The effect of after-treatment techniques on the correlations between driving behaviours and NO$_x$ emissions of passenger cars

Jianbing Gao [a, *], Haibo Chen [a, **], Ye Liu [a], Ying Li [b], Tiezhu Li [c], Ran Tu [c], Biao Liang [d], Chaochen Ma [e]

[a] Institute for Transport Studies, University of Leeds, Leeds, LS2 9JT, UK
[b] Dynnoteq Limited, International House, 24 Holborn Viaduct, London, EC1A 2BN, UK
[c] School of Transportation, Southeast University, Nanjing, 210096, China
[d] Nanjing Sample Technology Co. Ltd, Nanjing, 210049, China
[e] School of Mechanical Engineering, Beijing Institute of Technology, Beijing, 100081, China

ARTICLE INFO

ABSTRACT

Nitrogen oxides (NO$_x$) emissions from passenger cars are significantly dependent on after-treatment techniques, cold start conditions, and driving behaviours. The widely-used selective catalytic reduction (SCR) technique has low effectiveness of reducing NO$_x$ emissions during the cold start period or at low speeds. As a new technique, ammonia creation and conversion technology (ACCT) system can further decrease NO$_x$ emissions to achieve cleaner travelling. The correlations between driving behaviours and NO$_x$ emissions are different for vehicles equipped with SCR and ACCT systems over cold start and warm start driving cycles. In this paper, the effect of SCR and ACCT systems on the correlations between driving behaviours and NO$_x$ emissions were explored based on worldwide harmonized light vehicle test cycles (WLTC). The results indicated that vehicle fuel consumption rates almost linearly increased with acceleration when the acceleration was higher than -0.5 m/s^2. For cold start situations, vehicle speed range of 55 km/h~ 100 km/h presented the lowest NO$_x$ emission factors over SCR and ACCT scenarios. SCR efficiency was lower than 60% for the vehicle speed range of 25 km/h~ 40 km/h, and the efficiency of ACCT system was higher than 65% in the corresponding speed range. Regarding the warm start scenarios, average catalyst efficiency was higher than 80% for SCR system over the speed range of 25 km/h~ 40 km/h, and ACCT efficiency was higher than 95% for all the speed and acceleration ranges. Applications of ACCT systems provided a possibility of meeting stricter emission regulations, and the relationships between driving behaviours and NO$_x$ emissions provided the guidance for eco-driving to achieve cleaner travelling.

1. Introduction

As concerns regarding environmental pollutants are increasing, emission regulations of on-road vehicles are becoming stricter (Gao et al., 2018, 2021; Wei, 2019; Zhang et al., 2016). Investigations based on the assessments of diesel engines indicated that global warming potential and photochemical ozone formation potential from diesel engines accounted for 19.47% and 17.54% of total impacts, respectively (Li et al., 2013); additionally, the contributions of air pollution emissions from conventional vehicles to the total air pollution are eleven times of electric vehicles (Nanaki and Koroneos, 2013). Nitrogen oxides (NO$_x$) emissions are one of the main pollutants for both petrol and diesel vehicles (Abdel-Rahman, 1998), their damages are the highest among the regular gaseous emissions (Government, 2020). After-treatment systems which aim to eliminate NO$_x$ are essential to meet high emission regulations. Three-way-catalyst (TWC) (Ito et al., 2015) is usually used for petrol vehicles; and selective catalytic reduction (SCR) (Smit et al., 2019;

Zhang and Chen, 2015) and lean NO$_x$ trap (LNT) (García-Contreras et al., 2020; Hernández et al., 2020) are applied to diesel vehicles. Catalyst efficiency is excellent over normal driving conditions to achieve low pipe-out NO$_x$ emissions. However, NO$_x$ emissions are high under low exhaust temperature conditions which usually happen over cold start stages and low vehicle speed situations (Gao et al., 2019c), especially for diesel vehicles whose exhaust temperature is much lower than petrol vehicles due to lean-burn characteristics. It was demonstrated by Vijayan et al. (2008) that maximum difference of nitrogen monoxide (NO) concentration between cold stages and warm stages was higher than 600 ppm for buses, and it took more than 7 min for the cold start scenario to narrow the gap.

For Euro 6 compliant diesel vehicles, SCR systems are necessary to meet the emission limits (Kozina et al., 2020). The main concerns regarding NO$_x$ emissions from new vehicles are cold start where NO$_x$ after-treatments have low efficiency. High NO$_x$ emissions were observed in the work (Schmeisser et al., 2013) where NO$_x$ concentration drop by after-treatment was low in the period of 150 s−500 s due to low exhaust temperature before SCR system. It was also indicated that 80%−90% of the tailpipe emissions was emitted during the first test cycle in Federal test procedure (FTP), in which the cold start period was included (Gong et al., 2011). A variety of technologies are available to decrease cold start emissions such as burners (Akcayol and Cinar, 2005), reformers (Kirwan et al., 2002), thermal insulation (Burch et al., 1995; Daya et al., 2016), heat storage materials (Gumus and Ugurlu, 2011), electric catalytic converter (eHC) (Pace and Presti, 2011), ammonia creation and conversion technology (ACCT) (Wilson and Hargrave, 2018), ammonia storage and delivery systems (ASDS) (Johannessen et al., 2008). The main theory of these technologies is to increase exhaust temperature or provide an easier way to delivery gaseous ammonia, ensuring high efficiency of after-treatment systems. In order to meet stricter emission regulations (e.g. Euro 7), part of these technologies would be applied to vehicles beyond SCR. According to (Wilson and Hargrave, 2018), the performance of the ACCT system providing gaseous ammonia was tested; however, the real world tests of ACCT system installing on vehicles weren't reported. Compared with heavy duty vehicles, some after-treatment technologies lacked the flexibility to be installed on passenger cars, due to the limited space. Based on published materials, a summary of the retrofits technologies for dropping cold start NO$_x$ emissions are provided in Table 1. In the table, the effectiveness, energy penalty, and complexity are the key performance indicators. The levels of effectiveness, energy penalty, complexity were defined based on the proportions of emission reductions, energy increase, and the number and size of components for specific techniques, respectively. When choosing the techniques, balances among effectiveness, energy penalty, and complexity should be made to achieve the best "performance" from the global prospective.

In addition to cold start, driving behaviors are also important factors worsening exhaust emissions (Allison and Stanton, 2019; Luo et al., 2017), such as vehicle speed, acceleration, start-stop, and gear shift strategies (Jensen et al., 2008; Oglieve et al., 2017). Gao et al. (2019a) analyzed the sensitivities of eco-driving factors to exhaust emissions from a diesel passenger car. This analysis indicated that velocity was one of the most sensitive factors influencing NO$_x$ emission. An increase of NO$_x$ emission factors by high average vehicle speed was indicated by Zervas et al. (Zervas and Bikas, 2008) over the given driving cycles. However, NO$_x$ emission factors generally decreased with dropping average speed when the speed was lower than 60 km/h (Hu et al., 2012), with similar results obtained by Hu et al. (Gao and Checkel, 2007). Tang et al. (2014) demonstrated that increasing the deceleration distance could drop the total NO$_x$ emissions which also dropped with the increase of acceleration time. Pipe-out NO$_x$ emissions were jointly affected by engine-out NO$_x$ emissions and catalyst efficiency (exhaust temperature). Tang et al. (2015) indicated that driver's bounded rationality would reduce the speed during the start and improve traffic flow stability, which conducing to decreasing total NO$_x$ emissions. Route choice decision on dropping vehicle emissions were researched by Ahn et al. (Ahn and Rakha, 2008) who concluded that faster speed for highway choice may not be the environmentally friendly perspective, as even a small part of the trip involving high engine load would produce a significant increase in emissions (Ahn and Rakha, 2008). High engine load could significantly increase SCR efficiency but cause high engine-out emission rates. However, the driving in urban areas can be another story due to low vehicle speed and low exhaust temperature. In these investigations, the influence from catalysts performance was neglected, which may lead to unreasonable conclusions.

Rodríguez (Rodríguez et al., 2016) et al. researched the effect of driving patterns on NO$_x$ emissions using real-world emission test. It indicated that NO$_x$ emission rates presented a clear mathematical relationship to vehicle specific power (VSP) which was the functions of vehicle speed and acceleration. It also indicated that mathematical equations correlating NO$_x$ emission rates and VSP varied with vehicle types (passenger cars and light-duty vehicles), fuel types (gasoline and natural gas) and after-treatment systems (with and without TWC). However, the comparisons within the same categories were based on different vehicles, weakening the significance of the results. Based on the real-world test for diesel vehicles, 25% higher NO$_x$ emissions were generated by aggressive driving rather than normal driving. However, NO$_x$ emissions of petrol vehicles were found to decrease during aggressive driving when compared to normal driving (Varella et al., 2019). Aggressive driving led to high exhaust temperature, resulting in high efficiency of catalyst. It highlighted the significance of low exhaust temperature for diesel vehicles.

In order to meet the requirements of CO$_2$ emission from passenger cars, low energy penalty after-treatment technologies should be adopted. As indicated in Table 1, after-burner, extra-burner, and reformer had high energy penalty (Gao et al., 2019c) although their complexity was low and effectiveness was in a medium level. Thermal insulation and heat storage materials didn't have any energy penalty, but the effectiveness was quite low. Additionally, the widely reported correlations between driving behaviours and exhaust emissions, fuel consumption were based on statistical results of real world tests. The details such as the thermal status of catalysts were neglected; however, the cold start stages contributed big proportions to the vehicle total emissions, which may lead to the improper conclusions about the relationships between driving behaviours and vehicle emissions. ACCT system as a new technology aimed to decrease NO$_x$ emissions over cold start stages. It presented excellent NO$_x$ reduction efficiency because of its low light-off temperature. Its applications would

Table 1
Summary of retrofit techniques for passenger cars.

	Effectiveness	Energy penalty	Complexity
After-burner	♦♦♦	♦♦♦♦	♦
Extra-burner	♦♦♦♦	♦♦♦♦♦	♦♦♦
Reformer	♦♦	♦♦♦♦♦	♦♦♦
eHC	♦♦♦♦♦	♦♦♦	♦♦
Thermal insulation	♦	♦	♦♦
Heat storage materials	♦	♦	♦♦
ACCT	♦♦♦♦	♦	♦♦♦♦♦
ASDC	♦♦♦♦	♦♦	♦♦♦♦

Note: ♦♦♦♦♦, the highest level; ♦, the lowest level.

affect the relationships between driving behaviours and vehicle emissions. Driving behaviours not only affect NO_x formations, but also exhaust temperature determining catalyst efficiency. So it was important to explore the correlations of driving behaviours and NO_x emissions when vehicles were equipped with ACCT systems and conventional ones (SCR), considering the impacts from cold start stages. To the authors' knowledge, few materials are available to report the effect of after-treatment techniques on the correlations between driving behaviours and NO_x emissions. It included the impacts from both new NO_x reduction techniques and cold start stages.

In this paper, vehicle fuel consumption and NO_x emission characteristics were explored based on numerical simulations over WLTC when a diesel passenger car was equipped with SCR and ACCT systems separately. Moreover, the effect of cold start stages on the correlations between driving behaviours and NO_x emissions were explored in order to achieve low NO_x emissions. Low emission driving was one of the pathways to achieve cleaner productions of traffic modes. Integrations of ACCT systems and the vehicles would conduce to decreasing travel emissions; the explorations of the correlations of driving behaviours and NO_x emissions provided evidences of eco-driving for drivers.

2. Materials and methods

In this section, the simulation model was described and validated using experimental results.

