Evaluating Real Driving Emissions of Compressed Natural Gas Taxis in Chongqing, China—A Typical Mountain Cities

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Abstract: Compressed natural gas (CNG) taxis represent the most ubiquitous and dynamically active passenger vehicles in urban settings. The pollutant emission characteristics of in-use CNG taxis driving on a typical mountain city before and after three-way catalyst (TWC) replacement was examined using a modular on-board portable emissions measurement system (PEMS), the OBS-ONE developed by Horiba. The results showed that the exhaust NO of CNG taxis equipped with deactivation TWC exceeded the emission limits, even higher than gasoline vehicles. The high emission rate of CNG taxis is mainly concentrated on road slopes between a 2% and 6% gradient and a deceleration rate in the interval of [0.5, 4], respectively, which results in higher emissions from CNG taxis traveling in the mountain city of Chongqing than other cities and vehicles. Moreover, the pollutant emission rates of the in-use CNG taxis were highly correlated with the velocity and the vehicle specific power (VSP). After a new TWC replacement, the emission factors of carbon monoxide (CO), total hydrocarbons (THC), nitrogen oxides (NOx), and particle number (PN) decreased by 85.21–89.11%, 68.71–85.49%, 60.91–81.11%, and 62.26–68.39%, respectively. Our results will provide guidance for urban environments to carry out the comprehensive management of in-use vehicles and emphasize the importance of TWC replacement for CNG taxis.

Keywords: real-world emissions; compressed natural gas taxi; mountain cities; three-way catalysts

1. Introduction

On-road vehicles have emerged as significant contributors to air pollution in Chinese megacities [1–3]. As is well known, taxis are the most active passenger vehicles on urban roads compared with the other types of passenger vehicles. Generally, the length of service of a taxi is specified by the traffic management department, which stipulates that taxi vehicles can only run for approximately six years [4]. However, most owners drive more than 100,000 miles a year [5], which means that their accumulated mileage easily exceeds the emission control durability requirements, such as the 160,000 km specified by the China 5 standard. This excessive mileage may cause a temporary decrease in the efficiency of after-treatment devices like the three-way catalyst (TWC), and in some cases, even their failure [4,6,7]. As a result, the exhaust emissions from taxis will be high during the extra operating time and will seriously affect the city’s air quality.
Recently, there are about 762,000 compressed natural gas (CNG) taxis in China. In addition to being known as a mountain city, Chongqing is also known for its rich natural gas resources and is an important natural gas producing area in China. This advantageous position supports the promotion of CNG taxis and the exploration of alternative solutions to reduce dependence on foreign oil. Natural gas, being a clean energy source, holds promise as an effective solution to address environmental pollution concerns. With approximately 25,000 CNG taxi vehicles currently operating in Chongqing, it boasts the highest volume in the southwest region. Generally, electric taxis have gained significant traction in flat cities in recent years [8]. From an academic perspective, however, due to the topographical characteristics of mountainous cities, which increase the energy consumption of electric vehicles and limit their operational range, further scholarly evaluation is still required for the widespread application and promotion of electric taxis in Chongqing—a mountainous city characterized by a complex road network, rugged terrain, and numerous bridges and tunnels [9]. Especially in the context of a relatively low proportion of electricity generated from the renewable energy supply in Chongqing, the potential for carbon reduction through electric vehicles is comparatively limited [8,10]. Additionally, it is important to explore and assess the actual emission levels of CNG taxis, considering their role as a byproduct of oil and trams, particularly when operating in mountainous cities.

