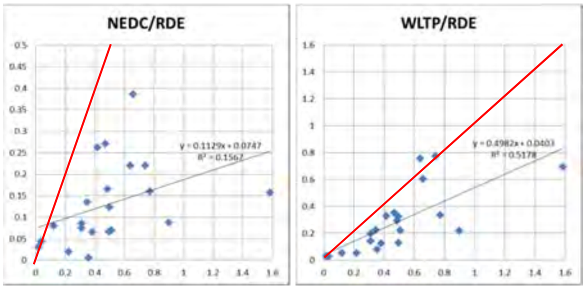


Figure 12 Comparison of real NOx emission factor with NEDC and WLTP

Because real road testing is very costly, risky and time consuming, it would be very convenient if we can predict real road emission factor by the results of NEDC or WLTP which are conducted in a well controlled laboratory dynamometer. Figure 12 shows the comparison of real road emission factor with that of NEDC and WLTP for the 21 tested vehicles. The relationship between real road and NEDC is not clear. Emission factor data scatter in a wild range. The R^2 value for linear regression is 0.1567, showing that the linear equation does not fit the data well. However, the relationship between real road and WLTP is much better. A clear trend exits for the data, especially in the range of low emission factor, which means that WLTP is close to real road emission. But the data scatter in a diverging way in the high emission range. The R^2 value for linear regression is 0.5178, showing that the linear equation is acceptable, even though not very good. It is still unlikely at the present time to estimate real road emission by this linear relationship.

The CO emission factors were also obtained in this study. Figure 13 shows the CO emission factor for all the 21 vehicles in each mode. It can be seen that the CO emission factors of light diesel vehicles are much closer to each other than that of NOx. Most vehicles emit less than 0.4g/km of CO for all the modes. Only one vehicle is the outlier which emits more than 1 g/km of CO in urban and rural areas.

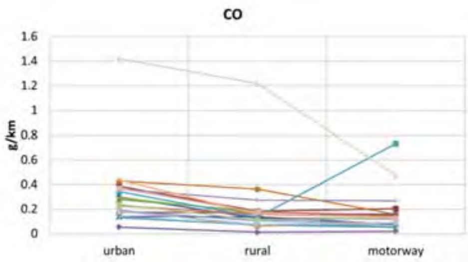


Figure 13 CO emission factors of 21 vehicles in three modes.

The averaged CO emission factors for all 21 vehicles are shown in Figure 14. It is 0.31 g/km in the urban area, 0.196 g/km in the rural area, and 0.168 g/km in the motorway. The averaged emission factor is 0.225 g/km for the whole trip. Similar to the trend in NOx, the tested vehicles emit the highest CO per kilometer in the urban area. The rural area has the second place in CO emission factor, and motorway has the lowest emission factor. The current emission standard for CO of light diesel vehicle is 0.5 g/km. The real road CO emission factors still comply with the regulation.

All the 21 vehicles were tested with NEDC in this study and the averaged emission factor is 0.119 g/km, much less than the regulation value. As a result, the real road emission factor of CO is 1.9 times higher than the results of laboratory test. In addition, the study of 21 vehicles for WLTP were carried out in this study. The averaged emission factor of CO for WLTP is 0.054g/km, about 24% of the real road value. It is noted that the CO emission factor of WLTP is lower than that of NEDC. This is because the duration of NEDC process only takes 1200 seconds, and cold start accounted for a large proportion of the entire test process. CO is formed majorly in the cold start portion while the catalytic converter has not been light up yet. In the WLTP test process, the whole duration is 1800 seconds, and the cold start takes a less share compared with that in NEDC. As a result, WLTP has lower CO emission factor than NEDC. It is interesting to note that all the modes in real road have CO emission factor higher than that in NEDC and WLTP. Even in motorway mode in which the vehicle always remains the same speed at all and the engine keeps hot all the way, the CO emission factor is still higher than that in NEDC that cold start takes a substantial part.

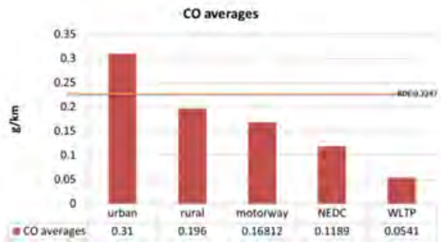


Figure 14 Averaged CO emission factors of 21 vehicles

4. **Conclusion**

(1). Real road driving is much more complicated than the specific driving pattern in laboratory. Vehicle speed varies in a much more rapid way. Acceleration and deceleration vary in a much more wilder range. The associated emission increases compared with that in laboratory.
(2). Urban mode has the highest NOx emission factor, and the largest NOx emission ratio. However, motorway has the highest NOx emission rate.
(3). There is no clear trend between NOx emission rate and vehicle acceleration. However, NOx emission rate is well correlated with vehicle load.
(4). The emission factor in real road is always higher than the laboratory emission factor. It is 3.7 times higher than that of NEDC, 1.7 times higher than that of WLTP.
(5). The real road emission factor does not fit with NEDC at all. The regression between real road and WLTP is better. However, the fitting is not good enough for prediction.
(6). The emission factor of CO in real road is also higher than that of NEDC and WLTP. However, all of them comply with current emission standard.

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