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Real-world fuel efficiency and exhaust emissions of light-duty diesel vehicles and their correlation with road conditions

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Abstract

The real-world fuel efficiency and exhaust emission profiles of CO, HC and NO*x* for light-duty diesel vehicles were investigated. Using a portable emissions measurement system, 16 diesel taxies were tested on different roads in Macao and the data were normalized with the vehicle specific power bin method. The 11 Toyota Corolla diesel taxies have very good fuel economy of (5.9 ± 0.6) L/100 km, while other five diesel taxies showed relatively high values at (8.5 ± 1.7) L/100 km due to the variation in transmission systems and emission control strategies. Compared to similar Corolla gasoline models, the diesel cars confirmed an advantage of ca. 20% higher fuel efficiency. HC and CO emissions of all the 16 taxies are quite low, with the average at (0.05 ± 0.02) g/km and (0.38 ± 0.15) g/km, respectively. The average NO*x* emission factor of the 11 Corolla taxies is (0.56 ± 0.17) g/km, about three times higher than their gasoline counterparts. Two of the three Hyundai Sonata taxies, configured with exhaust gas recirculation (EGR) + diesel oxidation catalyst (DOC) emission control strategies, indicated significantly higher NO_2 emissions and NO_2/NO*x* ratios than other diesel taxies and consequently trigger a concern of possibly adverse impacts on ozone pollution in urban areas with this technology combination. A clear and similar pattern for fuel consumption and for each of the three gaseous pollutant emissions with various road conditions was identified. To save energy and mitigate CO_2 emissions as well as other gaseous pollutant emissions in urban area, traffic planning also needs improvement.

Key words: portable emissions measurement system; fuel consumption; NO*x*; road conditions; diesel taxi

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Introduction

The skyrocketing growth of the vehicle population in China raises a substantial concern regarding imported petroleum dependence and the adverse impacts on the urban environment and human health. According to the census of emission data issued by the Ministry of Environmental Protection (MEP) of China (MEP China, 2010a), on-road vehicles contributed 31% of the NO*x* emissions in China in 2007. Among the vehicle fleet, the diesel vehicle is the largest contributor of both NO*x* and particulate matter (PM) emissions. For example, 59.6% of the vehicular NO*x* emissions in 2009 came from diesel vehicles (MEP China, 2010b). There have been several studies to assess the emission profiles and impacts of more stringent emission control policies and regulations for the heavy-duty diesel vehicles in China (Hao et al., 2001; Huang et al., 2007; Li et al., 2009; Liu et al., 2009; Westerdahl et al., 2009; Wu et al., 2011; Yang et al., 2011). Diesel cars are popular in European countries but have a small market share in China; specific studies about their real-world fuel efficiency and exhaust emission data are lacking. Due to the availability of advanced emission control technologies and their advantage in energy conservation and CO_2 mitigation, the diesel car is considered to be competitive to its gasoline counterpart and might increase its share in the auto market of China. Macao, as one of the two special administrative regions (SAR) in China, is a subtropical city developed with a European style and has more light-duty diesel vehicles operating on the roads than a typical Chinese city. The investigation of the real-world fuel efficiency and exhaust emissions of light-duty diesel vehicles in Macao will be a very useful and important input to the decision-making about the future development of diesel cars in China. The taxies in Macao, all with diesel engines, are excellent fleets to study as they cover the most recent models with varied emission control systems; further, their mileage distributions are sufficiently broad for the emission deterioration analysis.

Macao is comprised of the Macao Peninsula, Taipa Island and Coloane Island. It has an area of 29.2 km^2 and a population of 549,200. By 2008, the total vehicle

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population in Macao reached 182,765, with an ownership rate of about 330 vehicles per 1000 persons. Passenger cars and motorcycles account for about 95% of the total vehicle population (Macao Statistics and Census Service, 2009). Motor vehicle emissions are considered to be the dominant source of air pollution in Macao since the region is not directly influenced by local industrial emissions (Hao et al., 2000; Environment Council of Macao, 2006). According to the ambient air quality monitoring data of 2009–2010 for Macao, as shown in Fig. 1, higher PM_{10} and NO_2 concentrations were observed at the roadside and in the residential area of the Macao Peninsula as compared to the residential or background area of the two other islands. The results indicate the impact of local emissions, especially the vehicular emissions, on the ambient air quality as Macao Peninsula has one of the highest traffic densities in the world. The vertical, horizontal and chemical profiles of PM near major roads also confirm the significance of road traffic to the urban air quality in Macao (Wu et al., 2002, 2003). Furthermore, the interaction of the local wind field and surrounding building-geometry in the central business district results in a "street canyon" effect that will extend the residence time of pollutants (Chan et al., 2001), so the accumulation of local air pollution may be amplified. O_3, considered as a key secondary air pollutant, which is formed by the presence of NO_x and hydrocarbons mostly of vehicular emissions, was relatively high in concentration on Taipa Island. According to the updated 2005 WHO air quality guidelines (WHO, 2006), the O_3 concentrations at the two stations located in Taipa Island exceeded the 8 hr average O_3 threshold (100 $\mu g/m^3$) over 10% of the time in 2009–2010.