Several studies have indicated that bi-fuel vehicles, when using compressed natural gas NOx and THC, are more likely to exceed the standard limits compared to gasoline, which may attribute to the control devices in CNG cars that have higher technological barriers and are more prone to severe failures compared to gasoline-propelled cars [11,12]. Furthermore, through the survey, it was found that many CNG taxis have been in use for over two years, with their onboard diagnostic system (OBD) warning lights turned on, which may likely be mainly caused by catalyst aging, oxygen sensor malfunctions, and similar issues [3]. This suggests that a significant number of CNG taxis may be operating with inefficient or deactivated three-way catalysts, resulting in the emission of high concentrations of gaseous pollutants from their exhaust pipes [4,13]. Consequently, the urban air quality in Chongqing could be seriously impacted by these taxis during their regular service. In such cases, the use of natural gas may not be contributing to a better environment, but rather becoming an invisible factor in environmental degradation. Presently, the replacement of low-efficiency or deactivated TWC, a mitigation strategy often overlooked, appears to be the most effective approach to reducing pollution from taxi vehicles before the end of their eight-year service life [14]. Importantly, the impact of this strategy on vehicle emission characteristics and the potential for pollution reduction needs to be carefully measured and assessed.

Therefore, obtaining accurate real-world exhaust emission characteristics of on-road CNG taxis in mountain cities has become a crucial step in scientifically achieving pollution prevention and control [15]. Numerous studies have been conducted to investigate exhaust emission characteristics of various vehicles, including gasoline, diesel, natural gas, and hybrid electric vehicles, using model simulations and experimental investigations [16–22]. Recently, the pollutant emissions from CNG vehicles operating under real-world driving conditions have become a focus of research [23,24]. However, these studies often fail to reflect the pollutant emissions from CNG taxis operating in mountain cities under real-world driving conditions, which cannot scientifically guide local road planning, residential planning, and pollution prevention and control efforts. Moreover, there is a lack of comprehensive research on the emission characteristics of both CNG taxis. Currently, portable emissions measurement systems (PEMS) have been introduced to quantify pollutant emissions in real-world scenarios, revealing that gaseous pollutant emissions from vehicles are influenced by factors such as driving cycle (e.g., vehicle speed, road grade, specific power, and acceleration), fuel quality, and after-treatment [25–27]. These initial studies provide a foundation for further research on the real-world emission characteristics and control of in-use CNG taxis.
In this study, the aim was to identify the gaseous pollutants emitted by CNG taxis and assess the potential reduction in pollutants after the installation of a new three-way catalyst. The emission characteristics of in-use CNG taxis were measured using a portable emissions measurement system before and after TWC replacement. The study focused on the levels of real gaseous pollutants and ultrafine particles emitted by in-use CNG taxis on the roads of typical southwestern mountain cities. The results confirmed that a significant reduction in pollutant levels could be achieved by replacing a deactivated TWC with a new one. These findings provide valuable technical support for the effective control and prevention of pollution caused by in-use CNG taxis in mountain cities of southwestern China.

2. Materials and Methods

2.1. Tested Vehicles

CNG taxi vehicles in Chongqing are primarily categorized into two standard types: China IV and China V standards. Therefore, in this study, five in-use CNG taxis conforming to China IV and China V standards were selected. The accumulated mileage of these taxis had exceeded 160 thousand kilometers, and some of them were operating with the engine check light illuminated. Furthermore, these CNG taxis were equipped with a three-way catalyst and had not undergone TWC replacement. Detailed information about each CNG taxi is provided in Table S1. Before testing, vehicles are allowed to idle for 12 h, with the engine in normal operating condition, and the loading weight of all vehicles remains consistent before and after.

2.2. Test Route and Driving Cycles

The test route designed for this study aimed to simulate real-world driving conditions and capture the influences of these conditions on the exhaust emission characteristics of CNG taxis in Chongqing. The CNG taxis were primarily driven on urban roads and the motorway that traverses Chongqing City. Therefore, the test route encompassed urban freeways (UFs), primary roads (PRs), and secondary roads (SRs), which included ramp roads with an altitude difference of 160 m, bridges, and both long and short tunnels. The table provided (Table S2) presents the test distance, average speed, and duration for each CNG taxi on the respective road types. The altitude changes along the route are illustrated in Figure S1.

