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# 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

Corresponding author:

Haibo Chen, H.Chen@leeds.ac.uk

Institute for Transport Studies, University of Leeds, Leeds LS2 9JT, UK

Jianbing Gao, redonggaojianbing@163.com

Institute for Transport Studies, University of Leeds, Leeds LS2 9JT, UK

**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 traveling. 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.

**Keywords**: driving behaviors; $NO_x$ emission factors; after-treatment techniques; cold start; vehicle speed; vehicle acceleration

## 1. Introduction

As concerns regarding environmental pollutants are increasing, emission regulations of on-road vehicles are becoming stricter (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 pollutions 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. (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 minutes 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.

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

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. (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. (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. (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 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.

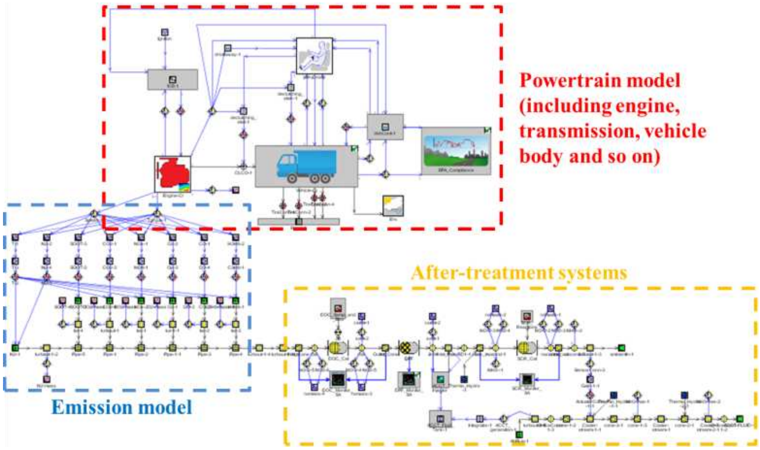
### 2.1 Simulation model description

#### 2.1.1. Descriptions of vehicle model

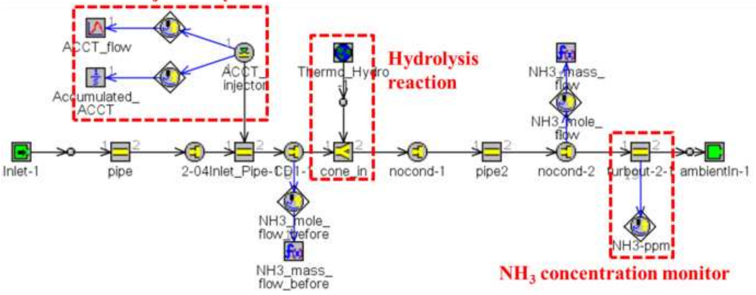
Specifications of the diesel passenger car which was used in this investigation are shown in Table 2. This type of passenger cars is on the market and is under an emission level of Euro 6. In order to meet stricter emission regulations (such as Euro 7 and real driving emissions), more effective after-treatment 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 Figure 1(a), more details are provided in Figure 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 (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 $NO_x$.

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 |




(a) Model of the diesel passenger car




(b) Model of ACCT fluid hydrolysis reactions

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

### 2.1.2. Descriptions of after-treatment systems

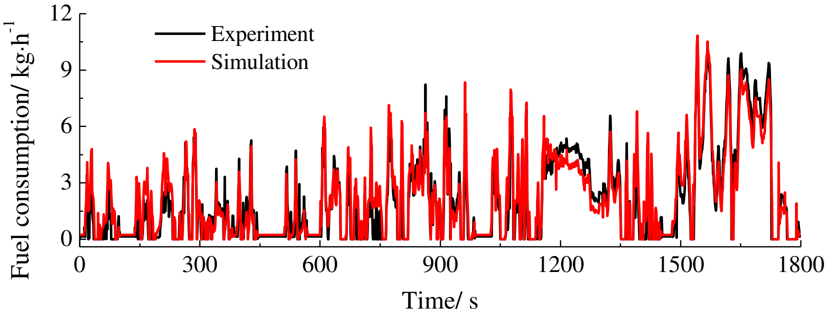
The SCR system was an original $NO_x$ reduction after-treatment system of this passenger car, which usually took a long period for the catalyst to light-off from engine cold start. The eHC device in the authors' previous work (Gao et al., 2019b) was used to heat the exhaust before DOC when the exhaust 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 Figure 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

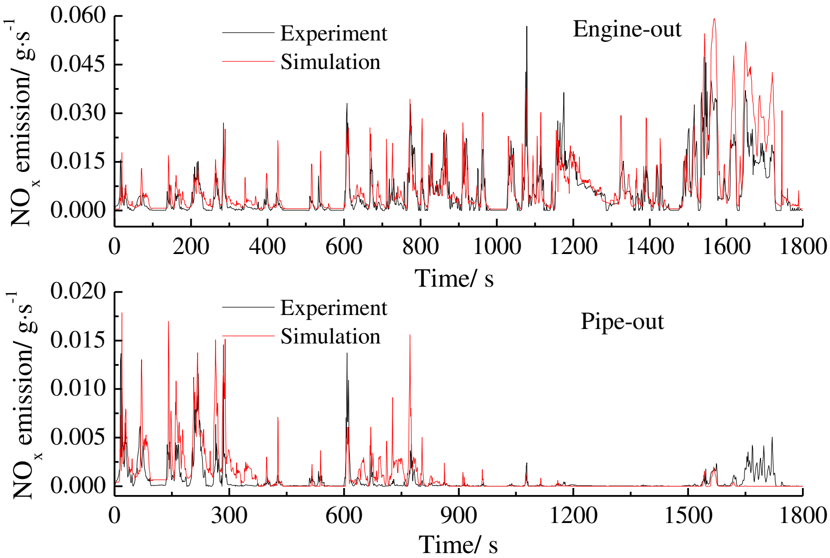
In this section, validations of simulation models including the powertrain system, standard $NO_x$ reduction system (SCR), and ACCT system were conducted.