With the development of the advanced portable emissions measurement system (PEMS) in recent years, researchers all over the world have been putting more effort on investigating the real-world vehicle emission characteristics. De Vlieger (1997) used on-road tests to study the effects of road types and driving conditions on vehicle emissions and fuel consumption. Frey et al. (2004) analyzed the on-road emission characteristics under different driving conditions and the influence of driving behaviour on vehicle emissions with an on-board emission testing system and set up a methodology which can determine the high emitters of on-road vehicles. In China, Tsinghua University (Hu et al., 2004; Yao et al., 2007;

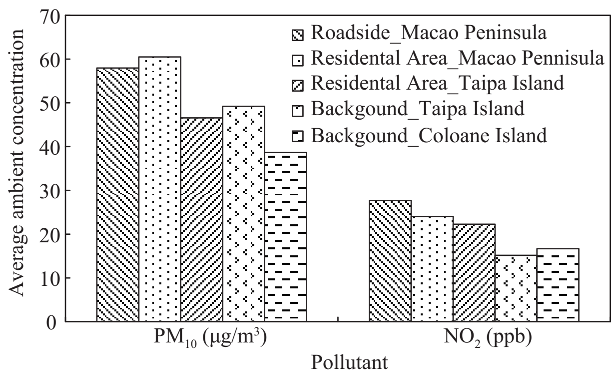

Fig. 1 Air quality monitoring data at different sites in Macao.

Liu et al., 2009; Zhou et al., 2010) obtained the emission factors from gasoline cars and heavy-duty trucks in various cities with different versions of PEMS. Tianjin University (Du et al., 2002) studied minivan emissions under on-road conditions in Tianjin, and the Shanghai Academy of Environmental Sciences (Chen et al., 2007; Huang et al., 2007) analyzed the real-world emission characteristics of diesel buses in Shanghai using PEMS. The Chinese Research Academy of Environmental Sciences (Li et al., 2009) compared the real-world emissions of heavy-duty diesel trucks using different emission control technologies and pointed out the variation of real emission reduction efficiency among technologies. These studies contribute to an understanding of China's real-world vehicle emissions and significantly support decision-making for policies, regulations and management initiatives for in-use vehicle emission control.

In this article, we investigated the real-world fuel efficiency and exhaust emissions of light-duty diesel vehicles tested by PEMS. The impacts of vehicle mileage, emission control technology configurations, and road conditions on the on-road fuel efficiency and emissions of diesel cars were evaluated. We also compared and discussed the trade-offs in fuel economy and emissions between diesel cars and their gasoline counterparts. We aimed to help policy-makers better understand the real emission profiles of diesel cars and promote development plans for cleaner light-duty diesel vehicles in China's future auto market.

1 Materials and methods

1.1 On-board emissions measurement system

The SEMTECH-DS (Sensor's Inc., USA) on-board emissions measurement system was used to measure the on-road second-by-second emissions of 16 light-duty diesel vehicles (all are taxies). It has a non-dispersive infrared analysis (NDIR) unit to measure CO and CO_2 concentrations, a heated flame ion detector (HFID) to measure total hydrocarbons (HC) concentration, and a non-dispersive ultraviolet (NDUV) unit to measure NO and NO_2 concentrations simultaneously. O_2 concentration was measured by an electrochemistry method. The exhaust flow rate from vehicle tailpipe was recorded by the SEMTECH-EFM mass flow measurement device so the fuel consumption and mass emissions of regulated pollutants could be calculated based on the pollutant concentration and exhaust mass flow rate. In addition, a GPS device was used to record vehicle speed as well as the vehicle's location information (longitude, latitude, and altitude). For quality assurance, zeroing and calibration were conducted for NDIR, HFID and NDUV units prior to testing each day during the campaign with standard zero and calibration gases. Second-by-second data of pollutant concentration, exhaust flow rate, vehicle speed, ambient temperature and humidity were obtained during the on-road emissions test. Figure 2 presents a sketch of the real-world vehicle emissions measurement system installed in a taxi.

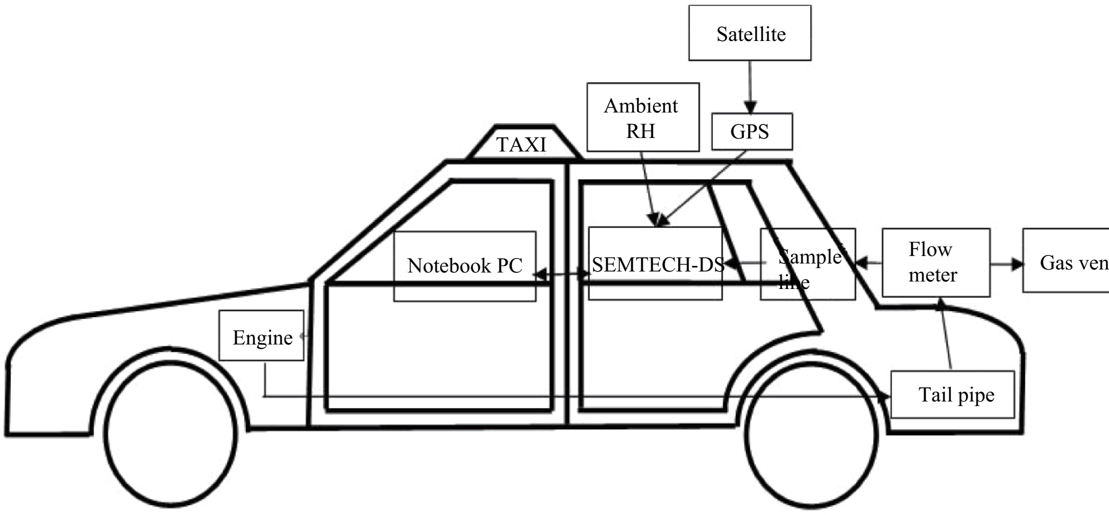

Fig. 2 Sketch of real-world vehicle emissions measurement system installed in a diesel taxi.

1.2 Vehicle samples

According to the database of the whole taxi fleet provided by the Macao Transportation Affairs Agency, 16 diesel taxies were selected for this research. These 16 vehicle samples covered various technology configurations, model years and mileages, and could be considered as representative of the whole taxi fleet. Table 1 summarizes the information for these vehicles, including the manufacturer, model, mileage, model year, and displacement data. It should be noted that the majority of the sampled taxies were made by Toyota, which should be attributed to the fact that more than 80% of the taxies running in Macao are Toyota Corollas. Macao does not have specific vehicle emission standards so the vehicles imported by Macao could not be classified by sets of emission standards. But in general, the vehicles should meet the emission standards of the country of production for their respective model year.