2.3. Measurement System

To evaluate the compliance of the taxis, acceleration simulation mode (ASM) using a dynamometer testing system obtained from the annual exhaust inspection station was utilized (Figure S2). Data on the gaseous pollutants and ultrafine particles emitted from the CNG taxis were collected using a portable emissions measurement system (OBS-ONE-GS-12, Horiba Co., Tokyo, Japan). The system consisted of a gas test unit, a particulate test unit, and a separate power unit. The gas test unit included non-dispersive infrared measurement technology for analyzing CO and CO₂, a flame ionization detector for analyzing total hydrocarbons, a chemiluminescent detection unit for analyzing NO and NO₂, and a condensation particle counter unit for analyzing the number concentration of solid particles. The precision of measurements is shown in Table S3. The PEMS system was powered using a separate power unit. Instantaneous exhaust flow rate was measured using a flow meter based on Pitot tube technology. Additionally, a global positioning system (GPS) recorded the instantaneous speed, altitude, latitude, and longitude. Before each test, zero correction was performed using nitrogen and gas calibration was carried out using standard gases. Details of the test system and routes are illustrated in Figures S1 and S3, respectively.

2.4. TWC Replacement Test

The replacement of TWC must be completed by entities holding a Class A automobile maintenance and repair business license or other motor vehicle maintenance and repair business licenses, and must be incorporated into the government-led M station (mainte-
nance station) system. The entire replacement process for each TWC, including cutting and welding, is completed within half a day. To ensure emission reduction performance and durability, specialized TWC for natural gas engines needs to be adopted. To replace the low-efficiency or deactivated TWC of the CNG taxis (Figure S4), a Series TWC from Sinocat Environmental Technology Co., Ltd., Chengdu, China (Table S4) was used. To ensure NVH levels, the TWC size was chosen to be larger than the engine displacement. Therefore, a 2 L catalyst volume, which is completely consistent with the original factory size, was selected to match the engine of CNG taxis. The selected TWC featured a cordierite monolithic substrate coated with a palladium (Pd)-based catalyst. The total content of precious metal in the TWC was 60 g/ft$^3$. Prior to the test, each CNG taxi requiring TWC replacement had already traveled over 10,000 km.

2.5. Data Processing

Based on the instantaneous pollutant emissions rate and the test distance, the distance-specific emission factors of the gaseous pollutants and the number of particles were calculated using the following methodology:

$$EF_i = 1000 \times \frac{\sum_t ER_{i,t}}{\sum_t V_t}$$  \hspace{1cm} (1)

where $EF_i$ is the emission factor of pollutant $i$ (g/km); $ER_{i,t}$ is the instantaneous emission rate of pollutant $i$ at time $t$ (g/s); and $V_t$ is the instantaneous speed at time $t$ (m/s).

Furthermore, the acceleration rate and road trade were calculated using Equations (2) and (3), respectively:

$$a_t = \frac{(V_t - V_{t-1})}{t_t}$$  \hspace{1cm} (2)

$$R_t = \frac{\Delta h}{d} \times 100\%$$  \hspace{1cm} (3)

where $a_t$ is the acceleration rate at second $t$ (m/s$^2$); $V_t$ is the speed at second $t$ (m/s); $t_t$ is the time between $V_t$ and $V_{t-1}$; $R_t$ is the road grade (%) at time $t$; $\Delta h$ is the elevation difference between $t$ and $t - 1$; and $d$ is the distance between $t$ and $t - 1$.

Vehicle specific power is a parameter that takes into account the vehicle’s speed, acceleration, and road slope, and it reflects the vehicle’s mass, aerodynamic drag, and rolling resistance [28–30]. The binning method is commonly used to connect the instantaneous emissions from vehicles with real-world driving conditions. In this study, a total of 22 operating mode bins were constructed. Bin 0 represents the deceleration mode, while Bin 1 represents the idling mode. The remaining 20 modes were further categorized into three speed operating ranges: low speed, medium speed, and high speed [31]. Based on the binning method, the VSP and speed parameters were used to define the operating mode of the CNG taxi (see Table S5). The VSP calculation followed the formula developed by Ghaffarpasand et al. [32]:

$$VSP_t = V_t \times (1.1a_t + 9.81 \times \text{signgrade}_t + 0.132) + 3.02 \times 10^4 \times V_t^3$$  \hspace{1cm} (4)

where $VSP_t$ is the estimated instantaneous VSP (kW/ton); $V_t$ is the speed at time $t$ (m/s); $a_t$ is the instantaneous acceleration rate at time $t$ (m/s$^2$); and grade is the instantaneous road grade (%).