#### 2.2.1 Validations of vehicle model

WLTC represents average driving characteristics around the world (Tutuianu et al., 2015), so it was selected in this paper (Tutuianu et al., 2015). 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 Figure 2(a). As can be seen, fuel consumption rates from simulation matched well with experimental results. Figure 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 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.




(a) Validation of fuel consumption and $NO_x$ emissions




(b) Validations of $NO_x$ emissions with SCR system

Figure 2 Validation of the vehicle fuel consumption and $NO_x$ emissions

### 2.2.2 Validations of ACCT system

Test conditions in the research by Wilson and Hargrave (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 ºC, 150 ºC, 200 ºC, 300 ºC, and 400 ºC; 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 Figure 1(b) were the same as the ones in Wilson and Hargrave's experiment (Wilson and Hargrave, 2018). Wilson and Hargrave (Wilson and Hargrave, 2018) indicated that $NH_3$ concentration was 410 ppm over the hot air temperature of 100 ºC 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.

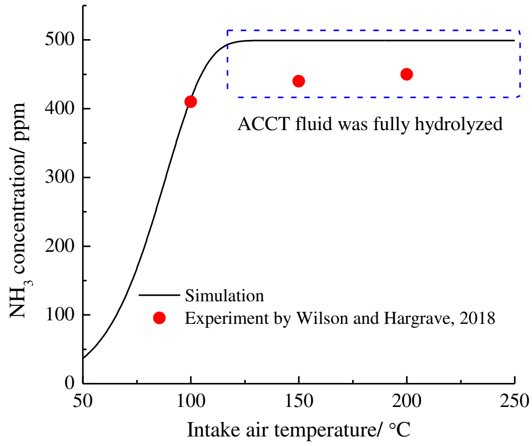



Figure 3 Validations of ACCT fluid hydrolysis reactions

## 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 behaviours.

### 3.1. Driving behaviour analysis over WLTC

Speed distributions by travel durations and distance are shown in Figure 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 Figure 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.

