

Article

Unregulated Emissions from Natural Gas Taxi Based on IVE Model

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Abstract: Emissions from motor vehicles have gained the attention of government agencies. To alleviate air pollution and reduce the petroleum demand from vehicles in China, the policy of “oil to gas” was vigorously carried out. Qingdao began to promote the use of natural gas vehicles (NGVs) in 2003. By the end of 2016, there were 9460 natural gas (NG) taxis in Qingdao, which accounted for 80% of the total taxis. An understanding of policy implementation for emission reductions is required. Experiments to obtain the taxi driving conditions and local parameters were investigated and an international vehicle emissions (IVE) localization model was established. Combined with vehicle mass analysis system (VMAS) experiments, the IVE localization model was amended and included the taxi pollutant emission factors. The result indicates that annual total carbon monoxide (CO) emissions from actual taxis are 6411.87 t, carbureted hydrogen (HC) emissions are 124.85 t, nitrogen oxide (NOx) emissions are 1397.44 t and particulate matter (PM) emissions are 8.9 t. When the taxis are running on pure natural gas, the annual emissions of CO, HC, NOx and PM are 4942.3 t, 48.15 t, 1496.01 t and 5.13 t, respectively. Unregulated emissions of annual total formaldehydes, benzene, acetaldehyde, 1,3-butadiene emissions from an actual taxi are 65.99 t, 4.68 t, 1.04 t and 8.83 t. When the taxi is running on pure natural gas, the above unregulated emissions are 12.11 t, 1.27 t, 1.5 t and 0.02 t, respectively.

Keywords: unregulated emissions; natural gas taxi; emission factor correction; operating condition; IVE model



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1. Introduction

Since China entered the 21st century, the national economy has developed rapidly and the pace of urban construction is increasing. With the gradual improvement of the urban road traffic network in recent years, the number of civilian cars in China has grown rapidly. The increase in the number of motor vehicles brings people convenient and fast travel, but it also causes an increasingly serious environmental pollution problem. Vehicle emissions draw more and more attention to the environment and society. The emissions from automobile exhausts are related to people's health [1–3]. The automobile power source is the key point of the continuous development of the automobile industry [4]. Good alternative fuels, such as biodiesel, alcohols and compressed natural gas (CNG), have solved some environmental problems, as well as some energy problems [5–7]. However, since the beginning of 2013, many places in China had hazy weather, which slowly spread to the surrounding areas from Beijing, Tianjin as well as Hebei. Urgent measures need to be taken to reduce vehicle emissions. The vehicle emission inventories of different cities and road grades have been researched [8–11].

Regarded as a promising alternative fuel, natural gas has comparatively large reserves, high combustion efficiency and low emissions. A few years ago, CNG vehicles were widely promoted in China to alleviate air pollution and reduce petroleum dependence. At present, many scholars have adopted various technological methods to reduce vehicle exhaust emissions and evaluated their effectiveness [12–15]. Due to this rapidly increasing alternative

motor vehicle population, estimates of its emission levels are required. The emissions from compressed natural gas fueled taxis and buses were measured using a portable emission measurement system (PEMS) [16] under actual driving conditions [17–21]. Nesamani estimated the emissions from on-road vehicles in Chennai using the International Vehicle Emission (IVE) model [22] that examined various mitigation options to reduce vehicular emissions [23,24]. A simulation study of engine failure of LPG taxi and its impact on emission and vehicle performance by Organ Bruce [25] shows that the daily mileage of a taxi is longer than that of a private car, and it is concentrated on the sections of crowded roads in urban areas. Therefore, although the number of taxis is less than that of private cars, it still accounts for a large part of the exhaust emissions of urban motor vehicles.

However, these studies are entirely about regulated emissions and are limited to the emissions of volatile organic compounds (VOCs) [26–32]. Few studies have investigated the unregulated emissions of urban taxis, such as formaldehydes, benzene, etc. In this study, taxi driving conditions and local parameters were obtained through experimental equipment, such as chassis dynamometer and taxi driving conditions, and an IVE positioning model of the main roads in three districts of Qingdao was established. Combined with vehicle mass analysis system (VMAS) [33–36] experiments, the IVE localization model was amended and then Qingdao taxi pollutant emission factors were included, and the effects of different fuel on regulated and unregulated emission characteristics of urban taxis were investigated. The urban area of Qingdao has the same road conditions as most urban areas, so this study is universal to other cities. This paper also provides a basis for the promotion of Qingdao's "oil to gas" policy.