2.1. Simulation model description

2.1.1. Descriptions of vehicle model

Specifications of the diesel passenger car which was used in this investigation are shown in Table 2. This type of passenger cars is on the market and is under an emission level of Euro 6. In order to meet stricter emission regulations (such as Euro 7 and real driving emissions), more effective after-treatment devices are necessary to limit the pipe-out emissions of passenger cars based on the current technologies. The mass of this passenger car was around 1505 kg. The power of this vehicle was a four-cylinder, four-stroke, turbocharged diesel engine with a maximum power and torque output of 103 kW and 325 N m respectively. The investigation was based on the simulation model which was conducted using GT-SUITE software. The simulation model is shown in Fig. 1(a), more details are provided in Fig. S1. This model included powertrain model, emission sources, and after-treatment devices. The powertrain model was consisted of a diesel engine, transmission systems, and vehicle body. This engine model was based on the engine maps (brake specific fuel consumption determined by engine speed and torque), and the engine maps were presented in the authors' previous work

Table 2
Specifications of the diesel passenger car, from (Gao et al., 2019a).

Specifications	Value
Vehicle mass	1505 kg
Maximum speed	170 km h^{-1}
Gear number	6
Fuel	Diesel
Engine type	In-line, four-cylinder, four-stroke
Intake type	Turbocharged intercooler
Fuel injection type	Direct injection
Engine max power/kW	103 kW @ 4000 rpm
Engine max torque/N·m	325 N m @ 1500 rpm
Stroke/mm	80.4
Bore/mm	79.1
Compression ratio	16.5
Emission regulation	Euro 6

(Gao et al., 2019a). The after-treatment systems included diesel oxidation catalyst (DOC), diesel particulate filter (DPF), and SCR (or ACCT). This investigation only focused on NO_x, consequently different NO_x reduction after-treatment devices were adopted. The performance of both after-treatment devices were compared with the authors' previous work (Gao et al., 2019b) where eHC was used to fast light-off catalyst for decreasing exhaust emissions including hydrocarbon (HC), carbon monoxides (CO), and NO_x.

2.1.2. Descriptions of after-treatment systems

The SCR system was an original NO_x reduction after-treatment system of this passenger car, which usually took a long period for the catalyst to light-off from engine cold start. The eHC device in the authors' previous work (Gao et al., 2019b) was used to heat the exhaust before DOC when the exhaust temperature was lower than the threshold value setting in the eHC control system, more details of the eHC system and its operation theory were presented in the authors' previous work (Gao et al., 2019b). ACCT system was firstly developed by Wilson (Wilson and Hargrave, 2018), and it aimed to provide an easy approach of delivering gaseous ammonia at low temperature conditions. Over normal driving conditions (high exhaust temperature), ACCT system used the exhaust energy to hydrolysis the AdBlue into gaseous ammonia, carbon dioxide (CO_2) and gaseous water which would form ACCT fluid after the gaseous mixture was cooled down; then the products were stored in the ACCT tank. In Wilson's work, ACCT fluid was only used when the vehicle was over cold start situations. However, ACCT fluid could be adopted any time. The main factor influencing NO_x reduction efficiency was the hydrolysis reactions of ACCT fluid. The simulation model of the hydrolysis reactions of ACCT fluid was shown in Fig. 1(b). The geometrical size of the hydrolysis reaction system was the same as the ones in Wilson's work (Wilson and Hargrave, 2018). Validations of the vehicle model and hydrolysis reactions of ACCT fluid were presented in the following sections.

2.2. Validations of simulation models

In this section, validations of simulation models including the powertrain system, standard NO_x reduction system (SCR), and ACCT system were conducted.
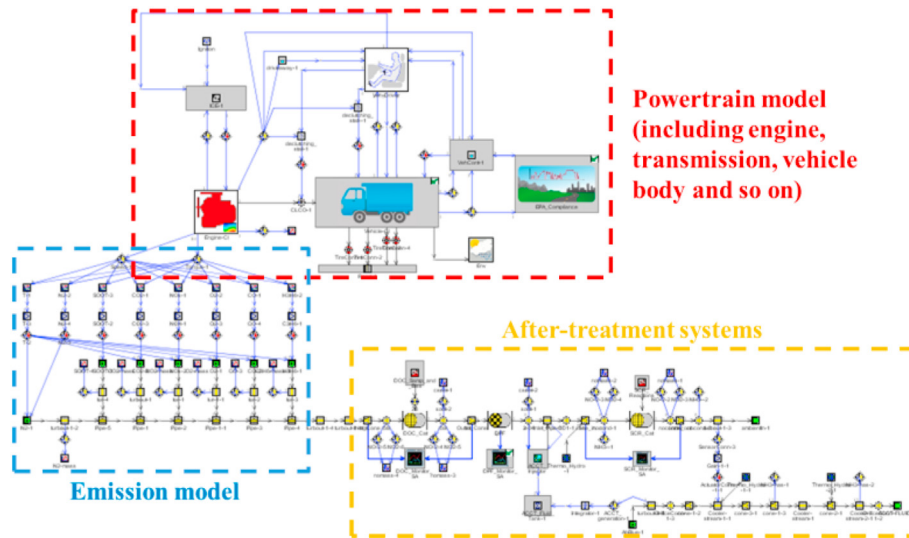
2.2.1. Validations of vehicle model

WLTC represents average driving characteristics around the world (Tutuianu et al., 2015), so it was selected as the target driving cycle in this investigation. Compared with New European Driving Cycle (NEDC), WLTC covered a broader range of acceleration, and included typical speed patterns for four different types of roads (Giakoumis and Zachiotis, 2017). This vehicle was tested in the lab over WLTC. Meanwhile, fuel consumption rates and exhaust emission rates were monitored. Fuel consumption rates from both experiment and simulation model are shown in Fig. 2(a). As can be seen, fuel consumption rates from simulation matched well with experimental results. Fig. 2(b) presents NO_x emissions from both engine-out (before after-treatments) and pipe-out (after SCR system). The difference of pipe-out NO_x emission rates between experiment and simulation results was minor, which indicated that the precision of the SCR model was acceptable for pipe-out NO_x estimations. Similar to the published data (Giakoumis and Zachiotis, 2017), NO_x emissions were low when operating over extra-high vehicle speed conditions, which was benefited from high catalyst efficiency. Since the fuel consumption rates and NO_x emissions (engine-out) were low under low vehicle speed conditions, the errors of the test results over low speed were higher than that of higher vehicle speed. When considering the contributions of the engine-out NO_x emissions to the total emissions, the errors
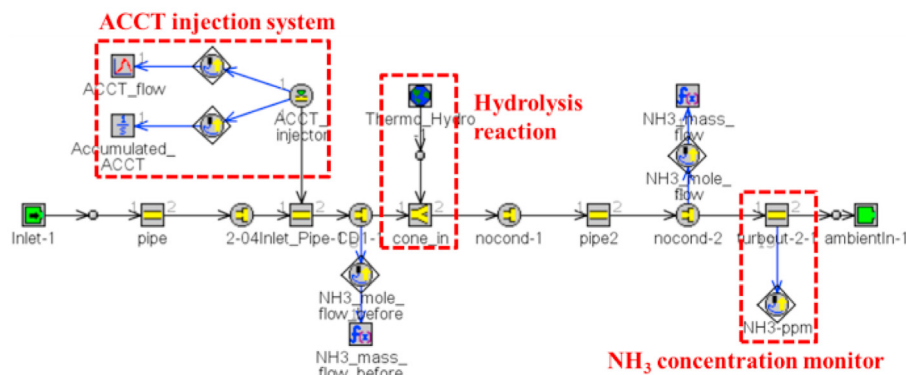
(a) Model of the diesel passenger car

(b) Model of ACCT fluid hydrolysis reactions

Fig. 1. Simulation model of the diesel passenger car equipped with after-treatment systems.

were negligible. In the engine cold start process, the coolant temperature which affected the thermal status of cylinder walls increased gradually. In this simulation, the emission sources were based on emission maps which were obtained after the engine warmed up. The sensitivity analysis of NO_x emissions over different coolant temperature (cylinder wall temperature setting) was conducted over three engine operation conditions, as shown in Table S1.

2.2.2. Validations of ACCT system

Test conditions in the research by Wilson and Hargrave (2018) were as the follows: hot air flow rates, 250 kg/h; ACCT fluid flow rates, 400 g/h; air temperature at 100 °C, 150 °C, 200 °C, 300 °C, and 400 °C; ammonia (NH_3) concentration monitor point, 800 mm downstream of the ACCT fluid injector. Each scenario lasted 30 s in the experiment (Wilson and Hargrave, 2018). The boundary conditions of the ACCT simulation model in Fig. 1(b) were the same as the ones in Wilson and Hargrave's experiment (Wilson and Hargrave, 2018). The conparisons of simulation and experimental results are show in Fig. 3. Wilson and Hargrave (2018) indicated that NH_3 concentration was 410 ppm over the hot air temperature of 100 °C although ACCT fluid was completely hydrolyzed (should be 500 ppm) because NH_3 film formed on the pipe wall in the

experiment. It was partly supported by the fact that higher air temperature contributed to the increase of NH_3 concentration; however, the increase was small. In the simulation model, formations of NH_3 film on the wall could not be performed, so NH_3 concentration from simulation was slightly higher than experimental results. In addition, the effect from NH_3 film in the experiments would be diminished after reaching the saturation status. As mentioned above, the process of NH_3 film formations was neglected which may generate the errors for the simulation, especially during the cold start. In the real test, the impacts caused by NH_3 film formations could be compensated by more ACCT fluid delivery at the cold stages and less injection after warm up. It could be achieved by NH_3 sensors installed after ACCT system. In order to compare the performance of SCR and ACCT systems, the scenarios of the vehicle model including SCR and ACCT systems were simulated separately.

3. Results

This section mainly included (1) driving behaviours over WLTC; (2) the relationships between fuel consumption and driving behaviours; (3) performance comparisons of SCR and ACCT systems; (4) the relationships between NO_x emissions and driving
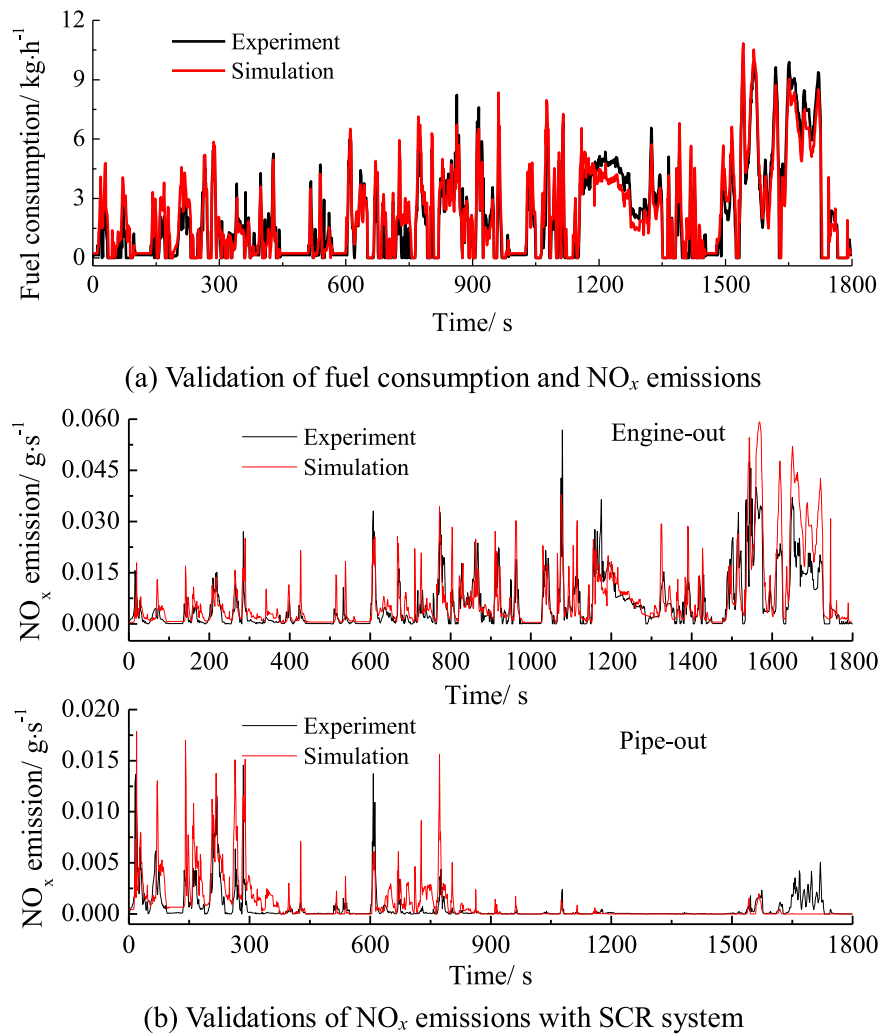
(a) Validation of fuel consumption and NO$_x$ emissions