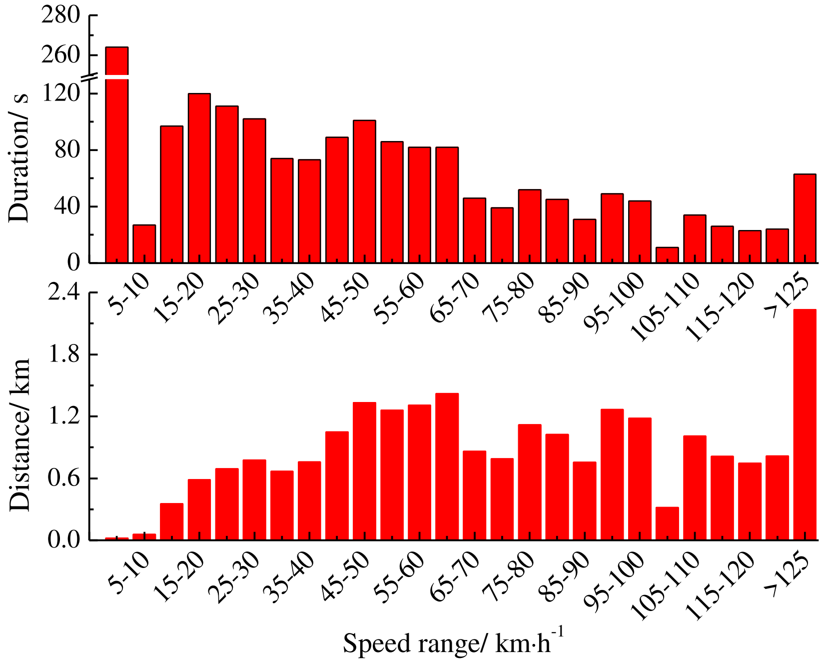



Figure 4 Speed distributions by travel durations and distance

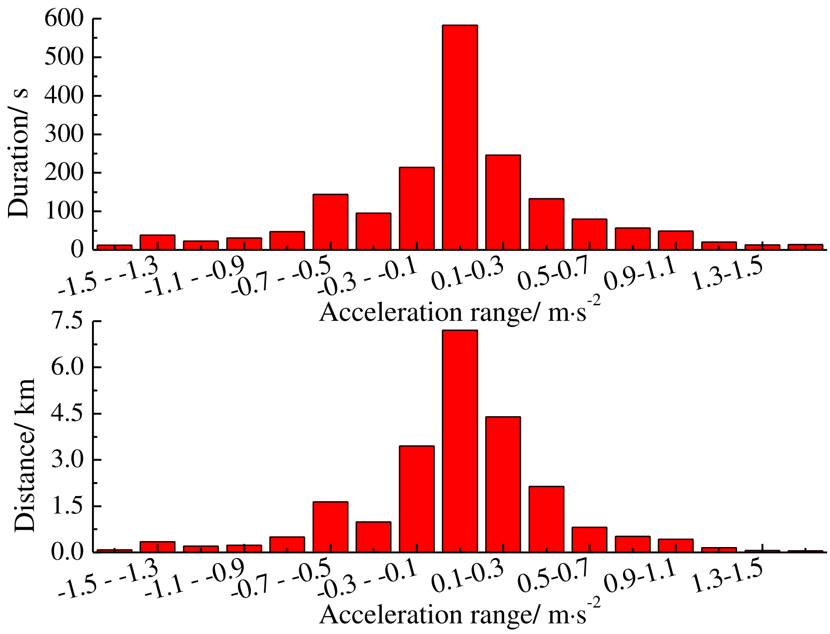
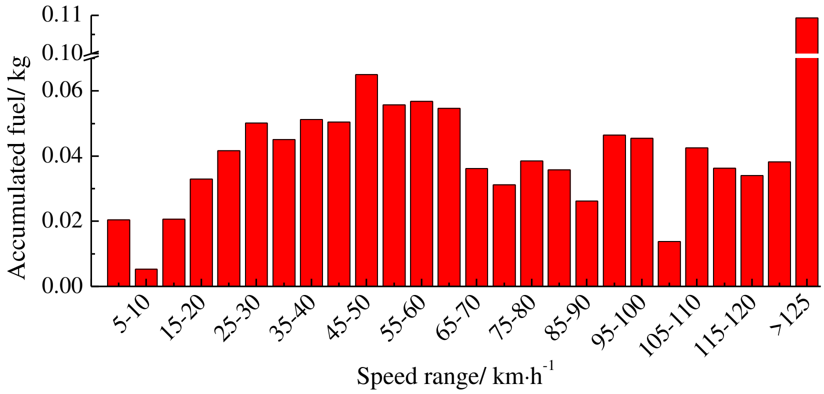


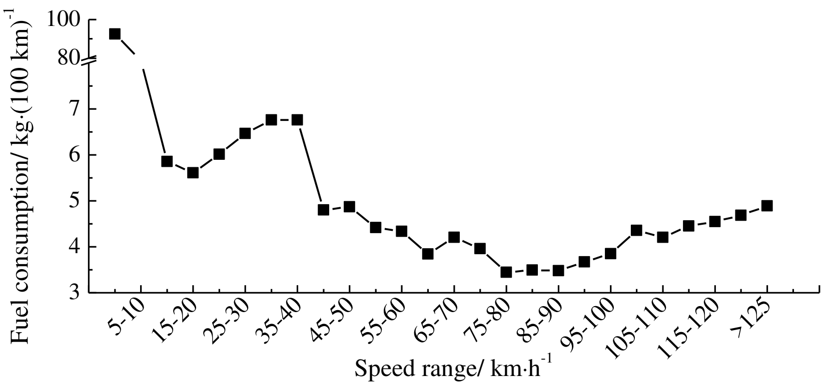

Figure 5 Acceleration distributions by travel durations and distance

### 3.2. Relationship between driving behaviours and fuel consumption

Accumulated fuel consumption over various vehicle speed ranges is shown in Figure 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 Figure 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.



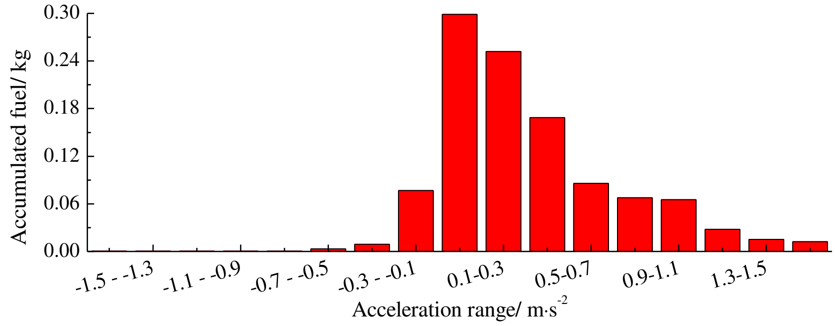

(a) Distributions of fuel consumption over various speed ranges



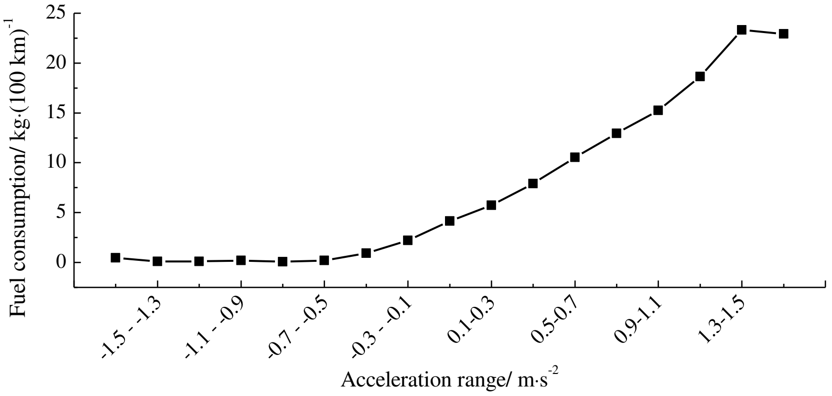

(b) Average fuel consumption rates over various speed ranges

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

Accumulated fuel consumption over various acceleration ranges was completely different from acceleration distributions by durations and distance, as shown in Figure 7(a). The accumulated fuel consumption was almost zero when vehicle acceleration was lower 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$^2$~ 1.5 m/s$^2$. Figure 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.