1.3 Test route and traffic conditions

The test route for real-world vehicle emissions measurement is shown in Fig. 3, with a total length of about 28 km and duration of about 1 hr. The route covers several road types with different traffic flows, including the local streets/roads and two bridges that connect the Macao Peninsula and Taipa Island. Given the traffic infrastructure, there is no typical high-speed freeway in Macao. Thus the maximum vehicle speed during the whole test was below 80 km/hr. The vehicle speed varied significantly during the test. A typical driving cycle is given in Fig. 4 as an example to present the speed variation during a complete on-road emission test. To enable further comparison, the whole route was divided into 6 sections and labelled sequentially, as shown in Figs. 3 and 4. Road sections No. 1 and 3 include the two bridges and represent the city 'expressway' as the vehicle speed at these two sections is generally higher than 30 km/hr without stops. Road sections No. 2, No. 4 and No. 6 are the gathering of selected roads in Taipa Island and the newly developed area of Macao Peninsula, and they represent the city roads with light traffic congestion according to the vehicle speed. Finally,

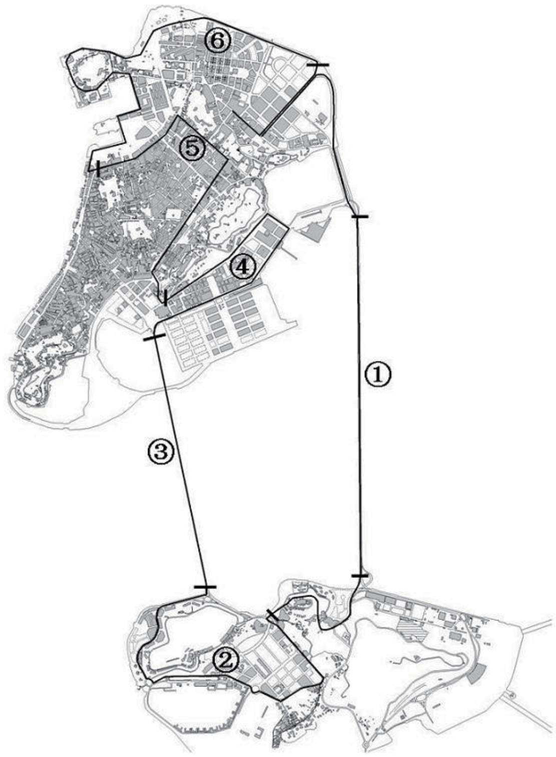

Fig. 3 The map of the on-road test route (①–⑥ means six sections).

road section No. 5, which goes across the downtown of Macao Peninsula, is typical of local streets with heavy traffic flow. The average speed at road section No. 5 was below 20 km/hr for all of the tested vehicles. The beginning and ending of the route were excluded from the analysis because the PEMS power or GPS signals are often inoperative during those periods. There is one more road section excluded from the analysis which is between the sections No. 1 and No. 2 as it goes across the campus of Macao University (built on a small hill). This part is not considered as a typical road type.

1.4 Data processing

Although all of the 16 vehicles were tested along the same route, the average speed of each taxi is slightly

Table 1 Information of the light-duty diesel vehicles selected for the emission tests

Vehicle No.	Manufacturer	Model	Odometer (km)	Model year	GVW[a] (kg)	Displacement (L)	After-treatment
1	Toyota	Corolla 2.0 Xli M/T	135,743	2009	1695	2.0	Without
2	Toyota	Corolla 2.0 M/T	210,830	2008	1695	2.0	Without
3	Toyota	Corolla 2.0 Xli M/T	372,194	2007	1630	2.0	Without
4	Toyota	Corolla 2.0 Xli M/T	547,646	2006	1630	2.0	Without
5	Toyota	Corolla 2.0 Xli M/T	569,324	2006	1630	2.0	Without
6	Toyota	Corolla 2.0 Xli M/T	634,272	2006	1630	2.0	Without
7	Toyota	Corolla 2.0 Xli M/T	687,171	2006	1630	2.0	Without
8	Toyota	Corolla 2.0 M/T	757,940	2003	1630	2.0	Without
9	Toyota	Corolla X ASSISTA	791,572	2002	1405	2.2	Without
10	Toyota	Corolla 2.2 X	842,805	2002	1405	2.2	Without
11	Toyota	Corolla X ASSISTA	> 1,000,000[b]	2002	1405	2.2	Without
12	Mazda	323 2.0L LX5	> 1,000,000[b]	1998	1600	2.0	Without
13	Hyundai	Sonata 2.0CRDI A/T	144,000	2008	2150	2.0	EGR+DOC[c]
14	Hyundai	Sonata 2.0CRDI A/T	262,065	2007	2150	2.0	EGR+DOC
15	Hyundai	Sonata 2.0CRDI A/T	371,966	2007	2150	2.0	EGR+DOC
16	Peugeot	406 HDI4-DO	1,065,000	2003	1870	2.0	Without

[a] GVW: gross vehicle weight.
[b] No actual odometer reading could be obtained after it exceeded the maximum (999,999 km).
[c] EGR: exhaust gas recirculation; DOC: diesel oxidation catalyst.