3. Results

3.1. Distance-Specific Emission Factors

The emission factors of gaseous pollutants and CO$_2$ are presented in Table 1 and Table S6, respectively. It can be observed that the emission levels of THC, CO, NO$_x$, and PN for China IV CNG taxis without TWC replacement are slightly higher than those for China
V CNG taxis. The pollutant emissions from CNG taxis significantly exceeded the emission limits prescribed by China’s in-use vehicle standard (ASM mode), with NOx being the primary pollutant exceeding the gaseous pollutant threshold (Table S7). After replacing the TWC, the emission factors of CNG taxis significantly decreased, with decreases of approximately 7–9 times for THC, 3–7 times for CO, 3–5 times for NOx, and 2–3 times for PN. These findings highlight the substantial impact of after-treatment technology on emission levels. TWC replacement plays a crucial role in reducing pollutant emissions from high-mileage CNG taxis. Moreover, the THC, CO and NOx emission levels of high-mileage CNG taxis exceeded the emission limits set for both China IV and China V standards.

When compared to other real-world road emissions levels of gasoline and CNG passenger cars in plain cities, as studied using PEMS, the gaseous pollutant emission factors of CNG taxis in Chongqing before and after TWC replacement were higher than the reported results of previous studies [4,28,32–36]. CNG taxis driving in mountainous cities may have higher emissions because their engines might work harder and consume more fuel to maintain the same average speed as vehicles in other cities [37]. However, there is limited reporting on the PN and CO\(_2\) emissions of in-use CNG passenger cars. Notably, the PN emissions from CNG taxis in this study were significantly lower than those of in-use gasoline and China VIib CNG passenger cars, indicating that CNG vehicles can contribute to reducing particulate matter emissions (Table S8).

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Emission Standard</th>
<th>Pollutants</th>
<th>THC (g/km)</th>
<th>CO (g/km)</th>
<th>NOx (g/km)</th>
<th>PN (#/km × 10(^{10}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>This study</td>
<td>CNG</td>
<td>China IV</td>
<td>2.02 ± 0.50</td>
<td>1.93 ± 0.60</td>
<td>1.80 ± 0.78</td>
<td>7.34 ± 3.87</td>
</tr>
<tr>
<td></td>
<td></td>
<td>China V</td>
<td>1.69 ± 0.20</td>
<td>1.47 ± 0.39</td>
<td>1.10 ± 0.29</td>
<td>13.7 ± 6.36</td>
</tr>
<tr>
<td></td>
<td></td>
<td>China IV (TWC replacement)</td>
<td>0.22 ± 0.05</td>
<td>0.28 ± 0.01</td>
<td>0.34 ± 0.20</td>
<td>2.32 ± 1.54</td>
</tr>
<tr>
<td></td>
<td></td>
<td>China V (TWC replacement)</td>
<td>0.25 ± 0.11</td>
<td>0.46 ± 0.03</td>
<td>0.43 ± 0.36</td>
<td>5.17 ± 1.38</td>
</tr>
<tr>
<td>Zheng et al. [4]</td>
<td>Gasoline</td>
<td>China IV (without TWC)</td>
<td>0.55 ± 0.07</td>
<td>0.09 ± 0.60</td>
<td>2.30 ± 0.6</td>
<td>-</td>
</tr>
<tr>
<td>Huang et al. [28]</td>
<td>Gasoline</td>
<td>Euro IV</td>
<td>0.047</td>
<td>1.07</td>
<td>0.17</td>
<td>15,700</td>
</tr>
<tr>
<td>Zhang et al. [30]</td>
<td>Gasoline</td>
<td>Euro IV</td>
<td>0.02 ± 0.01</td>
<td>0.40 ± 0.21</td>
<td>0.05 ± 0.03</td>
<td>-</td>
</tr>
<tr>
<td>Kontses et al. [34]</td>
<td>CNG</td>
<td>Euro IVb</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>14.00</td>
</tr>
<tr>
<td>Yao et al. [35]</td>
<td>CNG</td>
<td>Euro III</td>
<td>0.01 ± 0.00</td>
<td>0.90 ± 0.80</td>
<td>0.03 ± 0.02</td>
<td>-</td>
</tr>
<tr>
<td>Xie et al. [36]</td>
<td>CNG</td>
<td>Euro III</td>
<td>1.19</td>
<td>4.60</td>
<td>1.00</td>
<td>-</td>
</tr>
<tr>
<td>Emission limits 1</td>
<td>CNG</td>
<td>China IV</td>
<td>0.20</td>
<td>2.30</td>
<td>0.15</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>China V</td>
<td>0.10</td>
<td>1.00</td>
<td>0.60</td>
<td>60</td>
</tr>
</tbody>
</table>