(a) Distributions of fuel consumption over various acceleration ranges




(b) Average fuel consumption rates over various acceleration ranges

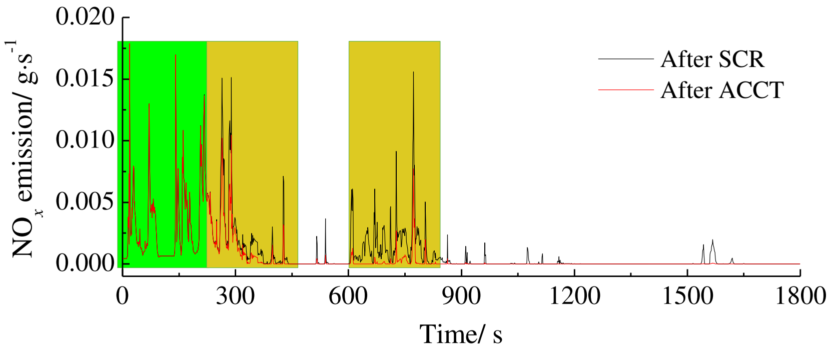
Figure 7 Fuel consumption distributions and average fuel consumption over various acceleration ranges

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

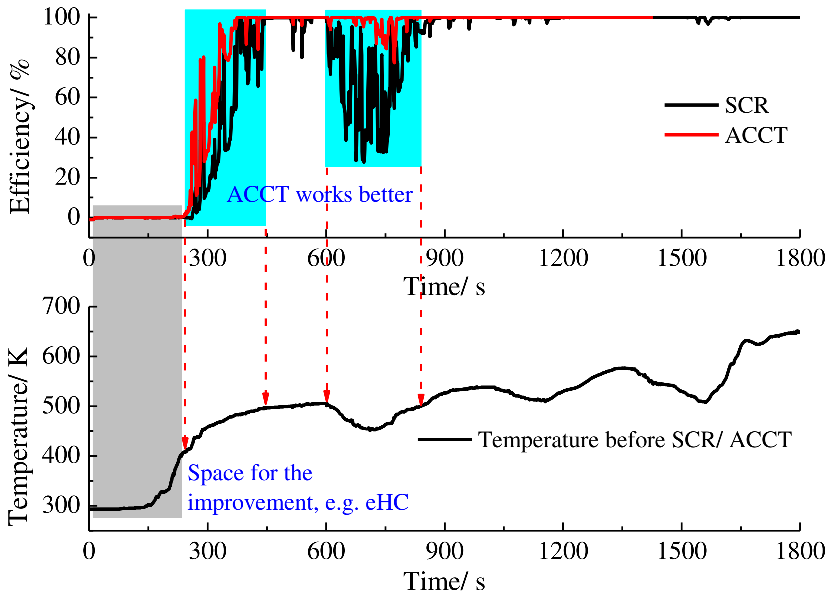
#### 3.3.1. Scenarios including cold start stages

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; Gao et al., 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. Figure 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 Figure 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. Figure 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.




(a) $NO_x$ emissions after SCR/ ACCT over WLTC




(b) Efficiency of SCR/ ACCT systems and exhaust temperature before SCR/ ACCT

Figure 8 $NO_x$ emissions, efficiency of SCR/ ACCT systems and exhaust temperature before SCR/ ACCT

### 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 Figure 9. The first short cycle (dark line) was excluded when analyzing $NO_x$ emission characteristics. Figure 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 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 Figure 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.

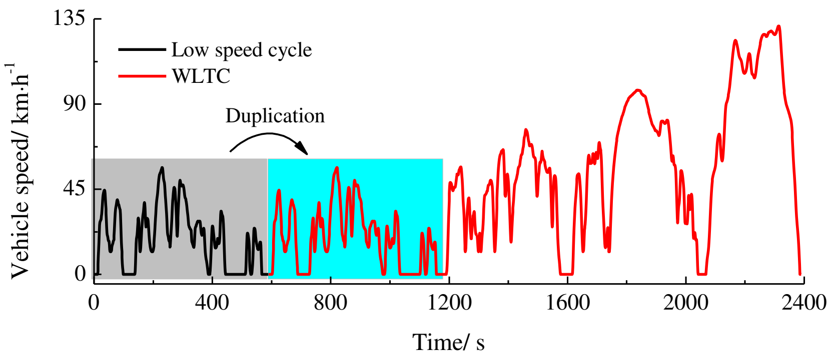
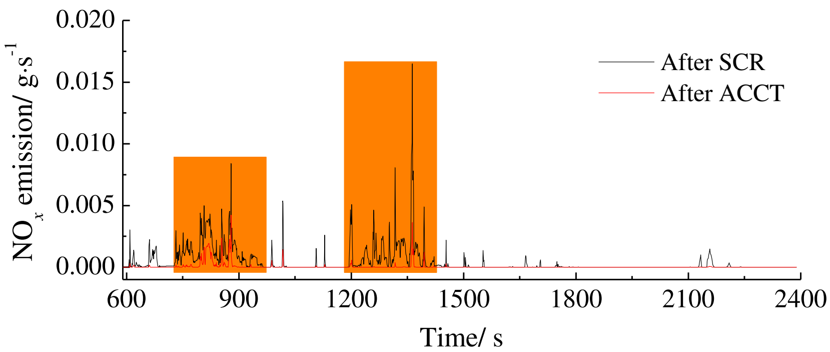
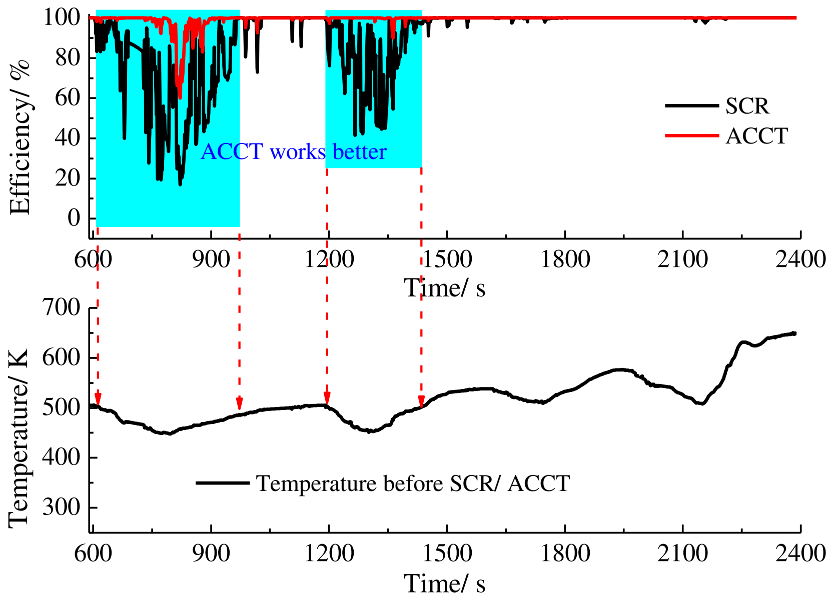