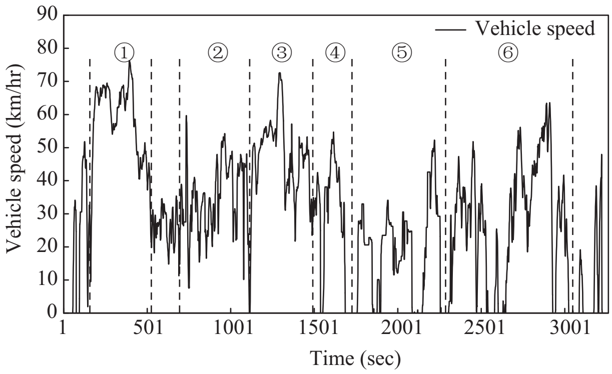

Fig. 4 A typical driving cycle of the on-road test with different road conditions.

different due to unpredictable changes in the real-world traffic conditions. The average vehicle speed ranges from 25 to 35 km/hr for all tested vehicles with the majority at about 30 km/hr. Since the distance-based emission factor is strongly relevant to vehicle speed, the emission data for these 16 diesel taxies were normalized to the same average speed using the vehicle specific power (VSP)-bin method before comparison. VSP is defined as the instantaneous power demand on the engine per unit vehicle mass which can be calculated by the vehicle speed, acceleration and other parameters. It can represent the driving conditions in an integrated way and show better correlations with emission rates of pollutants than other operating parameters. We established 22 operating mode bins defined by VSP and vehicle speed to normalize the fuel consumption and emission factors based on the averaged driving cycle profile (average speed = 29.8 km/hr) of the on-road tests conducted in Macao. The details of the VSP-bin method are presented in the following relevant documents: Koupal et al. (2004); Liu et al. (2009); Wang (2010).

The fuel consumption of diesel taxies was calculated by the carbon balance method that is widely used for light-duty vehicles. In this study the equation from the fuel economy standards for light-duty vehicles in China (AQSIQ China, 2003) was used to calculate diesel fuel consumption:

$$FC_d = \frac{0.1155}{D_d}((0.866 \times EF_{HC}) + (0.429 \times EF_{CO}) + (0.273 \times EF_{CO_2})) \quad (1)$$

where, FC_d (L/100 km) is the diesel fuel consumption; D_d (kg/L) is the density of diesel fuel, which was set to 0.85 kg/L (AQSIQ China, 2009); EF_{HC} (g/km), EF_{CO} (g/km) and EF_{CO_2} (g/km) are the emission factors of HC, CO and CO_2, respectively.

2 Results and discussion

2.1 Fuel consumption and emission factors

Fuel consumption and emission factors of the 16 diesel taxies are given in Fig. 5. Since there are 11 Toyota Corolla diesel taxies in the total 16 samples, the statistical results are illustrated for two vehicle groups – the Corollas and the remainder (others). As shown in Fig. 5d, the 11 Corolla diesel taxies have close fuel consumption. The fuel efficiency results of the Corolla diesel taxies, (5.9 ± 0.6) L/100 km, are favourable for city roads compared to the other taxies. The fuel consumption of the Corolla taxies is 37% lower than the (9.3 ± 1.4) L/100 km average of the selected three Sonata taxies. The higher fuel consumption of Sonata diesel taxies could be partly attributed to the variation in transmission systems and emission control strategies. The Sonata taxies are equipped with automatic transmission systems while the 11 Toyota Corolla taxies all have manual transmissions. A vehicle with an automatic transmission system has ca. 10% higher fuel consumption than its manual counterpart. Sonata models tested in this study were equipped with the exhaust gas recirculation (EGR) systems which may also bring fuel penalty by up to 10% (Bhattacharyya and Das, 1999).

The certified fuel consumption of the gasoline Corolla model with similar displacements was 7.6 L/100 km under the NEDC driving cycle (MIIT China, 2011). A multiplier of 1.15 was used to convert the certified NEDC data into