2. Materials and Methods

2.1. Data Collection and Test Methods

Three districts of Qingdao, Shinan, Laoshan and Licang, were selected. These were representative of the business district, a higher income area and a lower income area, respectively. Nine typical roads, including an expressway, main road and a neighborhood road in these three districts were tested. During experiments, distributions of Vehicle Specific Power (VSP) [37–40] and start status information were investigated. The typical daily traffic periods include morning peak hour, evening peak hour and off-peak hour. According to the actual situation of Qingdao, blocks which have more taxis were chosen as the test areas. Taxi operating history was measured using GPRS-V36. For other local parameters, such as taxi type, model-year, mileage, number of starts, fuel and emission, control levels were collected and analyzed by a questionnaire. The emissions of measured taxis were tested by vehicle mass analysis system (VMAS).

2.2. Taxi IVE Model Calculation Method

The IVE model modifies the emission factor of each vehicle's technology type according to its actual situation and combines the total number of vehicles in the study area to obtain the total emission of the entire fleet. Compared with other models, the main feature of the IVE model is that the engine power parameter VSP and the engine working intensity parameter ES are put together to comprehensively consider the relationship between vehicle driving state and emissions.

In the IVE model, emission unit Bin is used to connect the emission rate and driving condition, and the division of Bin is mainly based on specific power (VSP) and engine load (ES).

VSP represents a car made with the power to overcome running resistance in the unit time. Most studies show that VSP can truly reflect the relationship between vehicle driving cycles and the vehicle exhaust pollutant emissions. A VSP equation was calculated by Equation (1) [41]:

$$VSP = v[1.1a + 9.81 \times (\text{atan}(\sin(\text{grade}))) + 0.132 + 0.000302v^3] \quad (1)$$

where

v is the instantaneous velocity (m/s);
 a is acceleration (m/s²);
 $grade = (h_{t=0} - h_{t=-1}) / v_{(t=-1 \text{ to } 0)}$;
 h is altitude (m).

The IVE model introduces the concept of Engine Stress (ES). This parameter is used empirically to reflect the emission influence from vehicle status due to high engine RPM and the load on the catalyst just prior to the event of interest. That is, the IVE model takes emission history effects into account by using ES.

ES is a dimensionless parameter, which was calculated by Equation (2):

$$ES = RPM_{Index} + 0.08 \times PAP \quad (2)$$

where RPM_{Index} is engine speed index and PAP is the average of VSP 15 s before the time of interest,

$$RPM_{Index} = v_{t=0} / SpeedDivider \quad (3)$$

Values of $SpeedDivider$ for various velocities and powers can be found in the IVE user manual.

For the division of the Bin area, the first step is to classify the research object. VSP is calculated according to the formal data of the vehicle and mapped to the corresponding range in proportion, so 20 Bin areas can be allocated. Meanwhile, 60 Bin areas are formed by dividing the three loads between high and low.

The calculation formula of the IVE model for vehicle emission factor is as follows:

$$F_i = B_i \times T_i \times V_i \times O_i \quad (4)$$

where F_i is the actual emission factor; B_i is the basic emission factor; T_i is the correction factor of technical level; V_i is the correction factor of Bin distribution; O_i is other correction factors, including environment and fuel, etc.; i is the vehicle type.

2.3. VMAS Experiments

According to Qingdao taxi age distribution, a fleet of taxis was chosen. This fleet of taxis was tested on the chassis dynamometer under VMAS. The cycle employed was the Economic Commission for Europe cycle (ECE). Fifteen 1.6L taxis and thirty-five 1.8L taxis were tested. Of these fifty taxis, 89.1% were fueled with CNG, in which the odometers of 91.4% were more than 161,000 km. All of the taxis used the original equipment manufacturer (OEM) three-way catalyst (TWC). The regulated emissions for the fifty taxis tested are presented in Table 1. Then, the emission factor of CO, HC and NO_x were obtained. Emission factors of CO, HC NO_x of 1.6L taxis were 0.32 g/km, 0.0384 g/km, and 0.0216 g/km, respectively. Emission factors of CO, HC, NO_x of 1.8 L taxis were 5.56 g/km, 1.20 g/km, 0.68 g/km, respectively.

Table 1. Regulated emissions for fifty taxis.