1 NEDC (New European Driving Cycle) testing method.

3.2. Impact of Speed on Emission

The emission factors of CO, THC, NOx, NO, PN, and carbon dioxide (CO\(_2\)) for different velocity ranges are depicted in Figure 1. The overall trend demonstrates that the effect of velocity on CO, THC, and CO\(_2\) emissions monotonically decreases when the velocity is below 70 km/h. This can be attributed to the higher fuel consumption per kilometer traveled at low velocities, resulting in greater emission factors [38]. Conversely, at velocities above 70 km/h, the effect of velocity is reversed, with emission factors weakly increasing as velocity increases. This can be explained by the need for more fuel to overcome air resistance in order to achieve higher speeds, which aligns with the pattern of CO\(_2\) emissions [38,39]. The emission factor of NOx emissions exhibited fluctuations, with emission factors initially increasing, then decreasing, and then increasing again as velocity increased. The emission factor of PN showed a slight increase due to low engine combustion efficiency at low speeds, but it remained independent of speed.

The effects of velocity on CO\(_2\) and PN emission factors remained consistent before and after TWC replacement. However, after TWC replacement, significant reductions in the emission factors of CO, THC, and NOx were observed. Particularly at low velocities, the new TWC demonstrated excellent emissions reduction efficiency, as indicated by the decreased emission factors (1.08–94.17 for CO, 1.23–11.61 for THC, and 1.22–7.28 for NOx). Interestingly, the emission factors of CO, THC, and NOx for taxis with a TWC replacement...
were not affected by velocity, even with increased fuel consumption. The emission factors for taxis with a TWC replacement remained consistently low, attributed to the purification effect of the catalyst.

Figure 1. Average emission factors of taxis for different velocity ranges.

3.3. Impact of Road Slope on Emission

The test roads are categorized into level terrain and different road grade sections, with level terrain defined as roads with slopes between −2% and 2% (refer to Table S9). The other sections of the test road grade are divided into eight bins, ranging from −8% to +8% slopes. Figure 2 illustrates the effect of road slope on the emission rate of pollutants from CNG taxis. It can be observed that as the road slope increases, the emission rate of pollutants from CNG taxis initially increases but then slightly declines when the road grade exceeds 6%. Notably, the high emission rate of CNG taxis is primarily concentrated on road slopes between 2% and 6%, which are defined as moderate uphill slopes. However, the correlation between emission rates and road slopes decreases after the replacement of the TWC in CNG taxis. Unfortunately, the recommended road construction slopes in mountainous cities fall predominantly within this range [40]. According to the average emission rate of CNG taxis at different road slopes, the emission rate of pollutants from CNG taxis decreases as driving velocity decreases when driving on steep uphill slopes (road slope > 8%) under normal or conservative driving behavior (refer to Figure S6).
3.4. Impact of Instantaneous Acceleration on Emission