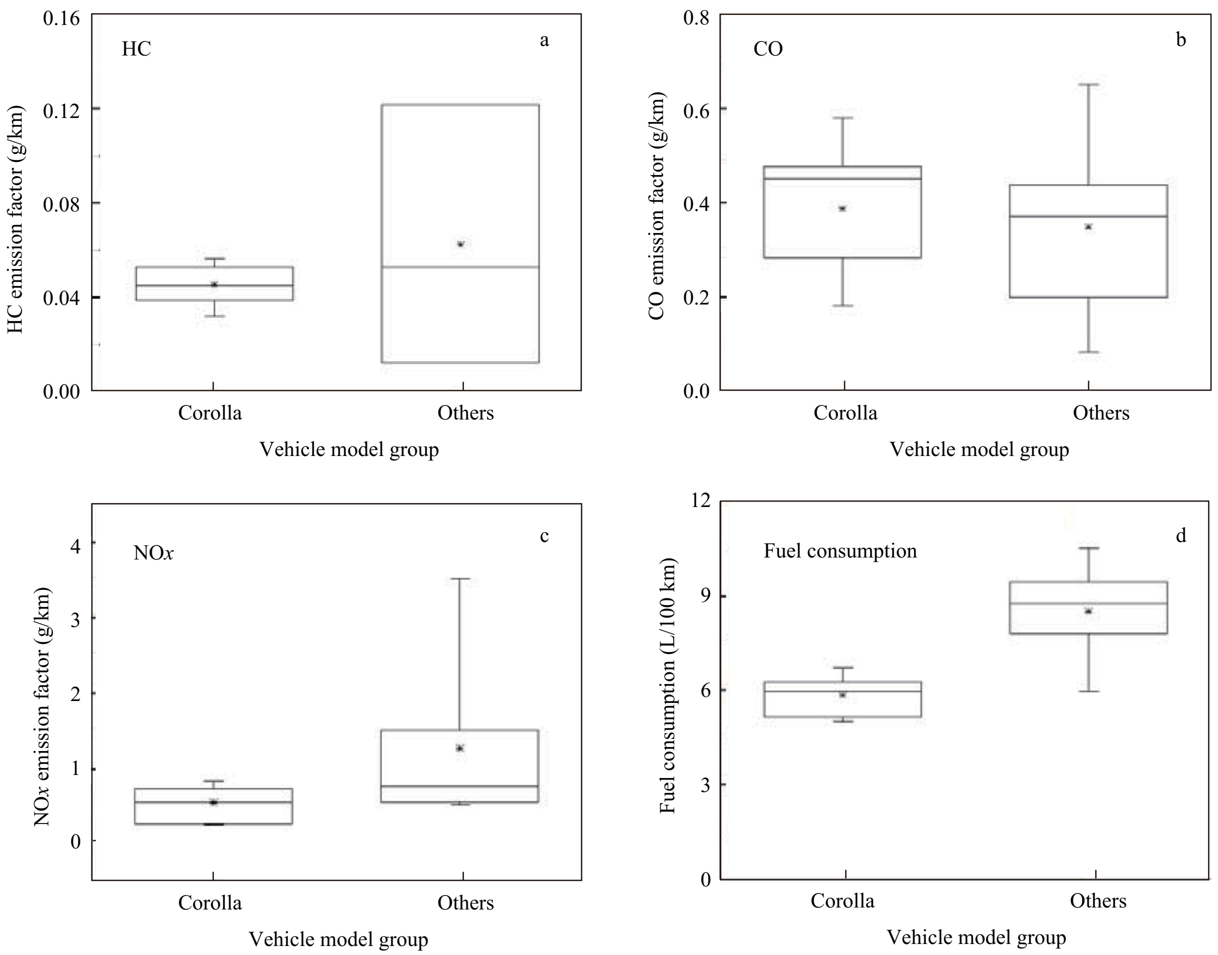

Fig. 5 Real-world averaged emission factors of the 16 diesel taxies (a, b, c) and fuel consumption (d). Line within box: median value; asterisk within box: mean value; top line of box: third quartile; bottom line of box: first quartile; top outlier: maximum; bottom outlier: minimum.

real-world fuel consumption (Lin, 2010). Therefore, the real-world fuel consumption of gasoline Corolla models would be around 8.7 L/100 km. Taking into account the difference in the heat value and density between diesel fuel and gasoline, a multiplier of 1.18 was applied in this study to convert diesel fuel consumption into gasoline equivalent. The gasoline consumption equivalent of Corolla diesel taxies is 7.0 L/100 km, 20% lower than the gasoline models. The sales weighted fuel economy for passenger cars in China in 2009 was 7.87 L/100 km under the NEDC cycle (Wagner et al., 2009). Applying the conversion factor, the real-world fuel consumption would be 9.05 L/100 km on average. In general, penetration of diesel cars will help save energy, similar to the advantage of Corolla diesel versus its gasoline counterpart. However, if diesel cars are equipped with specific emission control strategies (such as DOC plus EGR), such advantage in energy saving may be significantly weakened.

Similar to the fuel consumption, the Corolla diesel taxies have comparable NO*x* emissions with an average factor of (0.56 ± 0.17) g/km. The other five diesel taxies, however, have an average NO*x* emission factor of (1.84 ± 1.11) g/km, much higher and more scattered than the Corolla fleet (see Fig. 5c). HC and CO emissions of all the 16 diesel taxies are quite low, but again Corolla taxies show smaller deviation than the other 5 taxies. The average HC and CO emission factors of the 16 diesel taxies are (0.05 ± 0.02) g/km and (0.38 ± 0.15) g/km (Fig. 5a, b). It is unsurprising that HC and CO emissions of light-duty diesel vehicles are not a major air pollution problem.

To compare the emissions of light-duty diesel vehicles obtained in this study to light-duty gasoline vehicles, we used the data of four diesel taxies from Macao and four gasoline taxies from Beijing for further analysis. The four diesel taxies are No. 1 through four vehicles listed in Table 1, which are model year 2006–2009 Toyota Corolla 2.0 M/T (manual transmission) with odometer readings from 136,000 to 548,000 km. The four gasoline taxies are all model year 2010 Hyundai Elantra 1.6 M/T with odometer reading from 135,000 to 184,000 km. All of the four Elantra gasoline taxies could meet the China IV (equal to Euro IV) emission standards. The gasoline taxies were tested with the same PEMS on the typical roads in Beijing in the fall of 2010, and the emission data were also normalized with the same VSP-bin method and Macao driving cycle profile for comparison. The average emission factors of CO, NO*x* and CO_2 for the selected Corolla diesel taxies and Elantra gasoline taxies are presented in Table 2. As expected, the diesel taxies show a significant advantage in CO_2 and CO emissions compared to the gasoline taxies. In this study, the average emission factors of CO_2 and CO for the four diesel taxies are 32% and 46% lower than those for the four gasoline taxies, respectively. However, we found high NO*x* emissions for diesel taxies. The diesel

Table 2 Comparison in CO, NO*x*, and CO_2 emission factors for selected diesel and gasoline taxies

Fuel type	CO (g/km)	NO*x* (g/km)	CO_2 (g/km)
Gasoline	0.927 ± 0.429	0.148 ± 0.065	232 ± 16
Diesel	0.497 ± 0.049	0.572 ± 0.040	158 ± 15

taxies are nearly 3 times higher in NO*x* emissions than their gasoline counterparts (see Table 2). So the choice between diesel and gasoline really depends on the priority of the different goals. In the next decade, control of NO*x* emissions will be one of the top priorities for MEP. Light-duty gasoline vehicles are superior to the light-duty diesel vehicles in terms of NO*x* control. However, for energy conservation and CO_2 emissions mitigation, light-duty diesel engines have an advantage.

Another important finding is that the CO, HC and NO*x* emission results of these diesel taxies do not show any significant deterioration with the vehicle aging or accumulation of odometer reading, as shown in Fig. 6. A major reason is that diesel engines usually have less deterioration level than gasoline engines (Metz, 1990; Hao et al., 2000; Chiang et al., 2008). Moreover, the strong intention of taxi companies to save fuel cost by careful maintenance and driver training could be another factor.