No.	Model Year	Engine Size (L)	Temperature (°C)	Atmospheric Pressure (kPa)	Relative Humidity (%)	CO (g/km)	HC (g/km)	NO _x (g/km)
#01	2008	1.6	11.7	99.5	10.1	0.3	1.60	0.90
#02	2008	1.6	5	100.1	56.9	0.01	0.10	0.06
#03	2008	1.6	9.3	99.9	50.7	0.82	1.04	0.59
#04	2008	1.6	10.1	99.6	20.3	0.32	0.04	0.02
#05	2008	1.8	7.2	99.7	22.5	4.34	0.71	0.40
#06	2008	1.8	9.3	100.1	28.7	1.67	0.81	0.46
#07	2008	1.6	5.4	100.8	30.9	0.22	1.11	0.62
#08	2008	1.8	6.2	100.8	31.9	0.17	1.11	0.62

Table 1. Cont.

No.	Model Year	Engine Size (L)	Temperature (°C)	Atmospheric Pressure (kPa)	Relative Humidity (%)	CO (g/km)	HC (g/km)	NO _x (g/km)
#09	2008	1.6	7	100.8	30.5	0.77	1.32	0.75
#10	2008	1.8	6.8	100.9	29.7	0.77	0.70	0.39
#11	2008	1.8	6.5	100.9	30.4	2.49	0.58	0.33
#12	2009	1.8	11.7	99.4	9.3	5.09	0.86	0.48
#13	2009	1.8	5.2	100.5	52.5	0.16	0.01	0.01
#14	2009	1.8	9.1	100.1	29.7	0.59	0.69	0.39
#15	2009	1.8	5.9	100.8	31.7	0.26	1.05	0.59
#16	2009	1.6	9.4	100.1	28.9	0.11	0.56	0.31
#17	2009	1.8	6.6	100.8	29.2	5.56	1.20	0.68
#18	2009	1.8	13.4	99.1	13.2	0.35	0.03	0.01
#19	2009	1.8	7.1	100.8	31.7	2.67	1.46	0.82
#20	2009	1.8	4.6	100.1	56.5	0.25	0.08	0.05
#21	2009	1.8	6.3	100.8	32.1	8.21	0.83	0.47
#22	2009	1.8	7.7	99.9	50.2	0.46	0.04	0.03
#23	2009	1.8	8	100.7	21.1	0.61	0.04	0.03
#24	2009	1.8	13.6	99.1	11.3	0.58	0.06	0.03
#25	2009	1.6	6.6	100.9	29.7	1.81	1.74	0.98
#26	2009	1.6	6.6	100.9	29.7	1.81	1.90	1.07
#27	2010	1.8	13.1	100	34.5	2.47	0.88	0.49
#28	2010	1.8	7.4	100	54.3	2.83	1.04	0.58
#29	2010	1.8	7.4	100	54.3	2.83	1.04	0.58
#30	2011	1.8	0.3	101.1	33.4	1.93	0.22	0.12
#31	2011	1.8	0.1	101.2	34.6	0.35	0.05	0.03
#32	2011	1.8	−0.5	101.1	34.5	6.95	0.90	0.51
#33	2011	1.8	0.3	101.1	33.4	1.93	0.22	0.12
#34	2011	1.8	−1.1	101.1	34.6	7.07	0.91	0.51
#35	2011	1.8	−0.9	101.2	34.4	11.32	9.84	5.54
#36	2011	1.8	1.5	101.1	33.5	5.25	1.49	0.84
#37	2011	1.8	6.5	100.9	31.5	8.16	2.15	1.21
#38	2011	1.8	11.5	100.1	20.1	1.36	0.46	0.26
#39	2012	1.6	6.8	99.1	21.5	8.02	1.40	0.78
#40	2012	1.6	10.4	99.9	17.4	5.83	1.10	0.62
#41	2012	1.6	6.8	99.1	21.5	8.02	1.40	0.78
#42	2012	1.6	10.4	99.9	17.4	5.83	1.10	0.62
#43	2012	1.6	2.5	99.2	21.6	2.16	0.34	0.19
#44	2012	1.8	−0.5	101.1	38.7	8.87	0.92	0.52
#45	2013	1.8	6.5	101.1	38.7	1.62	0.84	0.47
#46	2013	1.8	6.8	99.1	21.5	2.08	0.74	0.41
#47	2013	1.8	6.8	99.1	21.5	2.53	0.41	0.23
#48	2013	1.8	6.5	100.9	31.5	1.02	0.56	0.31
#49	2013	1.8	5.2	100.5	52.5	1.93	0.77	0.43
#50	2013	1.8	5.2	100.5	52.5	2.31	0.88	0.50

3. Results and Discussion

3.1. Driving Condition and VSP Distribution

After the driving experiments were performed and the data had been analyzed, the driving conditions of the three areas for morning peak hour, evening peak hour and off-peak hour were obtained. Table 2 shows the driving conditions distribution of the business district for morning peak hour, evening peak hour and off-peak hour, respectively. The VSP distribution of the business district is shown in Table 3.