Figure 9 New driving cycles to exclude the cold start effect




(a) $NO_x$ emissions after SCR/ACCT systems over WLTC




(b) SCR and ACCT efficiency and exhaust temperature before SCR/ACCT

Figure 10 $NO_x$ emissions after SCR/ACCT systems, $NO_x$ reductions efficiency, and temperature before SCR/ACCT over WLTC

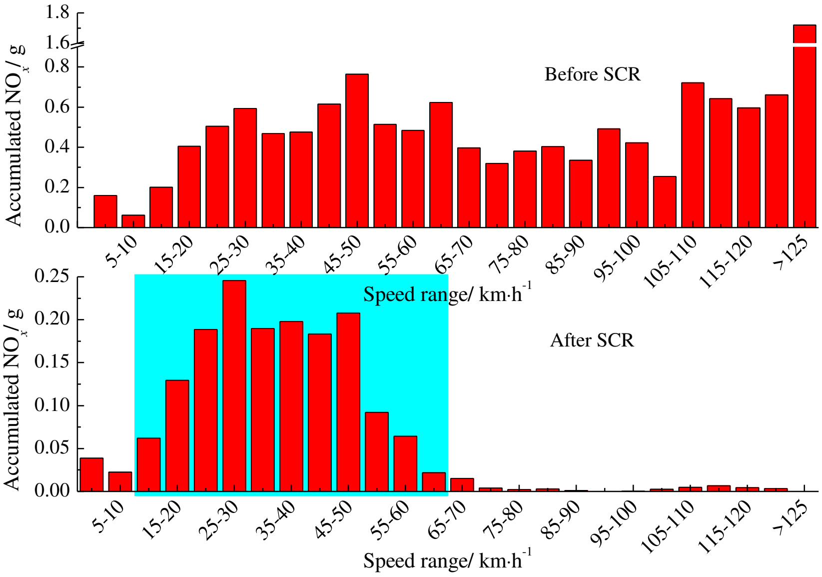
### 3.4. Relationships between driving behaviors and $NO_x$ emissions

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.

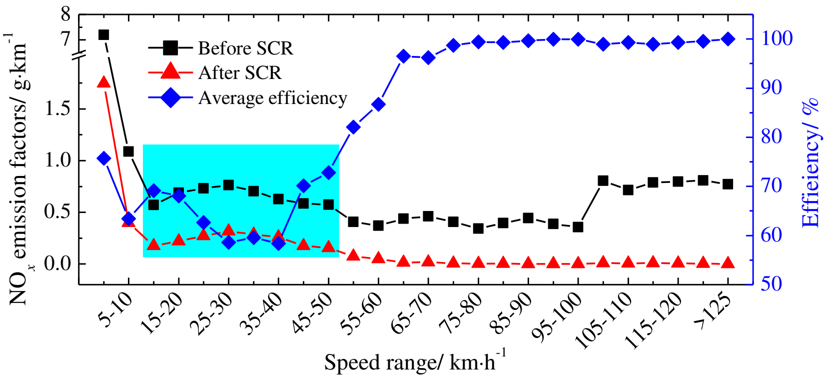
#### 3.4.1. Scenarios including cold start stages

##### 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 Figure 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 Figure 11(b)) and long accumulated travel distance (see Figure 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.