Furthermore, NO and NO_2 emissions were analyzed separately because of the increasing concern of high oxidation potential of NO_2. The emission factors of the 16 diesel taxies are shown in Fig. 7. Clearly, the No. 13 and No. 15 taxies have much higher NO_2 emission factors and NO_2/NO*x* ratios than those of the other 14 diesel taxies. For instance, the No. 13 and No. 15 taxies have NO_2 emission factors of 0.41 and 0.92 g/km, approximately one order of magnitude higher than those for other taxies (average in ca. 0.05 g/km). The NO_2/NO*x* ratios are 53% and 39%, respectively, also significantly higher than the average of other 14 diesel taxies (ca. 7%). Compared to NO, NO_2 is a much stronger oxidant. Thus, the significant increase in NO_2 emissions or NO_2/NO*x* ratios might have adverse impacts on ozone pollution in urban areas even though NO emissions are reduced. The higher NO_2 emission factors or NO_2/NO*x* ratios of No. 13 and No.

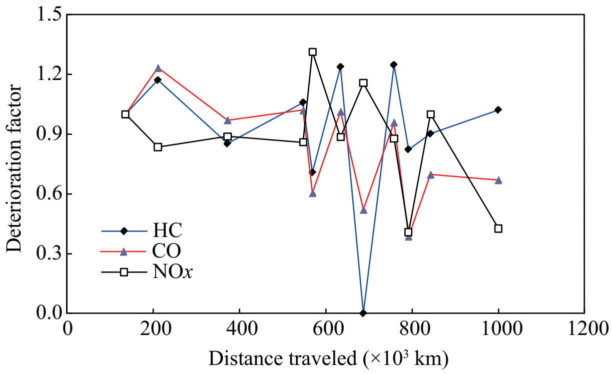

Fig. 6 Deterioration in emissions of the Corolla diesel taxies with distance traveled (factors of the newest car are all set to 1 and the others are presented by ratios).

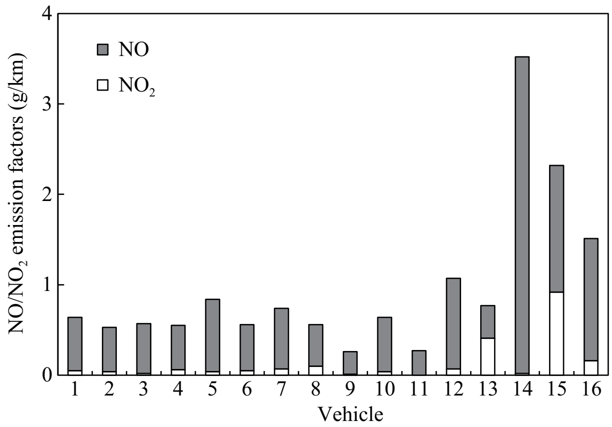

Fig. 7 NO and NO_2 emission factors of the diesel taxies.

15 diesel taxies are most probably related to their specific emission control strategies. These two diesel taxies both adopted EGR and DOC to reduce NO*x* and PM emissions. EGR and DOC could raise the NO_2/NO*x* ratio because exhaust NO might be oxidized further to NO_2 when it is recycled to the cylinder for secondary combustion, and DOC might oxidize the NO to NO_2 if the noble metal catalyst is too active. It should be noted that the No. 14 diesel taxi is also configured with the same control devices as No. 13 and No. 15 but with rather low NO_2 emissions, which indicates that EGR + DOC does not inevitably produce high NO_2. If the EGR + DOC are used properly, the NO_2/NO*x* ratio might be low as well. However, the possibility of an increase in NO_2 emissions as well as NO_2/NO*x* ratio (2 of the 3 vehicle samples in this study) triggers a concern regarding this technology combination, and a further complete evaluation needs to be conducted.

PM emissions from the diesel vehicles have been considered as a trouble for the local and regional air quality. Previous studies, including the laboratory dynamometer tests and roadside air quality monitoring, revealed that diesel vehicles without diesel particulate filter (DPF) would have much higher PM emissions, both in mass and number, than their gasoline counterparts (Williams et al., 1989; Schauer et al., 1996; Kittelson, 1998; Gertler, 2005; Geller et al., 2006). Other studies also indicated that diesel cars would emit higher carcinogens, e.g., polycyclic aromatic hydrocarbons (PAHs), than gasoline cars at typical driving conditions (Phuleria et al., 2007; Bergvall and Westerholm, 2009). However, with the implementation of Euro V Emission Standard (European Union, 2010), the new diesel car installed with DPF might have comparable low emissions in PM with its gasoline counterpart. Recently researchers have developed different on-board PM measurement systems for diesel trucks and buses driving on road (Brown et al., 2000; Booker et al., 2007; Liu et al., 2009, 2011; Johnson et al., 2011; Yao et al., 2011), while such PM measurement systems are still too bulky and complicated to measure on-road PM profiles in small diesel cars. Along with the development of on-board PM sampling and measurement technologies, on-road PM measurement might be considered for diesel cars in the near future.

2.2 Correlation between fuel consumption/emissions of the diesel taxies and road types

Vehicle fuel consumption and emissions change with road and traffic conditions. To better understand the relationship between fuel consumption/emissions of the diesel taxies and the road conditions, the test data were grouped into the six different road sections defined in Figs. 3 and 4. Since 80% of the taxies running in Macao are Toyota Corollas, and the fuel consumption and emissions of the tested 11 Corolla diesel taxies show small deviation, we used the data of these 11 taxies for further correlation analysis. The other five diesel taxies, which have a relatively large deviation in fuel consumption and emissions were only used to verify if the correlation pattern was correct.