(b) Validations of NO$_x$ emissions with SCR system

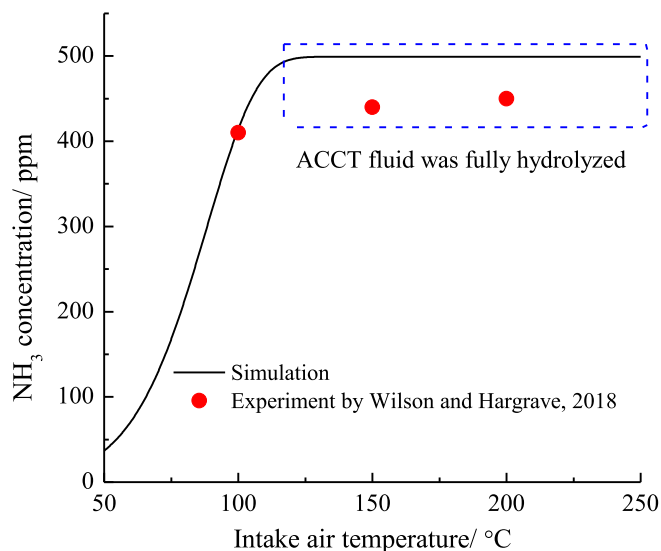**Fig. 2.** Validation of the vehicle fuel consumption and NO$_x$ emissions.

Fig. 3. Validations of ACCT fluid hydrolysis reactions.

behaviours.

3.1. Driving behaviour analysis over WLTC

Speed distributions by travel durations and distance are shown in Fig. 4 over WLTC which included four categories of vehicle speed (see the previous work for speed profile (Gao et al., 2019a)). In terms of the driving durations, low vehicle speed (lower than 5 km/h) accounted for the highest percentage in WLTC. Low vehicle speed usually resulted in high fuel consumption and exhaust emission factors (mass per unit distance). Generally, the durations of individual vehicle speed range dropped with speed increase over WLTC. For the travel distance over WLTC, the majority of the distance was contributed by medium and high vehicle speed ranges. Acceleration distributions by travel durations and distance over WLTC are shown in Fig. 5. Acceleration showed normal distributions by both travel durations and distance, with the median value being around zero. Vehicle acceleration range of −0.7 m/s^2~ 0.7 m/ s^2 accounted for more than 90% of the travel durations and distance.

3.2. Relationship between driving behaviours and fuel consumption

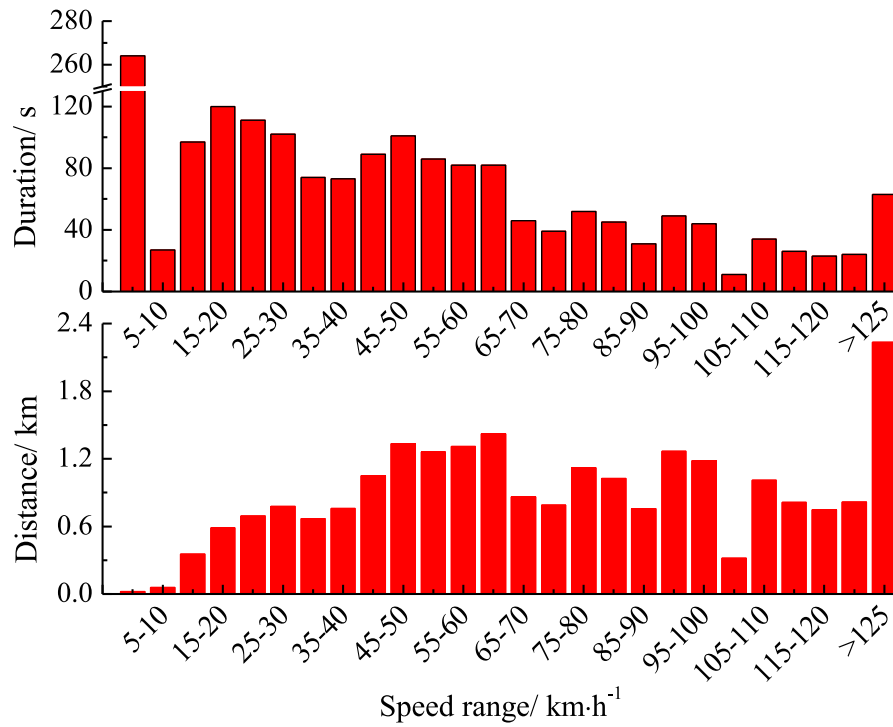Accumulated fuel consumption over various vehicle speed

Fig. 4. Speed distributions by travel durations and distance.
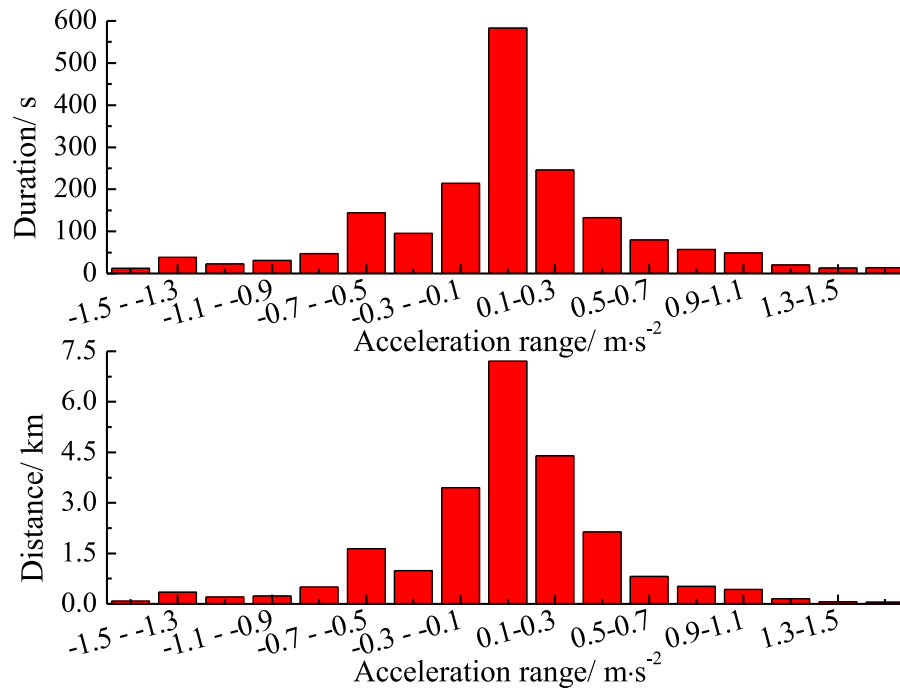

**Fig. 5.** Acceleration distributions by travel durations and distance.

ranges is shown in Fig. 6(a). As can be seen, the accumulated fuel consumption was approximately 0.02 kg for the speed range of 0 km/h~ 5 km/h although its corresponding travel distance was almost zero. Low-medium vehicle speed accounted for a large proportion of accumulated fuel consumption. Fuel consumption rates per unit distance over various vehicle speed ranges are shown in Fig. 6(b). Fuel consumption rates for the speed range of 0 km/h~

5 km/h were approximately 95 kg·(100 km)$^{-1}$, which was mainly caused by lots of idling stages where the fuel consumption per distance were the highest.

Accumulated fuel consumption over various acceleration ranges was completely different from acceleration distributions by durations and distance, as shown in Fig. 7(a). The accumulated fuel consumption was almost zero when vehicle acceleration was lower
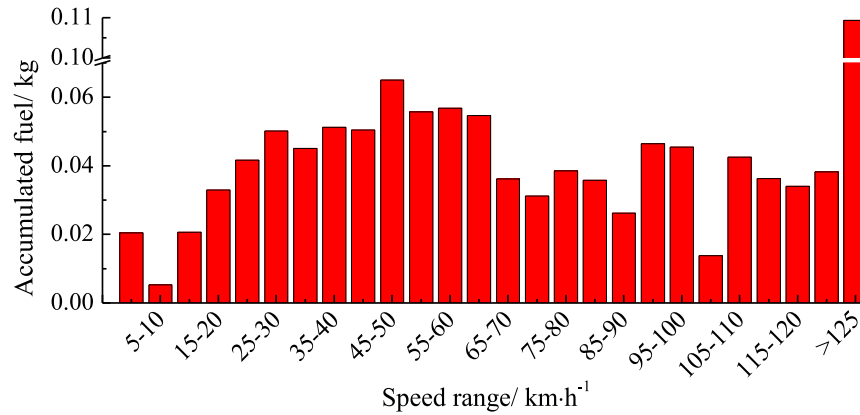
(a) Distributions of fuel consumption over various speed ranges
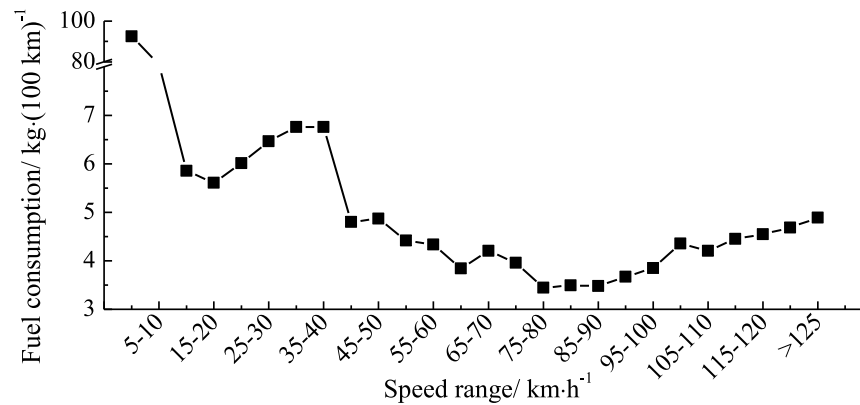
(b) Average fuel consumption rates over various speed ranges

Fig. 6. Fuel consumption distributions and average fuel consumption rates over various speed ranges.

than -0.3 m/s^2, which was caused by the fuel cut-off technology over aggressive deceleration events. Most of the fuel was consumed over the acceleration range of -0.3 m/s$^2 \sim 1.5$ m/s^2. Fig. 7(b) presents the fuel consumption rates per unit distance over various acceleration ranges. It showed that the fuel consumption rates almost linearly increased with acceleration when the acceleration was higher than -0.5 m/s^2. During the real driving, gentle driving was suggested to drop the fuel consumption rates by decreasing the frequent acceleration. The explorations of the relationships between fuel consumption and driving behaviours would provide the evidences to drivers on the eco-driving patterns. It helped to decrease the fuel consumption and CO_2 emissions to achieve the cleaner travelling.