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

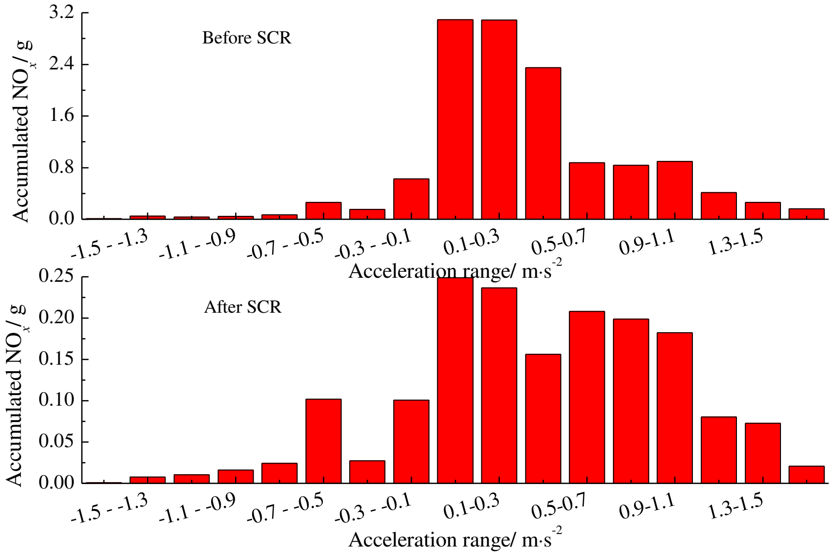



(b) Average NO$_x$ emission factors and SCR efficiency over various speed ranges

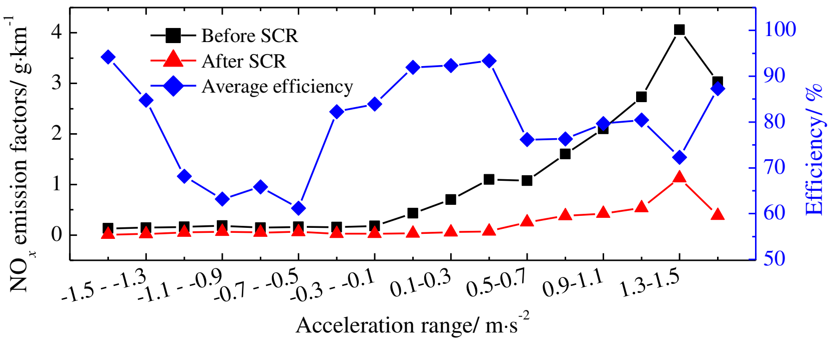
Figure 11 Accumulated NO$_x$ emissions, average NO$_x$ emission factors, and SCR efficiency over various speed ranges

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 Figure 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 Figure 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 Figure 12(b)). It presented the lowest average catalyst efficiency for the acceleration range of -1.1 m/s$^2$~ -0.5 m/s$^2$.




(a) Accumulated $NO_x$ emissions over various acceleration ranges



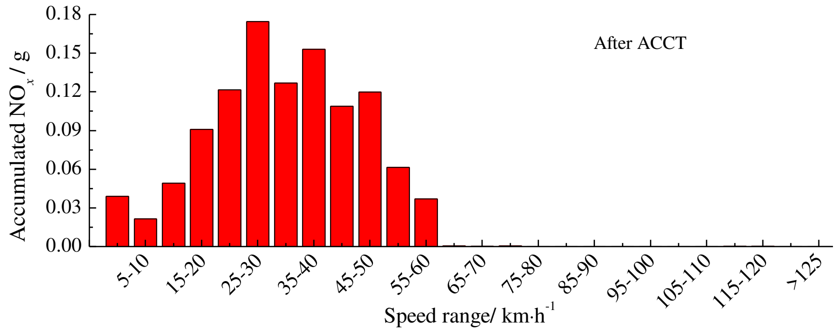

(b) Average $NO_x$ emission factors and SCR efficiency over various acceleration ranges

Figure 12 Accumulated $NO_x$ emissions, average $NO_x$ emission factors and SCR efficiency over various acceleration ranges

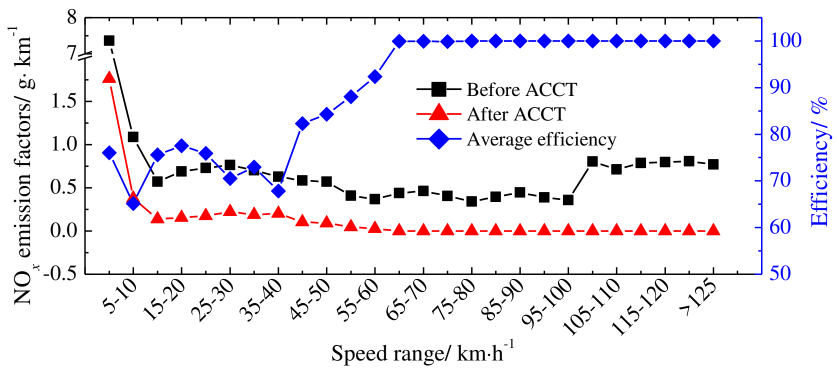
#### 3.4.1.2. Vehicle equipped with ACCT system

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 Figure 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 Figure 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.