Figure 8 presents the average fuel consumption and emissions of the 11 Corolla diesel taxies on six road sections, with the average speed at different road sections. A clear and similar pattern for fuel consumption as well as for the emissions of each of the three gaseous air pollutants with various road conditions could be identified. Road sections No. 1 and No. 3, which represent the city expressway, have the lowest fuel consumption and emissions of vehicles among the 6 road sections. Road section No. 5, a typical case of local streets with heavy traffic flows, has the highest fuel consumption and emissions of vehicles driven under such road condition. The average fuel consumption and NO*x*, CO and HC emissions of vehicles on road section No. 5 are ca. 80%–120% higher than those on road sections No. 1 and No. 3. Accordingly, the average vehicle speed for road section No. 5 is about 15 km/hr, much lower than the speed for road sections No. 1 and No. 3 (ca. 50–60 km/hr).

Traffic lights do not seem to have significant effects on the fuel consumption and emissions for those city roads with light traffic flows. Road section No. 2 represents the city roads with light traffic congestion but without traffic lights, while road sections No. 4 and No. 6 are those with light traffic congestion and with traffic lights. As shown in Fig. 8, they all have very close average fuel consumption, and NO*x*, CO and HC emission factors for the 11 diesel taxies. The average fuel consumption, NO*x*, CO and HC emission factors at road sections No. 2, No. 4 and No. 6 are ca. 20%–40% higher than those for road sections No. 1 and No. 3. The average vehicle speed at road sections No. 2, No. 4 and No. 6 is between 30 and 35 km/hr.

To confirm that such a correlation profile between fuel consumption/emissions and road types is correct, we chose the 3 Hyundai Sonata diesel taxies for the next verification analysis. Figure 9 presents the average fuel consumption and emissions of the 3 Sonata diesel taxies at the 6 road sections with the average speed over different sections. Again, we see the same trend although the absolute values at the *Y*- or *X*-axis are different. The fuel consumption results as well as the emissions of the three vehicles on

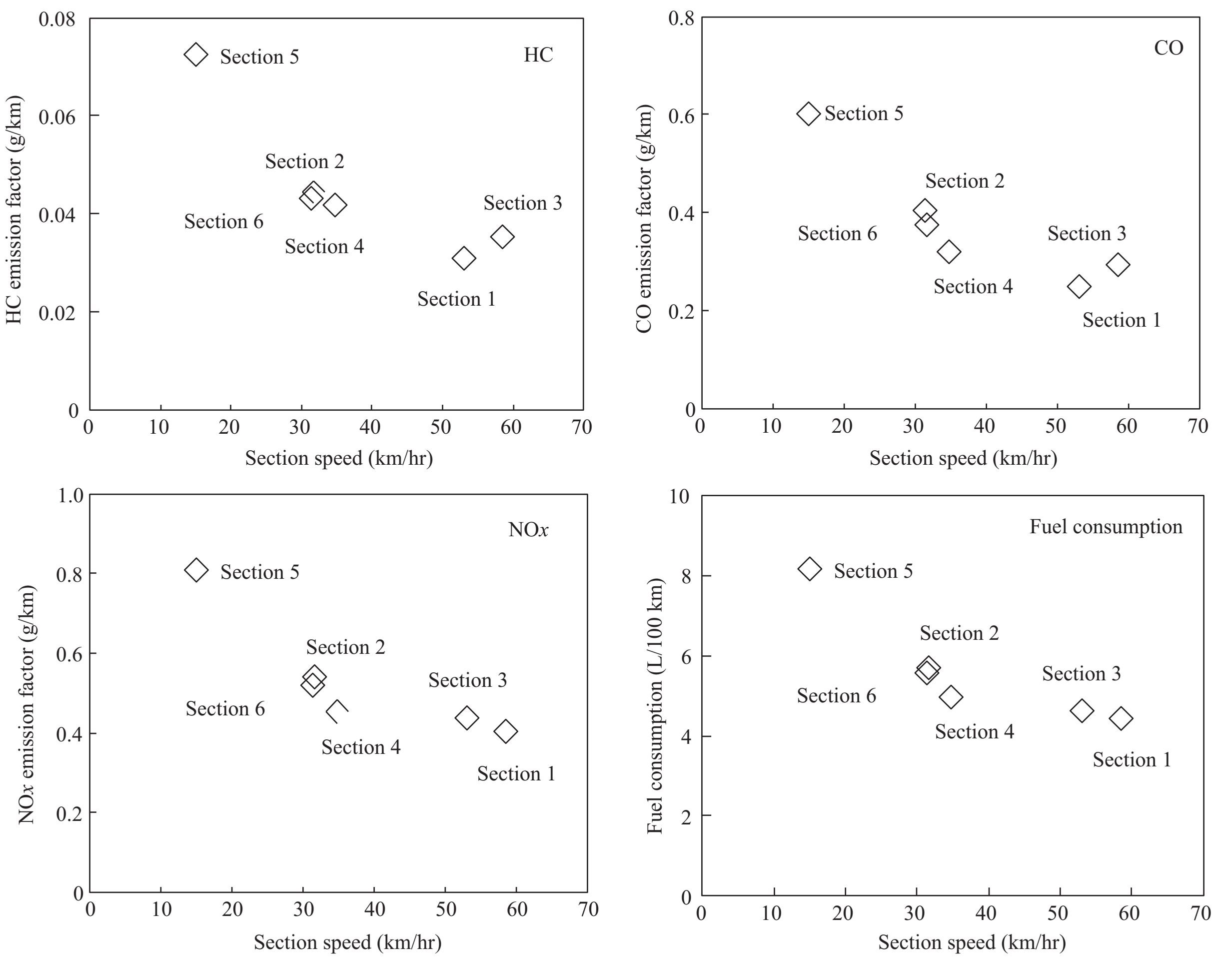

Fig. 8 Average fuel consumption and emission factors of the 11 Corolla diesel taxies with average vehicle speed on the six road sections.