### 3.3. Performance analysis of SCR and ACCT systems

3.3.1. Scenarios including cold start stages

In this section, WLTC started with a cold start stage where NO_x emissions accounted more than half of the total emissions, as indicated in the reported researches (Gao et al., 2019b, 2019c; Schmeisser et al., 2013). Exhaust emissions usually had a trade-off relationship with fuel consumption, gentle driving tended to provide relative low exhaust temperature with poor catalyst efficiency although fuel consumption was low. Fig. 8(a) shows NO_x emissions after SCR and ACCT systems over WLTC. NO_x emissions before SCR and ACCT systems were the same, and the values are shown in Fig. 2(b). As can be seen, NO_x emissions after SCR and ACCT systems

were the same at the first 250 s which was over the catalyst warm-up process, where temperature was too low to hydrolyze and pyrolyze AdBlue and ACCT fluid at the start of the driving cycle. Compared with SCR scenarios, NO_x emissions dropped significantly in the range of 600 s$-$800 s for ACCT scenarios. As mentioned above, temperature of hydrolysis and pyrolysis reactions of ACCT fluid was much lower than AdBlue, which caused lower NO_x emissions for ACCT system during some periods. In ACCT system, no extra energy was consumed; but it affected the application of other technologies, such as organic Rankine cycle (ORC) (Uusitalo et al., 2016) which was used to recycle waste exhaust energy. Fig. 8(b) shows the temperature before SCR and ACCT systems and their corresponding efficiency over WLTC. Catalyst efficiency was zero for both SCR and ACCT at the first 200 s of WLTC; then, it increased gradually. It reached nearly 100% after the catalyst was fully warmed up around 370 s for the ACCT system. There was a sudden drop for SCR efficiency in the range of 600 s$-$800s where the temperature before SCR was lower than 450 K.

3.3.2. Scenarios excluding cold start stages

In order to exclude the effect of cold start on the NO_x emission characteristics, an extra short cycle was used to warm up the catalyst before WLTC, as shown in Fig. 9. The first short cycle (dark line) was excluded when analyzing NO_x emission characteristics. Fig. 10(a) presents NO_x emissions when the vehicle was equipped with SCR and ACCT systems. NO_x emissions were nearly zero for ACCT scenarios in the whole driving cycle, except for several small
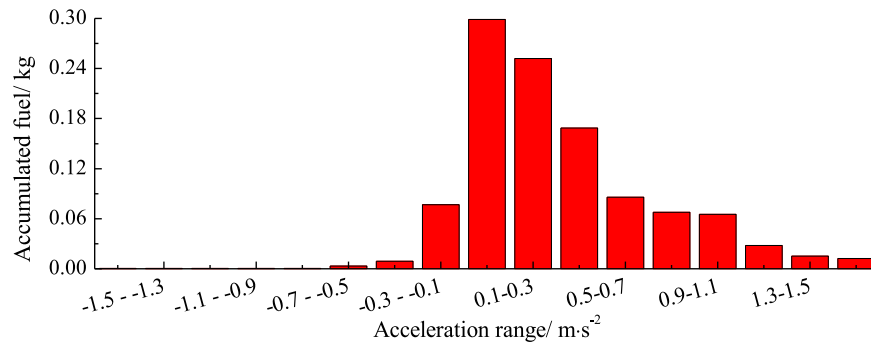
(a) Distributions of fuel consumption over various acceleration ranges
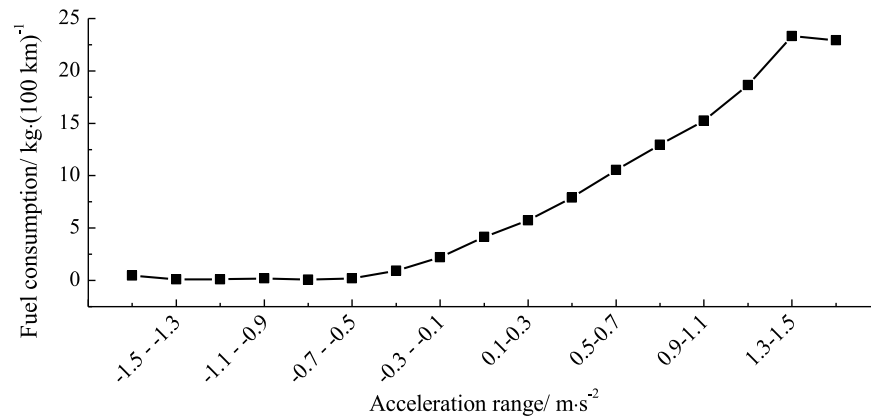
(b) Average fuel consumption rates over various acceleration ranges

Fig. 7. Fuel consumption distributions and average fuel consumption over various acceleration ranges.

peaks. However, NO_x emissions were still high after SCR system over specific situations where the exhaust temperature was not high enough to keep excellent efficiency, as shown in Fig. 10(b). Compared with cold start situation, NO_x emissions were much lower at the beginning of driving cycle. It implied that NO_x emission factors would be high if the travel duration was short, which couldn't provide enough time for the catalyst warm-up.

3.4. Relationships between driving behaviors and NO_x emissions

In this section, relationships between driving behaviors and NO_x emissions after SCR and ACCT systems were analyzed over both including and excluding cold start stages.

3.4.1. Scenarios including cold start stages
3.4.1.1. Vehicle equipped with SCR system.
Accumulated NO_x emissions before and after SCR system over WLTC including cold start stages are shown in Fig. 11(a). As can be seen, vehicle speed range of 0 m/h~ 15 km/h contributed a proportion to the total NO_x emissions before SCR system compared to other speed ranges due to the short corresponding distance. NO_x emissions after SCR system were almost zero for vehicle speed being higher than 70 km/h; meanwhile, accumulated NO_x emissions were dominated by the speed range of 10 km/h~ 60 km/h, which was mainly caused by poor catalyst efficiency (see Fig. 11(b)) and long accumulated travel distance (see Fig. 4). Maximum average NO_x emission factors reached up to 7.3 g/km before SCR system over the speed range of 0–5 km/h; then, NO_x emission factors dropped significantly with vehicle speed increase. NO_x emission factors were approximately 0.75 g/km when vehicle speed was higher than 100 km/h.

Regarding NO_x emission factors after SCR system, they were almost zero when speed was higher than 60 km/h.

When the vehicle speed was higher than 60 km/h, average catalyst efficiency was higher than 95%; the minimum efficiency was lower than 60%, corresponding to the vehicle speed range of 30 km/h~ 40 km/h which mainly occurred in the first 600 s where cold start stages were included. The average catalyst efficiency almost linearly increased with vehicle speed over the range of 40 km/h~ 60 km/h. It was interesting that the average catalyst efficiency was higher than 70% for vehicle speed being lower than 5 km/h where (1) NO_x formation rates were quite low, (2) exhaust temperature was high even the idle conditions after the catalyst was fully warmed up (e.g. around 1000 s, and 1450 s in WLTC). Idling durations were also an important factor that significantly affected vehicle pipe-out emissions. The issue would be significant over urban driving situations where the vehicle speed was low, and exhaust temperature before SCR could easily drop to below catalyst light-off temperature after short idling.

Accumulated NO_x emissions over various acceleration ranges for both before and after SCR system are shown in Fig. 12(a). NO_x emissions generated in the acceleration range of -0.1 m/s^2~ 1.1 m/s^2 accounted for the largest percentage of NO_x emissions before SCR. However, the acceleration range of -0.7 m/s^2~ 1.5 m/s^2 dominated pipe-out NO_x emissions. The acceleration range of -0.1 m/s^2~ 0.3 m/s^2 showed the highest percentage for both before and after SCR system due to its long driving distance (see Fig. 5). Average NO_x emission factors increased continuously with acceleration when acceleration was higher than -0.1 m/s^2; average catalyst efficiency was higher than 60% over all the acceleration ranges (see Fig. 12(b)). It presented the lowest average catalyst
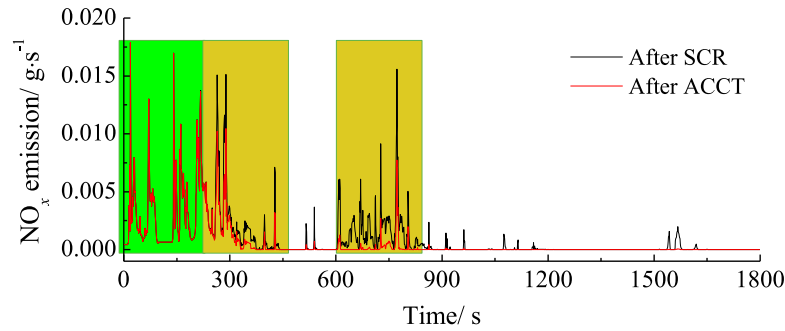
(a) NO$_x$ emissions after SCR/ ACCT over WLTC
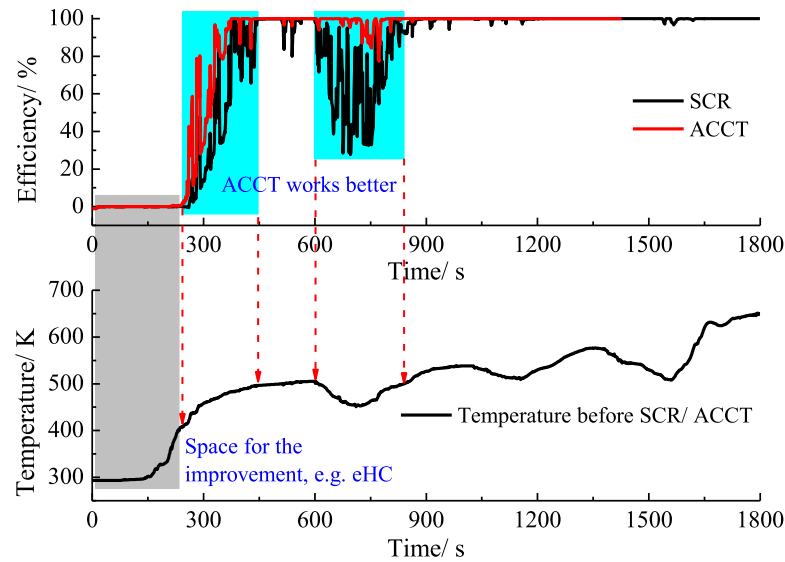
(b) Efficiency of SCR/ ACCT systems and exhaust temperature before SCR/ ACCT

Fig. 8. NO$_x$ emissions, efficiency of SCR/ACCT systems and exhaust temperature before SCR/ACCT.
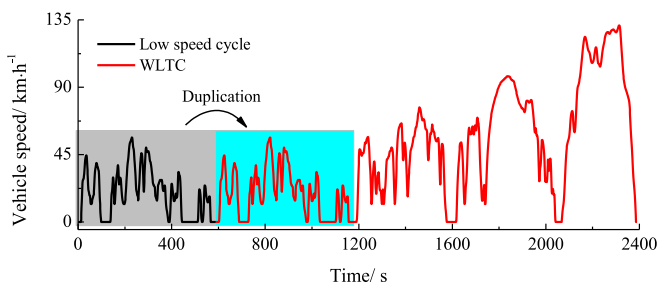
Fig. 9. New driving cycles to exclude the cold start effect.

efficiency for the acceleration range of −1.1 m/s^2 ~ −0.5 m/s^2.

3.4.1.2. Vehicle equipped with ACCT system. Accumulated NO$_x$ distributions over various speed ranges for the vehicle equipped with ACCT system differed greatly from those of SCR system, as shown in Fig. 13(a). Accumulated NO$_x$ emissions were nearly zero when vehicle speed was higher than 60 km/h which was beyond the speed range of urban driving. Vehicle speed range of 20 km/h~ 50 km/h presented the highest accumulated NO$_x$ emissions; however, they were much lower than those of SCR scenarios. Average NO$_x$ emission factors and catalyst efficiency over the cases of ACCT

system are shown in Fig. 13(b). The lowest average catalyst efficiency of ACCT was higher than 60%, and it was higher than SCR over the corresponding speed ranges. Average catalyst efficiency almost reached 100% when vehicle speed was higher than 60 km/h.

Fig. 14(a) provides the data of accumulated NO$_x$ emissions over various acceleration ranges for ACCT scenario. The distributions were similar to those of SCR scenarios, but the accumulated NO$_x$ were lower over all the speed ranges. Fig. 14(b) shows the average NO$_x$ emission factors and ACCT efficiency. It did not present obvious relationships between acceleration and NO$_x$ emission factors. High vehicle power output usually led to high exhaust temperature; however, high acceleration may occur over both low and high power output conditions. Therefore, high vehicle acceleration could not ensure high catalyst efficiency. High acceleration led to high NO$_x$ emission factors for both before and after ACCT system.