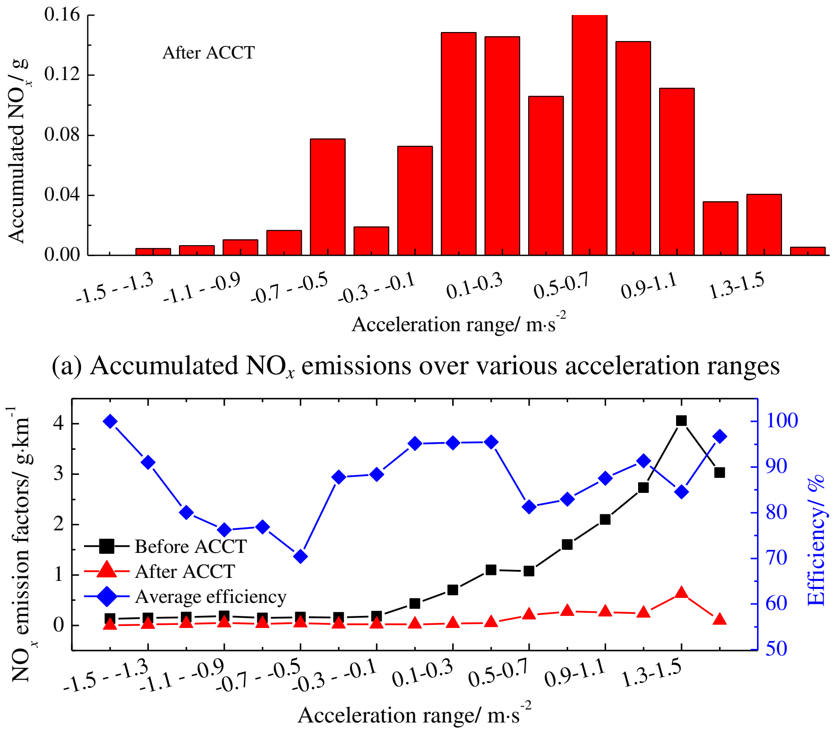

(a) Accumulated $NO_x$ emissions over various speed ranges




(b) Average $NO_x$ emission factors and ACCT efficiency over various speed ranges

Figure 13 Accumulated $NO_x$ emissions, average $NO_x$ emission factors and ACCT efficiency over various speed ranges

Figure 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. Figure 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.




(a) Accumulated $NO_x$ emissions over various acceleration ranges



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

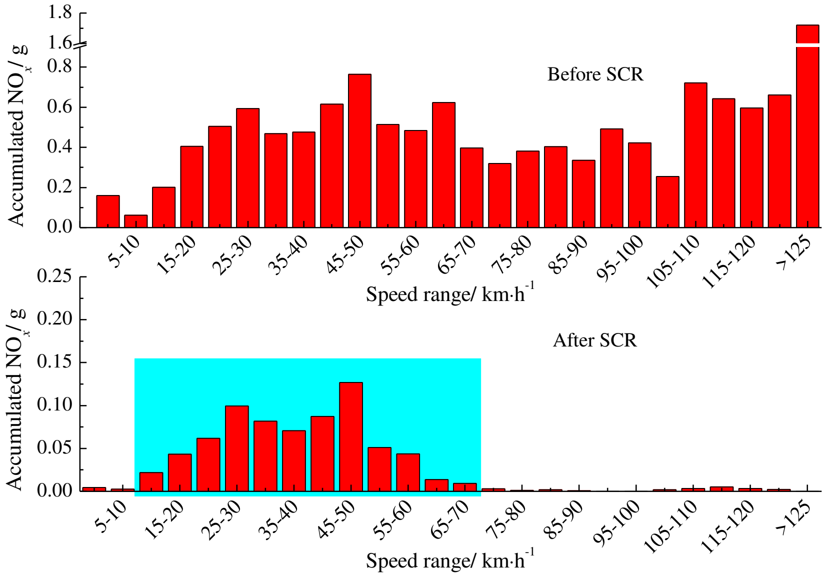
Figure 14 Accumulated $NO_x$ emissions, average $NO_x$ emission factors and ACCT efficiency over various acceleration ranges

### 3.4.2. Scenarios excluding cold start stages

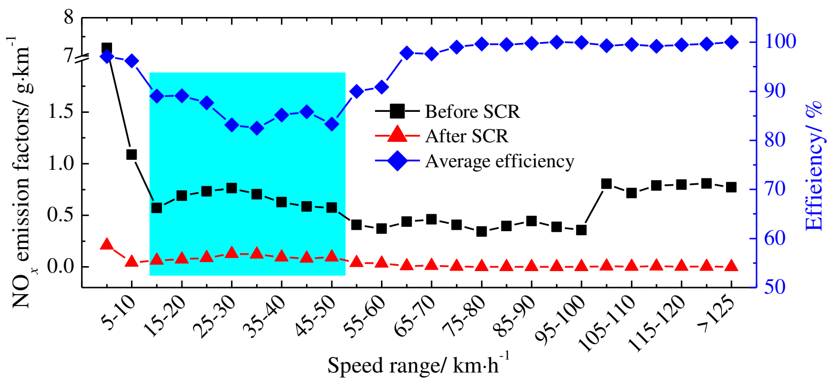
Cold start stages had a significant effect on $NO_x$ emissions which affected the analysis of the correlations between driving behaviours and $NO_x$ emissions. In this section, cold start stages were excluded using the method shown in Figure 9.

#### 3.4.2.1. Vehicle equipped with SCR system

Accumulated $NO_x$ emissions over various speed ranges under warm start conditions are shown in Figure 15(a). Maximum accumulated $NO_x$ emissions after 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 Figure 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.