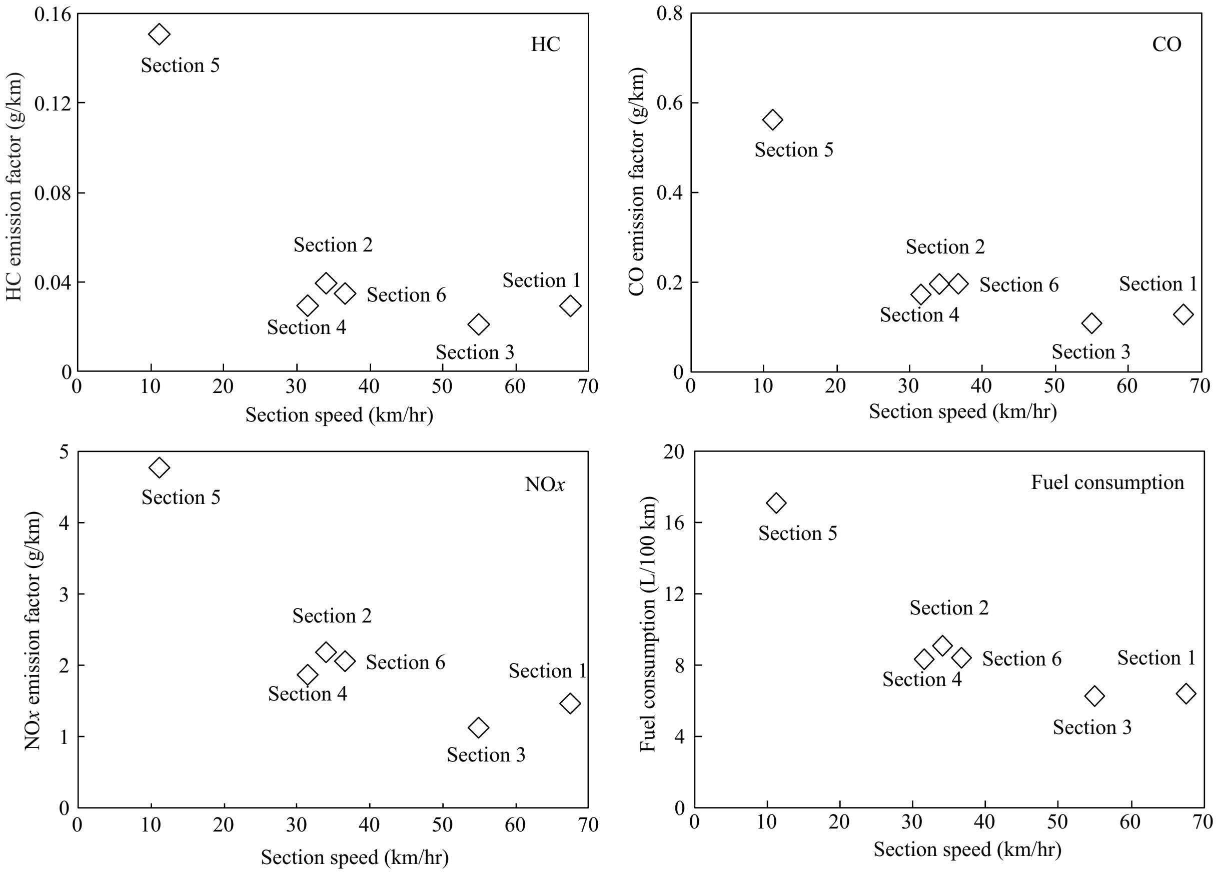

Fig. 9 Average fuel consumption and emission factors of the 3 Sonata diesel taxies with average vehicle speed on the six road sections.

road section No. 5 are even worse, ca. 170%–380% higher than those for road sections No. 1 and No. 3 due to an even lower average vehicle speed for the three Sonata diesel taxies during the test at road section No. 5 (ca. 10 km/hr).

Such a strong correlation between the fuel consumption/emissions of a vehicle and the road conditions indicates that a complete and precise emission inventory for on-road vehicles in Macao needs to be developed with a close function of input from the road conditions (or average vehicle speed). Although all of these diesel taxies are applied with advanced emission control strategies, they all show much worse results in both fuel consumption and emissions when driven on the roads with heavy traffic flows (in other words roads with low vehicle speed). Therefore, to save energy and mitigate the CO_2 emissions as well as other air pollutant emissions in an urban area, traffic planning also needs to be improved.

3 Conclusions

The on-road fuel efficiency and exhaust emission profiles of light-duty diesel vehicles are different from their gasoline counterparts. In terms of energy conservation, or mitigation of CO_2 or CO, generally light-duty diesel vehicles show an advantage compared to light-duty gasoline vehicles. However, NOx emissions of diesel taxies are much higher than their gasoline counterparts. Therefore, the choice between diesel and gasoline vehicles really depends on the priority of the different goals.

Those diesel cars with specific emission control devices (such as EGR + DOC) need special attention. First, they could penalize fuel economy. Second, they were usually found with significantly higher NO_2 emissions and NO_2/NOx ratios than the other diesel cars and consequently trigger a concern of possible adverse impacts on ozone pollution in an urban area with such a technology combination.

A clear and similar pattern for fuel consumption as well as for each of the three gaseous air pollutants with various road conditions was identified. Those roads representing the city expressway have the lowest fuel consumption and emissions for all the tested diesel cars, while the downtown local streets with heavy traffic flows have the highest fuel consumption and emissions. To save energy and mitigate the CO_2 emissions as well as other air pollutant emissions in urban area, improved traffic planning is also necessary.

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