3.4.2. Scenarios excluding cold start stages

Cold start stages had a significant effect on NO$_x$ emissions which affected the analysis of the correlations between driving behaviours and NO$_x$ emissions. In this section, cold start stages were excluded using the method shown in Fig. 9.

3.4.2.1. Vehicle equipped with SCR system. Accumulated NO$_x$ emissions over various speed ranges under warm start conditions are shown in Fig. 15(a). Maximum accumulated NO$_x$ emissions after
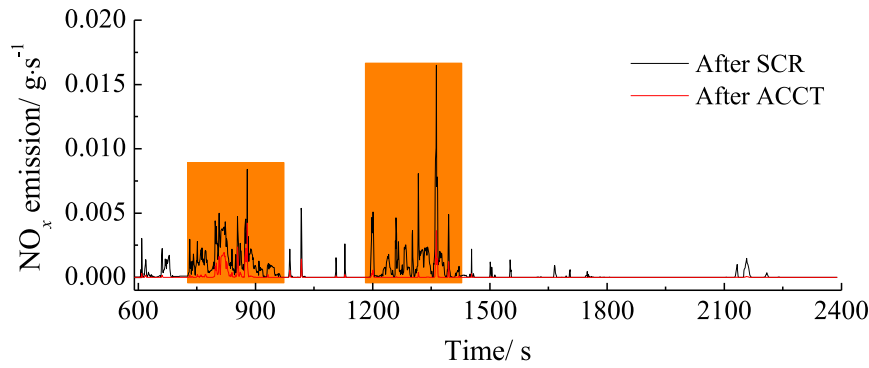
(a) NO$_x$ emissions after SCR/ACCT systems over WLTC
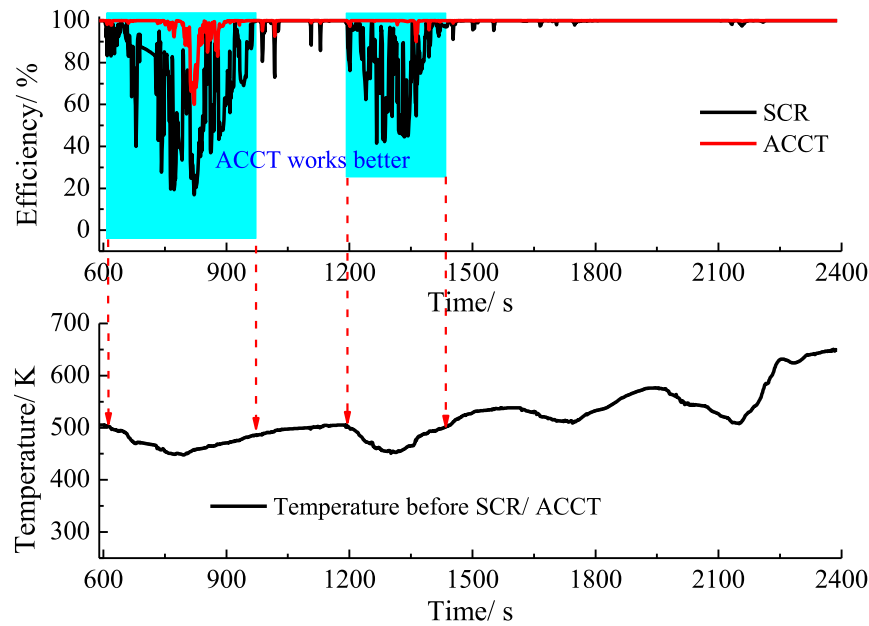
(b) SCR and ACCT efficiency and exhaust temperature before SCR/ACCT

Fig. 10. NO$_x$ emissions after SCR/ACCT systems, NO$_x$ reductions efficiency, and temperature before SCR/ACCT over WLTC.

SCR were lower than 0.15 g, corresponding to the speed range of 45 km/h~ 50 km/h. Accumulated NO$_x$ emissions over the speed range of lower than 60 km/h dropped significantly compared to cold start scenarios, especially for 0 km/h~ 10 km/h where NO$_x$ emissions dropped to nearly zero. Over the WLTC, warm start only affected NO$_x$ emissions from the first third of WLTC. Catalyst efficiency increased greatly when the driving cycle started with warm status that the efficiency was higher than 80% (see Fig. 15(b)). It implied that short travel distance would have high NO$_x$ emission factors than long distance driving if they had similar driving patterns because cold start stages kept for a long duration. Additionally, the effect from cold start would be reduced if the driving speed was low.

Accumulated NO$_x$ emissions over various acceleration ranges under warm start conditions are shown in Fig. 16(a). Similar to cold start driving cycle, acceleration range of 0.1 m/s^2~ 0.3 m/s^2 showed the highest accumulated NO$_x$ emissions; however, the value dropped by almost 50%. Catalyst efficiency was higher than 75% for all the acceleration ranges, and medium acceleration range of −0.2 m/s^2~ 0.5 m/s^2 had the maximum average catalyst efficiency (Fig. 16(b)).

3.4.2.2. Vehicle equipped with ACCT system. Accumulated NO$_x$ emissions over various speed ranges are shown in Fig. 17(a). It reached near zero-emissions, which demonstrated a significant contribution to dropping NO$_x$ emissions by ACCT system. NO$_x$ emissions after ACCT system over the speed range of 20 km/h~ 60 km/h were much lower than those of SCR cases. It indicated the excellent performance of the ACCT system. Fig. 17(b) shows average NO$_x$ emission factors and ACCT efficiency over warm start WLTC. Over all the speed ranges, the average catalyst efficiency was higher than 95%, and it reached almost 100% for high vehicle speed scenarios. The priority of ACCT to SCR was focused on the speed range of 30 km/h~ 60 km/h which was the regular driving speed in urban and sub-urban area. It meant that ACCT system performed much better than SCR system over low vehicle speed conditions where the vehicle would benefit greatly.

With regards to the warm start driving cycle, accumulated NO$_x$ emissions in the acceleration range of 0.5 m/s^2~ 1.7 m/s^2 were much higher than other ranges although the accumulated NO$_x$ emission level was quite low (see Fig. 18(a)). Compared with SCR system, the reductions of accumulated NO$_x$ emissions for ACCT system were focused on the acceleration range of smaller than
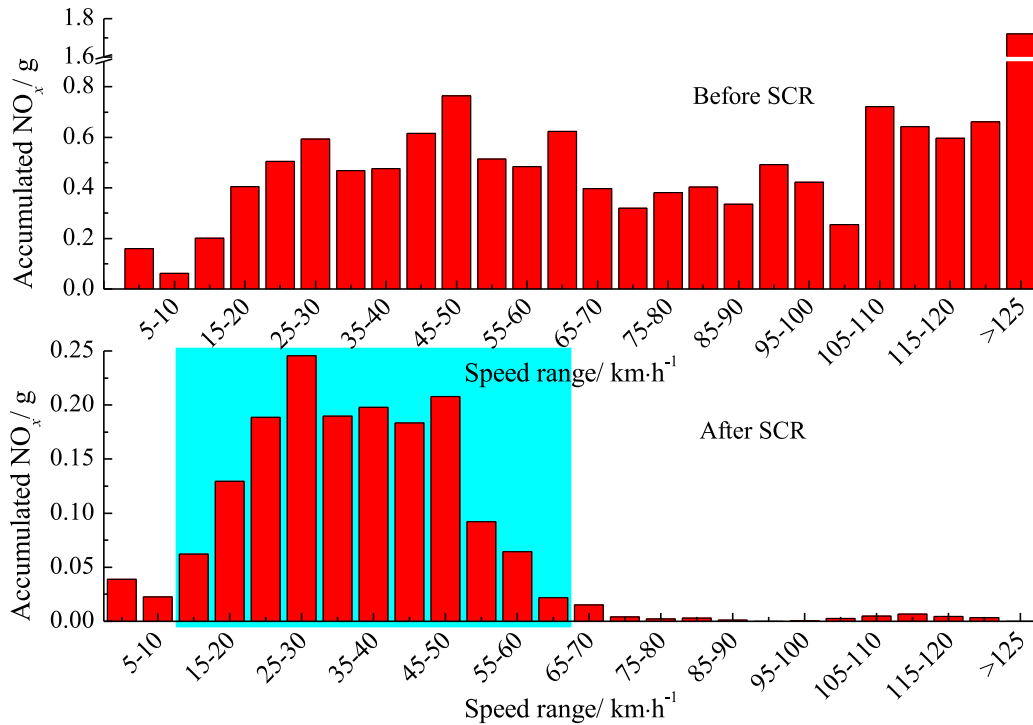
(a) Accumulated NO_x emissions over various speed ranges
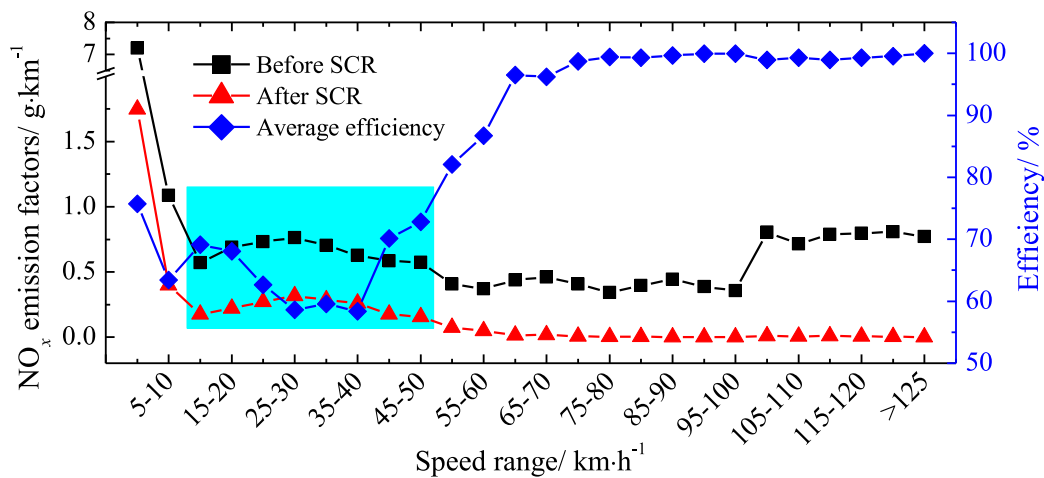
(b) Average NO_x emission factors and SCR efficiency over various speed ranges

Fig. 11. Accumulated NO_x emissions, average NO_x emission factors, and SCR efficiency over various speed ranges.

0.7 m/s^2 despite that the accumulation of NO_x emissions at high acceleration dropped significantly. Fig. 18(b) presented the average NO_x emission factors and ACCT efficiency over various acceleration ranges. The average ACCT efficiency was higher than 95% over all the acceleration ranges.