The acceleration of CNG taxis during real driving is categorized into 10 intervals. Figure 3, Table S10, and Figure 4 illustrate the distribution of acceleration in different road grade bins and the emission rates of exhaust pollutants from CNG taxis in different acceleration bins, respectively. In different road grade sections, acceleration and deceleration are concentrated on roads with slopes between 2% and 6%. As the slope increases, acceleration and deceleration become more challenging, especially during sustained acceleration. Therefore, it can be observed that vehicles driving on mountainous city roads experience particularly frequent acceleration and deceleration. Throughout the entire testing procedure, both acceleration and deceleration are observed. The lowest pollutant emission rate was observed when the deceleration rate was within the interval of \(-2 \text{ m/s}^2\) to \(-1 \text{ m/s}^2\). During the acceleration process, the pollutant emission rate of CNG taxis increases initially, then reaches a peak, and finally decreases slightly. The highest pollutant emission rate was observed when the acceleration rate was within the interval of \(0.5 \text{ m/s}^2\) to \(4 \text{ m/s}^2\). However, after the completion of the TWC replacement, the exhaust pollutant emission rate decreased significantly. With the exception of NOx, acceleration does not have a noticeable effect on the emission rate of other exhaust pollutants. The NOx emission rate exhibits a slight increase within the acceleration interval of \(0.5 \text{ m/s}^2\) to \(4 \text{ m/s}^2\), which is consistent with the results presented in Section 3.1. These findings indicate that NOx emissions from CNG taxis are more prone to exceeding the emission standards compared to other exhaust pollutants.

![Figure 2. Distribution of pollutant average emission rates in different road grade bins.](image)

![Figure 3. Distribution of acceleration in different road grade bins: (a) CNG taxis without TWC replacement, (b) CNG taxis with TWC replacement.](image)
Figure 4. Distribution of pollutant average emission rates in different instantaneous acceleration bins.

3.5. Impact of Natural Gas Consumption

According to the carbon balance formula proposed by Liu, the natural gas consumption of CNG taxis before and after TWC replacement during real driving was calculated [41]. The natural gas consumption for China IV and China V CNG taxis was determined to be 6.61 ± 0.28 m³/100 km and 6.34 ± 0.06 m³/100 km, respectively. After TWC replacement, there was a slight increase in natural gas consumption for China IV and China V, resulting in values of 6.78 ± 0.28 m³/100 km and 6.61 ± 0.18 m³/100 km, respectively.

Furthermore, the New European Driving Cycle (NEDC) testing method was utilized to measure the natural gas consumption of the CNG taxis before and after TWC replacement. As shown in Figure S7, the natural gas consumptions for China IV and China V were determined to be 8.34 ± 0.52 m³/100 km and 8.79 m³/100 km, respectively. It can be observed that the natural gas consumption per 100 km of the China V CNG taxis was slightly higher compared to China IV. When considering the results of real driving natural gas consumption, the natural gas consumption for China IV and China V taxis is at a similar level. Consistent with the findings from real driving, all CNG taxis with TWC replacement exhibited a slight increase in natural gas consumption.

3.6. Emission Rates by Operating Mode

To analyze the relationship between driving conditions and emissions, the vehicle specific power and average emission rates were calculated for different velocity ranges. As shown in Figure 5 and Figure S8, the average emission rates of pollutants and CO₂ for taxis without a TWC replacement increased with increasing VSP in low-speed operating modes (bin 11 to bin 18) and medium-speed operating modes (bin 21 to bin 28). However, these emission rate trends weakened after TWC replacement. Apart from CO, the average emission rates of other pollutants and CO₂ for China IV CNG taxis were significantly higher than those for China V CNG taxis. For taxis without TWC replacement, the average emission rates of CO, CO₂, THC, NOx, NO, NO₂, and PN for China IV and China V CNG taxis increased by 4.03 and 2.52 times, 4.40 and 3.89 times, 1.14 and 1.41 times, 8.04 and 6.90 times, 8.67 and 6.81 times, 6.82 and 7.07 times, and 31.20 and 0.37 times from bin 11 to bin 18, respectively.