Table 2. Driving condition distribution of business district for peak hour.

v/km/h	Morning Peak (%)	Off Peak (%)	Evening Peak (%)
0 < v ≤ 10	26.4	13.1	27.6
10 < v ≤ 20	34.8	28.2	40.1
20 < v ≤ 30	20.4	25.5	27.3
30 < v ≤ 40	15.1	14.1	5
40 < v ≤ 50	3.3	18.1	0
50 < v ≤ 60	0	1	0
idle ratio	54.1	49.4	66.1
acceleration ratio	19.4	22	15
constant ratio	6.7	7.1	4.2
deceleration ratio	19.8	21.5	14.7

Table 3. VSP distribution of business district.

	ES Low Load	ES Middle Load	ES High Load
VSP range(kW/t)	[−1.6, 3.1)	[3.1, 7.8)	[7.8, 12.6)
[−80.0, −44.0)	0.000	0.000	0.000
[−44.0, −39.9)	0.000	0.000	0.000
[−39.9, −35.8)	0.000	0.000	0.000
[−35.8, −31.7)	0.000	0.000	0.000
[−31.7, −27.6)	0.000	0.000	0.000
[−27.6, −23.4)	0.000	0.000	0.000
[−23.4, −19.3)	0.000	0.000	0.000
[−19.3, −15.2)	0.002	0.000	0.000
[−15.2, −11.1)	0.006	0.000	0.000
[−11.1, −7.0)	0.017	0.000	0.000
[−7.0, −2.9)	0.062	0.000	0.000
[−2.9, 1.2)	0.618	0.000	0.000
[1.2, 5.3)	0.169	0.000	0.000
[5.3, 9.4)	0.086	0.000	0.000
[9.4, 13.6)	0.027	0.000	0.000
[13.6, 17.7)	0.007	0.002	0.000
[17.7, 21.8)	0.002	0.001	0.000
[21.8, 25.9)	0.001	0.000	0.000
[25.9, 30)	0.000	0.000	0.000
[30, 1000)	0.000	0.000	0.000

3.2. Correction of the Vehicle Emission Factor

The taxis' operating histories were imported into the VSP calculator, then the VSP distribution of three districts and comprehensive of Qingdao were drawn. Localized parameters were imported into the IVE model and emission factors were calculated. Table 4 shows the average emission factors for Qingdao taxis before correction.

Table 4. Qingdao taxi pollutant emissions factor before correction (g/km).

	CO	HC	NO _x	SO _x	PM
business district	14.96	0.13	0.95	0.005	0.001
higher income area	14.17	0.12	0.85	0.004	0.001
low income area	10.53	0.1	0.7	0.004	0.001
comprehensive	10.6	0.1	0.74	0.005	0.001

The VMAS experimental study only tested the emission factor of CO, HC and NO_x of the fleet. Therefore, the CO, HC and NO_x emission factors for the three pollutants were amended. The parameter correction factors are defined as follows:

$$PCF = \frac{VMAS}{IVE} \quad (5)$$

PCF represents the parameter correction factor, VMAS represents the measurements of VMAS for the emissions, and IVE represents the IVE analog value of the emissions.

The parameters correction factors of CO, HC and NO_x are shown in Table 5:

Table 5. Modification factor of taxi IVE in Qingdao (g/km).

	CO	HC	NO _x
measurements of VMAS for the emissions	2.771	0.64	0.36
IVE analog value of the emissions	10.6	2.59	0.74
parameter correction factor	0.26	0.25	0.5

The calculated correction factor of CO, HC and NO_x are 0.26, 0.25 and 0.5, respectively. Revised comprehensive emission factors of the business district, higher income areas, lower income area and the whole of the Qingdao City taxi fleet are shown in Table 6.

Table 6. Revised emission factors of Qingdao taxi (g/km).

	CO	HC	NO _x	SO _x	PM
business district	3.45	0.13	0.48	0.005	0.001
higher income area	3.4	0.12	0.42	0.004	0.001
low income area	2.53	0.1	0.35	0.004	0.001
comprehensive	2.55	0.1	0.37	0.004	0.001

3.3. Regulated Emission Characteristics of Taxis with Different Fuels

According to random questionnaires of 1000 taxis in Qingdao, the total annual mileage of taxis in Qingdao can be calculated. Then, the total annual emissions of taxis in Qingdao, both for regulated and unregulated emissions, can be obtained by the IVE model.

Changing the percentage of the IVE model fleet and refitting gasoline vehicles with different fuels, the emission characteristics of taxis with different fuels were obtained. Total regulated emissions from natural gas taxis and gasoline taxis were contrasted with current taxis in Figure 1.