4. Discussion

Pathak et al. (2016) compared the driving patterns of WLTC and real driving, indicating that the real driving patterns were more complex WLTC. It implied that more effective after-treatment systems should be adopted to meet the emissions of real driving. Sileghem et al. (2014) analyzed the characteristics of WLTC, where

large acceleration events were mainly occurred in the speed range of 20 km/h~ 50 km/h which was the regular speed over the urban and sub-urban area. It implied high contributions to fuel consumption by the vehicle speed range over urban driving. The optimal vehicle speed for the fuel economy was in the range of 60 km/h~ 100 km/h, and low vehicle speed resulted in much higher fuel consumption rates in the authors' research. It was consistent with Walnum's opinion (Walnum and Simonsen, 2015) that the lowest fuel consumption rates usually occurred over medium-high vehicle speed. Lee et al. (Lee and Son, 2011) indicated that fuel economy was significantly affected by acceleration pedal position in highway driving where the largest gear was engaged; additionally, fuel consumption also showed high correlations with
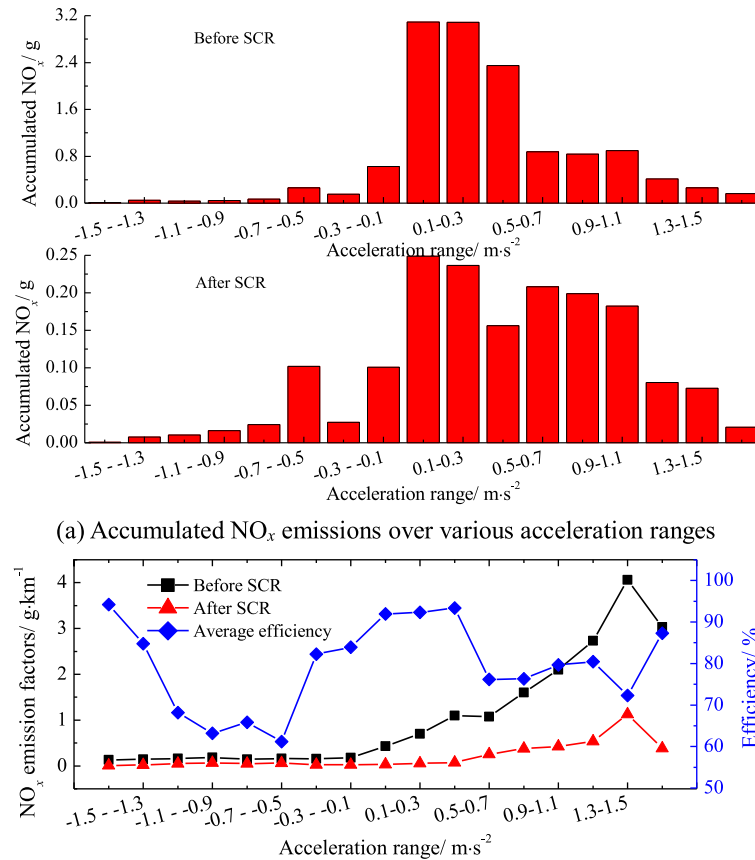
(a) Accumulated NO_x emissions over various acceleration ranges

(b) Average NO_x emission factors and SCR efficiency over various acceleration ranges

Fig. 12. Accumulated NO_x emissions, average NO_x emission factors and SCR efficiency over various acceleration ranges.

steering. Meseguer et al. (2015) demonstrated higher fuel consumption rates over aggressive driving than normal and gentle driving using quantitative analysis. Aggressive driving tended to provide high vehicle acceleration, and high frequency of acceleration and deceleration process. In the authors' results, fuel consumption rates over the acceleration range of 1.3 m/s^2~1.5 m/s^2 were approximately three time of 0.3 m/s^2~0.5 m/s^2. Gao et al. (2020) indicated that fuel consumption rates depended more on acceleration than speed based on heavy duty trucks over the real driving tests.

Cold operations increased NO_x emissions by 55% compared to hot operations based on real driving emissions (RDE) tests, as demonstrated by Varella et al. (2019). Sileghem et al. (2014) indicated that it was important to have enough trips where vehicle speed and load were high enough to light-off the catalyst. It would ensure high catalyst efficiency to drop the overall NO_x emission factors. Okui (2018) also indicated that NO_x emissions from tailpipes were almost zero for high speed ranges, which was consistent with the authors' research. In the authors' previous work (Gao et al., 2019b), eHC technology was used to drop the cold start emissions. The warm up duration (approximately 20 s) of the catalyst was much shorter than SCR and ACCT system. If eHC technology was applied to this vehicle, combined with prediction control, catalyst efficiency could reach almost 100% in theory over all the speed and acceleration ranges due to its quick response. However, much energy penalty was generated. The combinations of eHC and ACCT systems could be an effective method to significantly drop NO_x emissions and energy penalty over all the driving situations.

Maximum average NO_x emission factors reached the minimum

value in the speed range of 50 km/h~ 100 km/h for the passenger car over both ACCT and SCR scenarios, which was consistent with published data (Carrese et al., 2013). Pipe-out NO_x emission factors decreased with average speed when vehicle speed was lower than 60 km/h (Hu et al., 2012), which agreed with the authors' results. Low speed range in WLTC presented the highest NO_x emission factors (Okui, 2018), and nearly zero NO_x emissions were observed over high speed ranges (Okui, 2018). In the real world situations, the lowest NO_x emission factors were obtained by the drivers who provided the highest average speed (Carrese et al., 2013), which was caused by excellent after-treatment efficiency under high exhaust temperature.

In the real driving conditions, the number of stop-and-go also played an important role (Carrese et al., 2013). Because high proportions of stop periods contributed to significant cooling effect on after-treatment systems by low temperature exhaust; additionally, the engine-out NO_x emission rates were low during stops. The pipe-out emissions were the trade-off between NO_x formations and catalyst efficiency. This opinion was consistent with the authors' analysis in this research. Based on a driver simulator, Hiraoka et al. (2009) indicated that acceleration for eco-driving tended to concentrate in low acceleration ranges and had a high percentage of coasting in distance. This conclusion agreed with the authors' results. It was demonstrated that NO_x emission factors were almost zero when the product of velocity and acceleration was lower than -10 m^2/s^3, which produced a similar phenomenon for the value higher than 30 m^2/s^3 over aggressive driving, and 10 m^2/s^3 for gentle driving (Gallus et al., 2017). Van Mierlo et al. (Van Mierlo et al., 2004) also indicated that the economic driving could
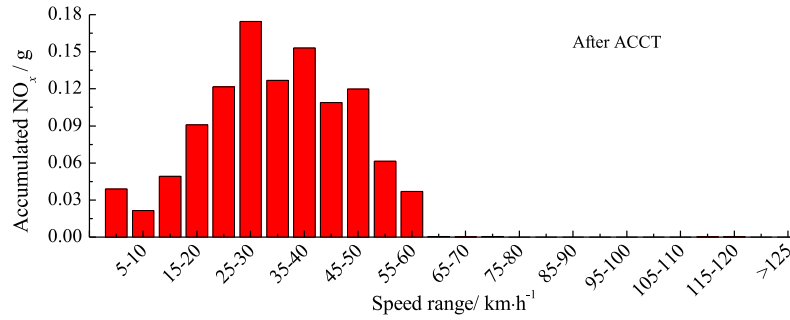
(a) Accumulated NO$_x$ emissions over various speed ranges
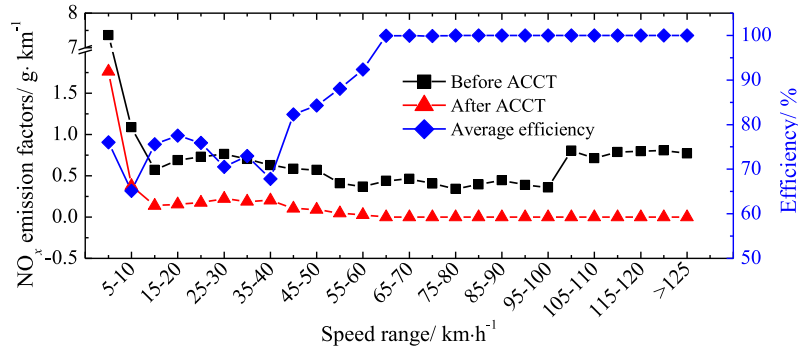
(b) Average NO$_x$ emission factors and ACCT efficiency over various speed ranges

Fig. 13. Accumulated NO$_x$ emissions, average NO$_x$ emission factors and ACCT efficiency over various speed ranges.
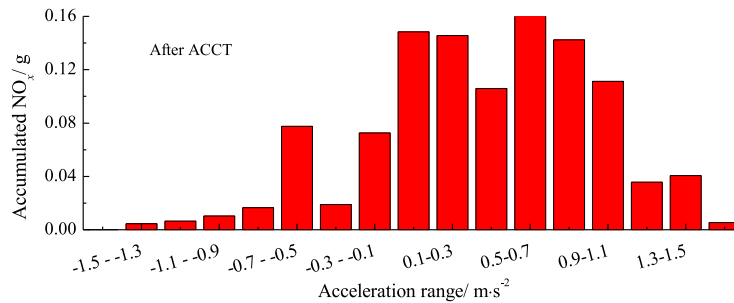
(a) Accumulated NO$_x$ emissions over various acceleration ranges
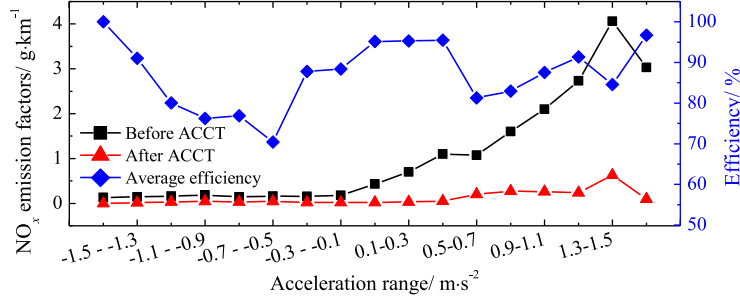
(b) Average NO$_x$ emission factors and ACCT efficiency over various acceleration ranges

Fig. 14. Accumulated NO$_x$ emissions, average NO$_x$ emission factors and ACCT efficiency over various acceleration ranges.

decrease both NO$_x$ emissions and particles emissions compared to sportive driving.

In fact, energy harvest could also be used as a key performance indicator to evaluate drivers' driving habits; proper driving behaviours conduced to recycle the energy from mechanical motions and vibrations, the approaches were indicated by (Zou et al., 2019). The relationship between the driving behaviours and exhaust emission was different from that of driving behaviours and energy consumption. The multi-objective optimizations would be conducted to achieve the optimal driving behaviours for eco-driving
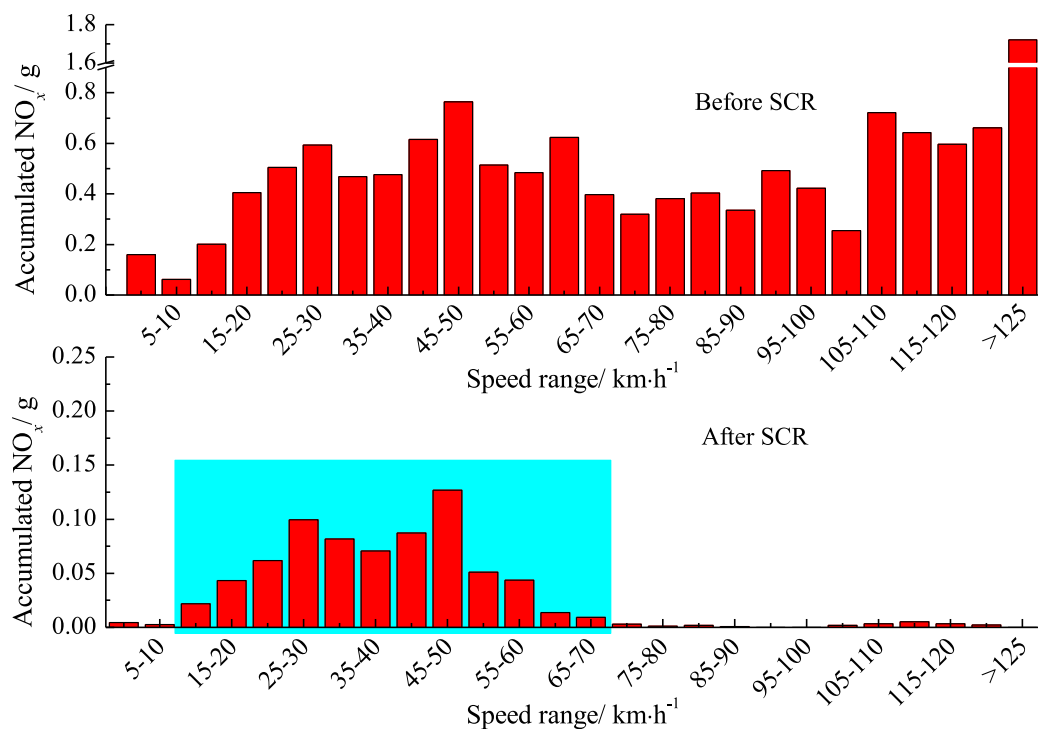
(a) Accumulated NO$_x$ emissions over various speed ranges
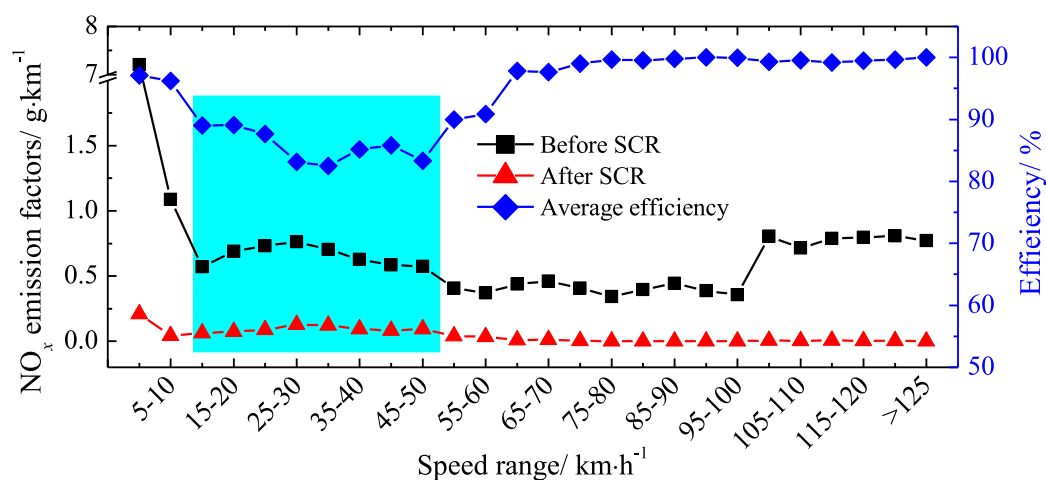
(b) Average NO$_x$ emission factors and SCR efficiency over various speed ranges