Similarly, the average emission rates of CO, CO₂, THC, NOx, NO, NO₂, and PN increased by 3.86 and 2.73 times, 3.99 and 5.09 times, 1.04 and 0.97 times, 6.45 and 7.04 times, 6.54 and 8.15 times, 6.30 and 8.15 times, and 4.65 and 1.94 times from bin 21 to bin 28, respectively. CO₂, NOx, NO, NO₂, and PN emissions increased for high-velocity operating
modes, while VSP, CO, and THC did not exhibit significant patterns. For instance, the emission rates of NOx increased from 0.0051 ± 0.0012 g/s for bin 11 to 0.041 ± 0.0091 g/s for bin 18, from 0.0087 ± 0.0051 g/s for bin 21 to 0.056 ± 0.015 g/s for bin 28, and from 0.016 ± 0.0052 g/s for bin 35 to 0.083 ± 0.027 g/s for bin 38 for China IV taxis.

Figure 5. Average pollutant and CO\textsubscript{2} emission rates for the CNG taxis for the different operating modes.

For CNG taxis with a TWC replacement, CO\textsubscript{2}, NOx, NO, NO\textsubscript{2}, and PN exhibited similar emission patterns as taxis without a TWC replacement. CO and THC emission rates were low due to the high conversion efficiency of the new TWC, and they showed weak correlations with VSP. The pollutant and CO\textsubscript{2} emission rates of China IV and China V CNG taxis were at the same level after TWC replacement, indicating that the new TWC enabled both types of taxis to achieve similar emission levels. Furthermore, compared to taxis without a TWC replacement, taxis with a new TWC had significantly lower pollutant emission rates, especially for CO, THC, and NOx. For example, the emission rate of NOx for China IV taxis decreased from 0.041 ± 0.009 g/s to 0.010 ± 0.008 g/s for bin 18, from 0.056 ± 0.015 g/s to 0.012 ± 0.007 g/s for bin 28, and from 0.036 ± 0.009 g/s to 0.013 ± 0.010 g/s for bin 38. In general, under different VSP conditions, the NOx reduction rates for China IV and China V CNG taxis after TWC replacement were in the range of 63.59% to 95.94% and 27.86% to 91.79%, respectively. Therefore, the emission reduction efficiency of China IV CNG taxis was higher than that of China V CNG taxis after TWC replacement, mainly due to the partial functioning of the TWC in China V taxis.

4. Discussion

The distance-specific emission factor results indicate that the emission factors of CNG taxis are significantly higher than those reported in other studies and exceed the emissions of gasoline vehicles in Chongqing. This discrepancy can be attributed to two main factors. On the one hand, the extensive cumulative mileage of CNG taxis lead to TWC reaching
its mileage limit, resulting in decreased conversion efficiency or failure. On the other hand, there are more challenging driving conditions in mountainous cities compared to plains cities. Among these emissions, NOx is particularly notable, becoming one of the primary pollutants. This may be due to the higher power requirements and combustion temperatures of natural gas engines when driving on mountainous roads, as well as the increased sensitivity of NOx emissions to TWC performance.

During the construction of mountainous city roads, sections designed for a driving speed of 50 km/h have recommended gradients of 6%, with a maximum gradient of 8%. Emission rate data for CNG taxis show that road gradients of 2–6% correspond to the highest emission rates, which is a primary reason why vehicle emissions in mountainous cities are significantly higher than those in plains cities. Additionally, the frequent acceleration and deceleration on mountainous roads, particularly in the 2–6% gradient range, further exacerbates emission rates. This combination of increased pollutant emission rates on gradient roads and the concentrated, frequent acceleration and deceleration processes significantly contributes to the higher emission rates.