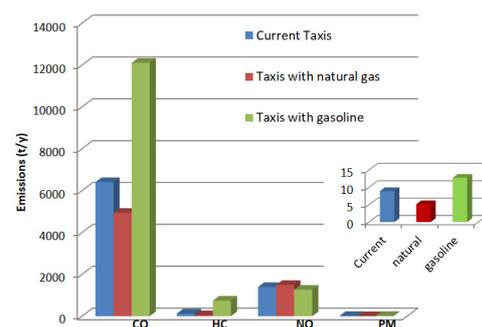


Figure 1. Total regulated emissions from taxis with different fuels.

In Figure 1, according to the same proportion of the new and old taxis, if the taxi fleet was changed into natural gas taxis, CO and HC emissions will be reduced by 23% and 61%, respectively. However, if the taxi fleet was changed to gasoline, CO and HC emissions will increase by 89% and 498%, respectively. The “Oil to Gas” policy will reduce CO and HC emissions greatly.

Compared with current taxis, NO_x emissions from taxis with natural gas increased by 7%. However, according to the same proportion of the new and old taxis, if the taxi fleet changed their fuel to gasoline, NO_x emissions will be reduced by 9%. As can be seen, the “Oil to Gas” policy does not reduce NO_x emissions but slightly increases them.

PM is a pollutant that has received great attention in recent years. As shown in Figure 1, if the current taxi fleet changes to natural gas, according to the proportion of old and new taxis, PM emissions will be lowered to nearly half the current amount. While taxis are fueled with gasoline, PM emissions will increase by 43%. With the increase in the taxi mileage, PM emissions significantly increase.

3.4. Unregulated Emission Characteristics of Taxis with Different Fuels

Total unregulated emissions from natural gas taxis and gasoline taxis are contrasted with current taxis in Figure 2.

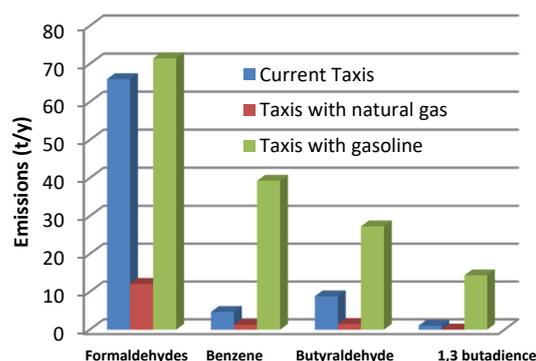


Figure 2. Total unregulated emissions from taxis with different fuels.

In Figure 2, if the current taxis are fueled with natural gas, formaldehydes, benzene, acetaldehyde and 1,3-butadiene, emissions will be reduced. Furthermore, formaldehyde emissions will decrease by 82%. However, taxis with gasoline will increase all of the unregulated emissions. Whether fueled with natural gas or gasoline, taxis will produce more unregulated emissions with increased mileage.

4. Conclusions

Experiments to obtain the taxi driving conditions and local parameters were investigated, and the IVE localization model was established. Combined with VMAS experiments, the IVE localization model was amended and then taxi pollutant emission factors were drawn. The result indicated that the annual total level of CO emissions from actual taxis is 6411.87 t, HC emissions is 124.85 t, NO_x emissions is 1397.44 t and PM emissions is 8.9 t. When the taxi is running on pure natural gas, the annual emissions of CO, HC, NO_x and PM are 4942.3 t, 48.15 t, 1496.01 t and 5.13 t, respectively. The annual total formaldehydes, benzene, acetaldehyde, and 1,3-butadiene emissions from an actual taxi are 65.99 t, 4.68 t, 1.04 t and 8.83 t. When the taxi is running on pure natural gas, the annual emissions of formaldehydes, benzene, acetaldehyde, 1,3-butadiene are 12.11 t, 1.27 t, 1.5 t and 0.02 t, respectively. Although a taxi cannot run on pure natural gas to reduce emissions of all types of pollutants, it can still largely reduce pollutant emissions. The “Oil to Gas” policy greatly reduces CO, HC, PM, formaldehydes, benzene, acetaldehyde and 1,3-butadiene emissions.

According to the experimental analysis in this paper, the implementation of the policy of “replacing oil with gas” will not only improve social benefits in terms of emissions, but it will also reflect economic benefits. The price of natural gas is about half of that of gasoline and diesel with the same equivalent calorific value. Therefore, the “Oil to Gas” policy should be reinforced and increase the frequency of taxis.

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