Fig. 15. Accumulated NO$_x$ emissions, average NO$_x$ emission factors and SCR efficiency over various speed ranges.

(a) Accumulated NO$_x$ emissions over various acceleration ranges

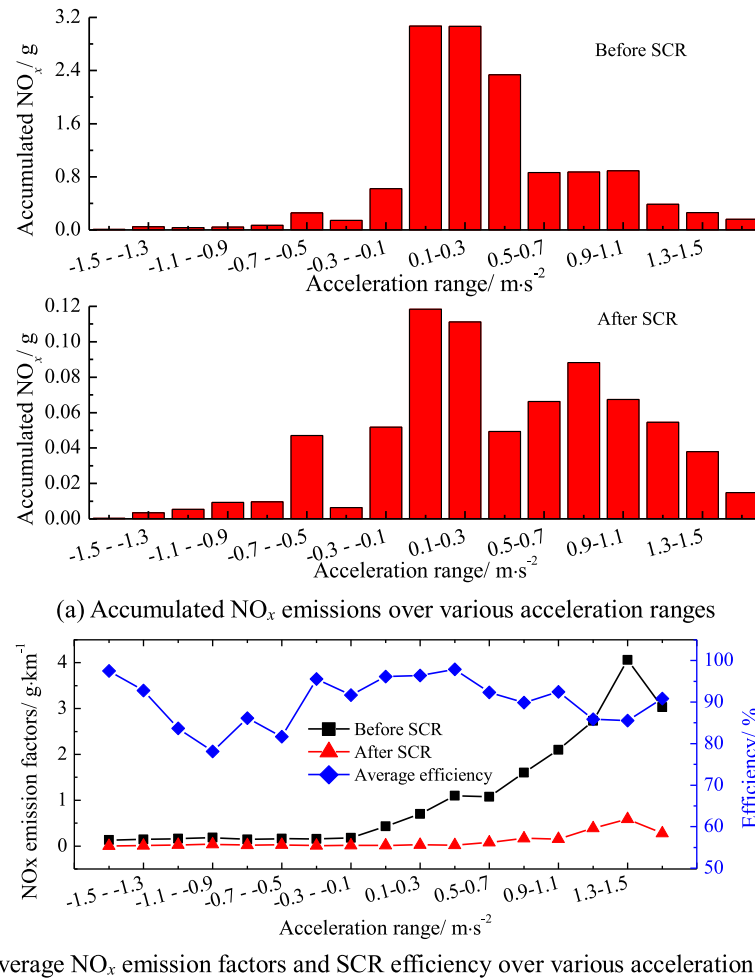(b) Average NO$_x$ emission factors and SCR efficiency over various acceleration ranges

Fig. 16. Accumulated NO$_x$ emissions, average NO$_x$ emission factors and SCR efficiency over various acceleration ranges.

considering emission factors and energy efficiency.

5. Conclusions

In this paper, fuel consumption and NO$_x$ emission characteristics over various scenarios were analyzed; the correlations between NO$_x$ emissions and driving behaviours under the scenarios of SCR and ACCT systems were explored using simulation methods. The main conclusions are as follows:

(1) Medium and extra-high vehicle speed contributed the highest proportions to the fuel consumption in WLTC. Fuel consumption rates over vehicle speed showed a "V" shape, with the highest fuel consumption rate being under low vehicle speed. Operations with low acceleration had the highest proportions of total fuel consumption, and the fuel consumption rates almost linearly increased with positive acceleration.

(2) The performance difference of ACCT and SCR systems was slightly affected by thermal status of the start period in driving cycle. In the cold start process, NO$_x$ reduction efficiency of ACCT system was much higher than SCR system due to low light-off temperature, accompanied by a shorter light-off duration.

(3) Regarding WLTC including cold start stages, the relationships between speed range, acceleration range and accumulated

NO$_x$ emissions showed similar patterns for ACCT scenarios and SCR scenarios; however, ACCT scenarios presented lower accumulated NO$_x$ emissions than SCR scenarios.

(4) As for WLTC excluding cold start stages, the relationships between vehicle speed range and accumulated NO$_x$ emissions for SCR scenarios differed significantly with those of ACCT scenarios whose accumulated emissions were almost zero within high speed range. NO$_x$ emissions only focused on high vehicle acceleration range for ACCT scenarios; however, it was low and high acceleration ranges for SCR scenarios.

ACCT system provided a new technique for further NO$_x$ reductions, which could promote low emission driving; however, only NO$_x$ emissions were included in this study. In the future research, more regulated and non-regulated emissions would be considered, especially particulate matter. The suggestion would be provided for drivers for eco-driving based on multi-objective optimization for cleaner travelling, considering fuel consumption, gaseous emissions, and particulate matter. Additionally, the drivers should be trained to achieve eco-driving from the long-term perspectives to verify the effectiveness of the driving patterns.

CRediT authorship contribution statement

Jianbing Gao: Formal analysis, Investigation, Methodology, Resources, Validation, Visualization, Writing - original draft, Writing -
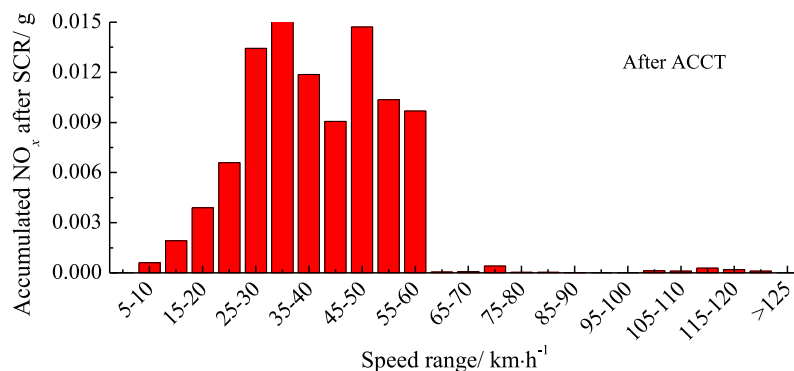
(a) Accumulated NO$_x$ emissions over various speed ranges
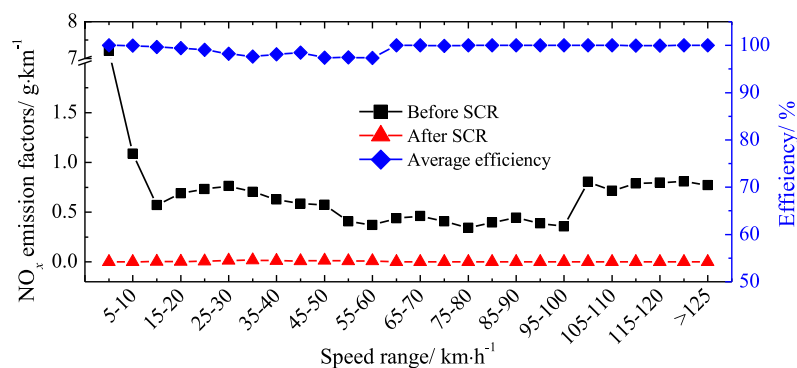
(b) Average NO$_x$ emission factors and ACCT efficiency over various speed ranges

Fig. 17. Accumulated NO$_x$ emissions, average NO$_x$ emission factors and ACCT efficiency over various speed ranges.
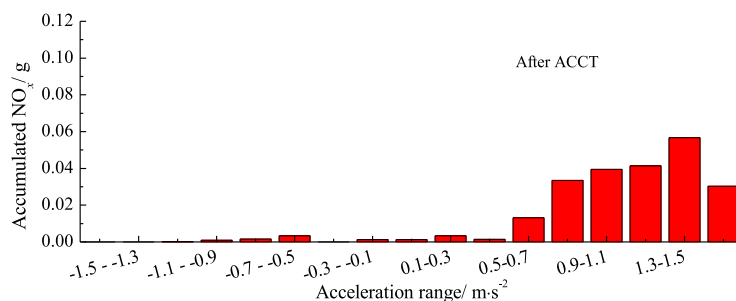
(a) Accumulated NO$_x$ emissions over various acceleration ranges
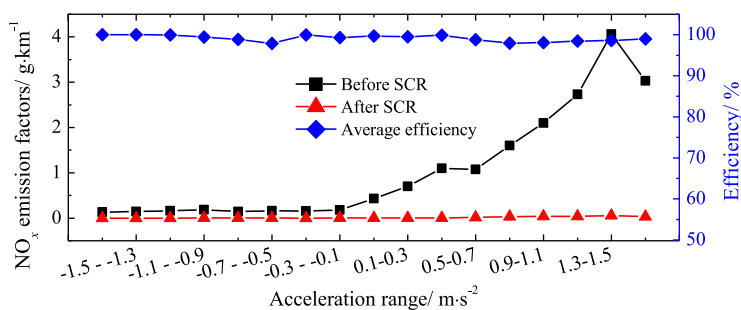
(b) Average NO$_x$ emission factors and ACCT efficiency over various acceleration ranges

Fig. 18. Accumulated NO$_x$ emissions, average NO$_x$ emission factors and ACCT efficiency over various acceleration ranges.

review & editing. **Haibo Chen:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Software, Supervision, Visualization, Writing - review & editing. **Ye Liu:** Investigation, Writing - review & editing. **Ying Li:** Visualization, Writing - review & editing. **Tiezhu Li:** Conceptualization, Data collections. **Ran Tu:** Writing - review & editing. **Biao Liang:** Writing - review & editing. **Chaochen Ma:** Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.125647.

References

Abdel-Rahman, A., 1998. On the emissions from internal-combustion engines: a review. IJER 22 (6), 483−513.

Ahn, K., Rakha, H., 2008. The effects of route choice decisions on vehicle energy consumption and emissions. Transport. Res. Transport Environ. 13 (3), 151−167.

Akcayol, M.A., Cinar, C., 2005. Artificial neural network based modeling of heated catalytic converter performance. Appl. Therm. Eng. 25 (14−15), 2341−2350.

Allison, C.K., Stanton, N.A., 2019. Eco-driving: the role of feedback in reducing emissions from everyday driving behaviours. Theor. Issues Ergon. Sci. 20 (2), 85−104.

Burch, S.D., Potter, T.F., Keyser, M.A., Brady, M.J., Michaels, K.F., 1995. Reducing cold-start emissions by catalytic converter thermal management. SAE Trans. 348−353.