Considering the impact of road gradient, acceleration, and speed on vehicle emission rates, it is evident that in low- and medium-speed driving conditions, both road gradient and acceleration/deceleration promote pollutant emissions. Therefore, road type and traffic environment have a significant correlation with vehicle emissions. Improving road types and traffic environments can be beneficial for reducing CNG taxi emissions. However, this emission reduction pathway is highly costly. In this study, replacing TWC has been shown to effectively and efficiently purify exhaust pollutants in real-time, significantly reducing the correlation between CNG vehicle emissions and road gradient and traffic environment. Consequently, replacing failing TWCs can effectively reduce excessive pollutant emissions from CNG taxis on mountainous city roads.

5. Conclusions

In this study, the real-world exhaust pollutants and CO$_2$ emission characteristics of CNG taxis operating in mountain cities were monitored and analyzed by using PEMS, and their emission reduction efficiency was evaluated by triple-acting catalyst replacement. All of the exhaust emissions from the in-use CNG taxis exceeded the emission standard limits and NOx was the main pollutant that exceeded the limit. Furthermore, the emission factors of exhaust pollutants from CNG taxis are significantly higher than that of gasoline cars and CNG cars in plain cities. After TWC replacement, the CO, THC, NOx, and PN from the exhaust of CNG taxis were effectively converted, and were reduced by 3–7, 7–9, 3–5, and 2–3 times, respectively. Therefore, the use of natural gas vehicles after TWC deactivation has not resulted in a better environment; instead, it has become a major hidden factor in environmental degradation.

Regarding the impact of velocity, the emission factors of CO, THC, and CO$_2$ for CNG taxis without TWC replacement initially decreased and then increased with increasing velocity. The effect of velocity on NOx emissions fluctuated, while the PN emission factor remained unaffected. After TWC replacement, the emission factors of CO, THC, and NOx significantly decreased and were not influenced by velocity. Notably, road slopes between 2% and 6% exhibited the highest emission rates for CNG taxis, particularly when the deceleration rate was in the interval of 0.5 m/s$^2$ to 4 m/s$^2$. Additionally, the average pollutant and CO$_2$ emission rates of taxis without a TWC replacement increased with increasing VSP in low-speed and medium-speed operating modes, but decreased after TWC replacement. The pollutant and CO$_2$ emission rates of China IV and China V CNG taxis were at the same level after TWC replacement. The research findings provide data support for the study and prevention of traffic pollution in mountain cities.
Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/atmos15060715/s1. Table S1: Information on taxis fueled by compressed natural gas. Table S2: Driving condition parameters used in the testing of each taxi fueled by compressed natural gas. Table S3: The precision of measurements. Table S4: The parameters of the replaced three-way catalytic converter. Table S5: Definition of operating mode bins by using vehicle specific power (VSP) and vehicle speed (v). Table S6: The average distance-specific emission factors of NO, NO₂ and CO₂ for taxis with/without TWC replacement. Table S7: The results of ASM mode testing. Table S8: The average distance-specific emission factors of passenger car fueled by gasoline. Table S9: Road grade distribution ratio of test route. Table S10: The acceleration patterns on different road gradients. Figure S1: The test routes for the CNG taxis in Chongqing. Figure S2: ASM test operating cycle. Figure S3: The portable emissions measurement system used to test the CNG taxis. Figure S4: The deactivated and new TWCs. Figure S5: The emission rates of taxis according to different velocity. Figure S6: Distribution of velocity in different road grade bins: (a) CNG taxis without TWC replacement, (b) CNG taxis with TWC replacement. Figure S7: The natural gas consumption of CNG taxis before and after TWC replacement. Figure S8: Average emission rates of NO and NO₂ from CNG taxis according to operating mode.

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Abbreviations

The following abbreviations are used in this manuscript:

- CNG: Compressed natural gas
- TWC: Three-way catalyst
- PEMS: Portable emissions measurement system
- VSP: Vehicle specific power
- OBD: On-board diagnostic system
- UF: Urban freeways
- PRs: Primary roads
- SRs: Secondary roads
- ASM: Acceleration simulation mode
- GPS: Global positioning system
- I/M: Inspection/Maintenance
- NEDC: New European Driving Cycle

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