Carrese, S., Gemma, A., La Spada, S., 2013. Impacts of driving behaviours, slope and vehicle load factor on bus fuel consumption and emissions: a real case study in the city of Rome. Procedia-Social Behavioral Sciences 87, 211-221.

Daya, R., Singh, M.R., Hoard, J., Chanda, S., 2016. In: Insulated Catalyst with Heat Storage for Real World Vehicle Emissions Reduction, ASME 2016 Internal Combustion Engine Division Fall Technical Conference. American Society of Mechanical Engineers. V001T004A006-V001T004A006.

Gallus, J., Kirchner, U., Vogt, R., Benter, T., 2017. Impact of driving style and road grade on gaseous exhaust emissions of passenger vehicles measured by a Portable Emission Measurement System (PEMS). Transport. Res. Transport Environ. 52, 215−226.

Gao, J., Chen, H., Dave, K., Chen, J., Li, Y., Li, T., Liang, B., 2020. Analysis of driving behaviours of truck drivers using motorway tests. Proc. Inst. Mech. Eng. - Part D J. Automob. Eng., 0954407020925568

Gao, J., Chen, H., Li, Y., Chen, J., Zhang, Y., Dave, K., Huang, Y., 2019a. In: Fuel Consumption and Exhaust Emissions of Diesel Vehicles in Worldwide Harmonized Light Vehicles Test Cycles and Their Sensitivities to Eco-Driving Factors, vol. 196. Energy Conversion & Management, pp. 605−613.

Gao, J., Ma, C., Tian, G., Chen, J., Xing, S., Huang, L., 2018. Oxidation Activity Restoration of Diesel Particulate Matter by Aging in Air. Energy Fuels 32 (2), 2450−2457.

Gao, J., Tian, G., Sorniotti, A., 2019b. In: On the Emission Reduction through the Application of an Electrically Heated Catalyst to a Diesel Vehicle. Energy Science & Engineering.

Gao, J., Tian, G., Sorniotti, A., Karci, A.E., Di Palo, R., 2019c. Review of thermal management of catalytic converters to decrease engine emissions during cold start and warm up. Appl. Therm. Eng. 147, 177−187.

Gao, Y., Checkel, M.D., 2007. In: Emission Factors Analysis for Multiple Vehicles Using an On-Board, In-Use Emissions Measurement System. SAE Technical Paper.

Gao, J., Xing, S., Tian, G., Ma, C., Zhao, M., Jenner, P., 2021. Numerical simulation on the combustion and NO$_x$ emission characteristics of a turbocharged opposed rotary piston engine fuelled with hydrogen under wide open throttle conditions. Fuel 285, 119210.

García-Contreras, R., Soriano, J.A., Fernández-Yáñez, P., Sánchez-Rodríguez, L., Mata, C., Gómez, A., Armas, O., Cárdenas, M.D., 2020. Impact of regulated pollutant emissions of Euro 6d-Temp light-duty diesel vehicles under real driving conditions. J. Clean. Prod. 124927.

Giakoumis, E.G., Zachiotis, A.T., 2017. Investigation of a diesel-engined vehicle's performance and emissions during the WLTC driving cycle—comparison with the NEDC. Energies 10 (2), 240.

Gong, C., Huang, K., Deng, B., Liu, X., 2011. Catalyst light-off behavior of a spark-ignition LPG (liquefied petroleum gas) engine during cold start. Energy 36 (1), 53−59.

Government, U., 2020. In: Affairs, D.f.E.F.R. (Ed.), Air Quality Appraisal: Damage Cost Guidance.

Gumus, M., Ugurlu, A., 2011. Application of phase change materials to pre-heating of evaporator and pressure regulator of a gaseous sequential injection system. ApEn 88 (12), 4803−4810.

Hernández, J.J., Rodríguez-Fernández, J., Calle-Asensio, A., 2020. Performance and regulated gaseous emissions of a Euro 6 diesel vehicle with Lean NOx Trap at different ambient conditions: sensitivity to the type of fuel. Energy Convers. Manag. 219, 113023.

Hiraoka, T., Terakado, Y., Matsumoto, S., Yamabe, S., 2009. Quantitative evaluation of eco-driving on fuel consumption based on driving simulator experiments. In: Proceedings of the 16th World Congress on Intelligent Transport Systems, pp. 21−25.

Hu, J., Wu, Y., Wang, Z., Li, Z., Zhou, Y., Wang, H., Bao, X., Hao, J., 2012. Real-world fuel efficiency and exhaust emissions of light-duty diesel vehicles and their correlation with road conditions. JEnvS 24 (5), 865−874.

Ito, Y., Shimoda, T., Aoki, T., Yuuki, K., Sakamoto, H., Kato, K., Thier, D., Kattouah, P., Ohara, E., Vogt, C., 2015. In: Next Generation of Ceramic Wall Flow Gasoline Particulate Filter with Integrated Three Way Catalyst. SAE Technical Paper.

Jensen, T.K., de Wit, J., Andersen, S.D., Frederiksen, H., Nielsen, M., 2008. The Influence of Engine Start and Stop on Total Emission from Natural Gas Fired CHP Engines.

Johannessen, T., Schmidt, H., Svagin, J., Johansen, J., Oechsle, J., Bradley, R., 2008. In: Ammonia Storage and Delivery Systems for Automotive NOx Aftertreatment. SAE Technical Paper.

Kirwan, J.E., Quader, A.A., Grieve, M.J., 2002. In: Fast Start-Up On-Board Gasoline Reformer for Near Zero Emissions in Spark-Ignition Engines. SAE Technical Paper.

Kozina, A., Radica, G., Nižetić, S., 2020. Analysis of methods towards reduction of harmful pollutants from Diesel engines. J. Clean. Prod., 121105

Lee, T., Son, J., 2011. In: Relationships between Driving Style and Fuel Consumption in Highway Driving. SAE Technical Paper.

Li, T., Liu, Z.-C., Zhang, H.-C., Jiang, Q.-H., 2013. Environmental emissions and energy consumptions assessment of a diesel engine from the life cycle perspective. J. Clean. Prod. 53, 7−12.

Luo, X., Dong, L., Dou, Y., Zhang, N., Ren, J., Li, Y., Sun, L., Yao, S., 2017. Analysis on spatial-temporal features of taxis' emissions from big data informed travel patterns: a case of Shanghai, China. J. Clean. Prod. 142, 926−935.

Meseguer, J.E., Calafate, C.T., Cano, J.C., Manzoni, P., 2015. Assessing the Impact of Driving Behavior on Instantaneous Fuel Consumption, 2015 12th Annual IEEE Consumer Communications and Networking Conference (CCNC). IEEE, pp. 443−448.

Nanaki, E.A., Koroneos, C.J., 2013. Comparative economic and environmental analysis of conventional, hybrid and electric vehicles−the case study of Greece. J. Clean. Prod. 53, 261−266.

Oglieve, C.J., Mohammadpour, M., Rahnejat, H., 2017. Optimisation of the vehicle transmission and the gear-shifting strategy for the minimum fuel consumption and the minimum nitrogen oxide emissions. Proc. Inst. Mech. Eng. - Part D J. Automob. Eng. 231 (7), 883−899.

Okui, N., 2018. Effects of the Differences in Driving Behavior on Fuel Economy and Emission Characteristics during Vehicle Simulator Execution. SAE Technical Paper.

Pace, L., Presti, M., 2011. An Alternative Way to Reduce Fuel Consumption during Cold Start: the Electrically Heated Catalyst. SAE Technical Paper.

Pathak, S.K., Sood, V., Singh, Y., Channiwala, S., 2016. Real world vehicle emissions: their correlation with driving parameters. Transport. Res. Transport Environ. 44, 157−176.

Rodríguez, R.A., Virguez, E.A., Rodríguez, P.A., Behrentz, E., 2016. Influence of driving patterns on vehicle emissions: a case study for Latin American cities. Transport. Res. Transport Environ. 43, 192−206.

Schmeisser, V., Weibel, M., Hernando, L.S., Nova, I., Tronconi, E., Ruggeri, M.P., 2013. Cold start effect phenomena over zeolite scr catalysts for exhaust gas aftertreatment. SAE International Journal of Commercial Vehicles 6 (2013−01-1064), 190−199.

Sileghem, L., Bosteels, D., May, J., Favre, C., Verhelst, S., 2014. Analysis of vehicle emission measurements on the new WLTC, the NEDC and the CADC. Transport. Res. Transport Environ. 32, 70−85.

Smit, R., Keramydas, C., Ntziachristos, L., Lo, T.-s., Ng, K.-l., Wong, H.-l.A., Wong, C.K.-l., 2019. Evaluation of real-world gaseous emissions performance of selective catalytic reduction and diesel particulate filter bus retrofits. Environ. Sci. Technol. 53 (8), 4440−4449.

Tang, P., Yu, L., Song, G., 2014. Effect of Driving Behaviors on Emissions in Eco-Driving at Intersections.

Tang, T.-Q., Huang, H.-J., Shang, H.-Y., 2015. Influences of the driver's bounded rationality on micro driving behavior, fuel consumption and emissions. Transport. Res. Transport Environ. 41, 423−432.

Tutuianu, M., Bonnel, P., Ciuffo, B., Haniu, T., Ichikawa, N., Marotta, A., Pavlovic, J.,

Steven, H.J.T.r.p.D.t., 2015. Development of the World-wide harmonized Light duty Test Cycle (WLTC) and a possible pathway for its introduction in the European legislation. Transport. Res. Transport Environ. 40, 61–75.

Uusitalo, A., Uusitalo, V., Grönman, A., Luoranen, M., Jaatinen-Värri, A., 2016. Greenhouse gas reduction potential by producing electricity from biogas engine waste heat using organic Rankine cycle. J. Clean. Prod. 127, 399–405.

Van Mierlo, J., Maggetto, G., Van de Burgwal, E., Gense, R., 2004. Driving style and traffic measures-influence on vehicle emissions and fuel consumption. Proc. Inst. Mech. Eng. - Part D J. Automob. Eng. 218 (1), 43–50.

Varella, R.A., Faria, M.V., Mendoza-Villafuerte, P., Baptista, P.C., Sousa, L., Duarte, G.O., 2019. Assessing the influence of boundary conditions, driving behavior and data analysis methods on real driving CO2 and NOx emissions. ScTEn 658, 879–894.

Vijayan, A., Kumar, A., Abraham, M., 2008. Experimental analysis of vehicle operation parameters affecting emission behavior of public transport buses with alternative diesel fuels. Transport. Res. Rec. 2058 (1), 68–78.

Walnum, H.J., Simonsen, M., 2015. Does driving behavior matter? An analysis of fuel consumption data from heavy-duty trucks. Transport. Res. Transport Environ. 36, 107–120.

Wei, H., 2019. Impacts of China's national vehicle fuel standards and subway development on air pollution. J. Clean. Prod. 241, 118399.

Wilson, J.G., Hargrave, G., 2018. Analysis of a Novel Method for Low-Temperature Ammonia Production Using DEF for Mobile Selective Catalytic Reduction Systems. SAE Technical Paper.

Zervas, E., Bikas, G., 2008. Impact of the driving cycle on the NOx and particulate matter exhaust emissions of diesel passenger cars. Energy Fuels 22 (3), 1707–1713.

Zhang, H., Wang, S., Hao, J., Wang, X., Wang, S., Chai, F., Li, M., 2016. Air pollution and control action in Beijing. J. Clean. Prod. 112, 1519–1527.

Zhang, J.-H., Chen, M., 2015. Assessing the impact of China's vehicle emission standards on diesel engine remanufacturing. J. Clean. Prod. 107, 177–184.

Zou, H.-X., Zhao, L.-C., Gao, Q.-H., Zuo, L., Liu, F.-R., Tan, T., Wei, K.-X., Zhang, W.-M., 2019. Mechanical modulations for enhancing energy harvesting: principles, methods and applications. ApEn 255, 113871.