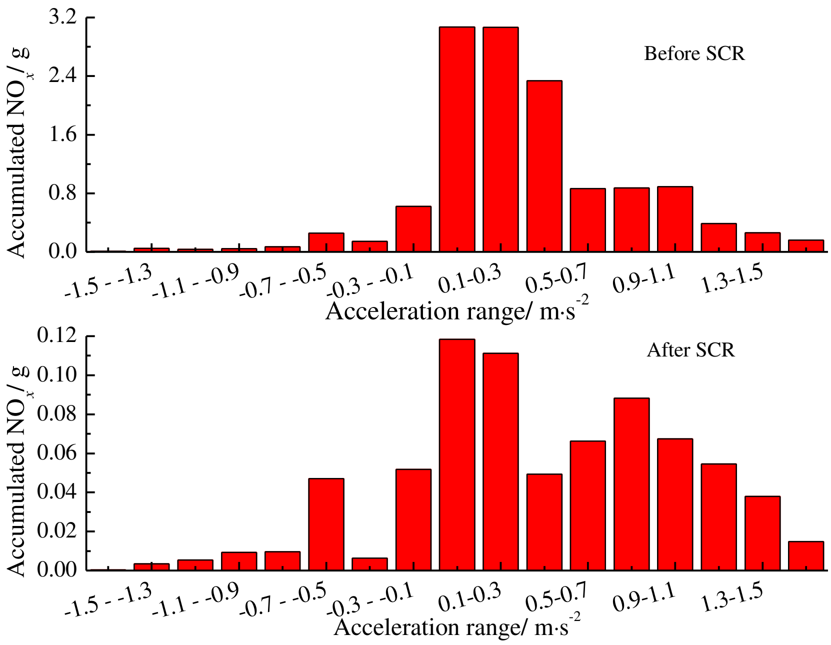

(a) Accumulated $NO_x$ emissions over various speed ranges



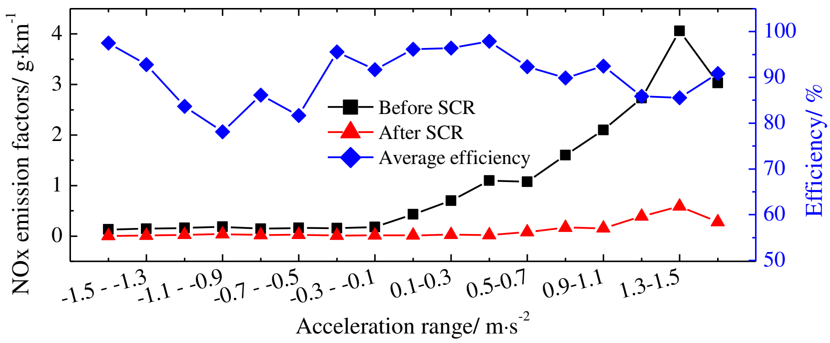

(b) Average $NO_x$ emission factors and SCR efficiency over various speed ranges

Figure 15 Accumulated $NO_x$ emissions, average $NO_x$ emission factors and SCR efficiency over various speed ranges

Accumulated $NO_x$ emissions over various acceleration ranges under warm start conditions are shown in Figure 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 (Figure 16(b)).




(a) Accumulated $NO_x$ emissions over various acceleration ranges

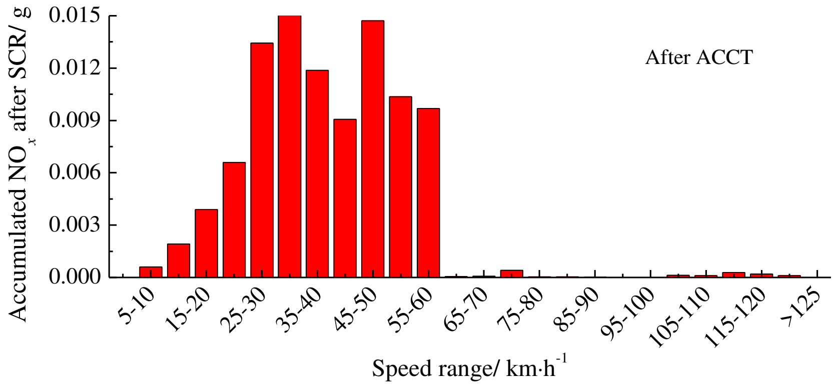



(b) Average $NO_x$ emission factors and SCR efficiency over various acceleration ranges

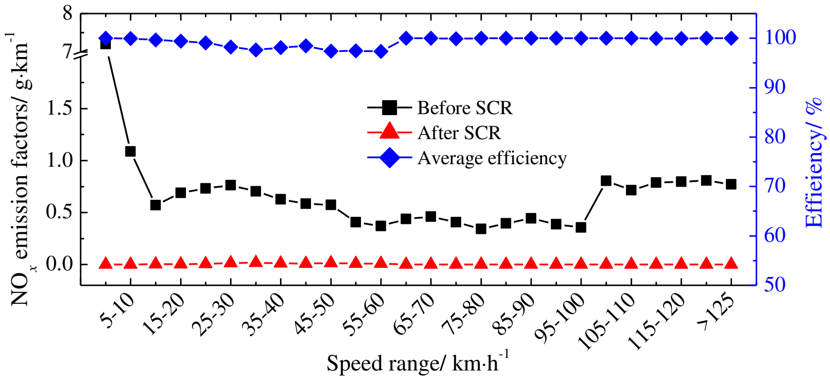
Figure 16 Accumulated $NO_x$ emissions, average $NO_x$ emission factors and SCR efficiency over various acceleration ranges

#### 3.4.2.2. Vehicle equipped with ACCT system

Accumulated $NO_x$ emissions over various speed ranges are shown in Figure 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. Figure 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.



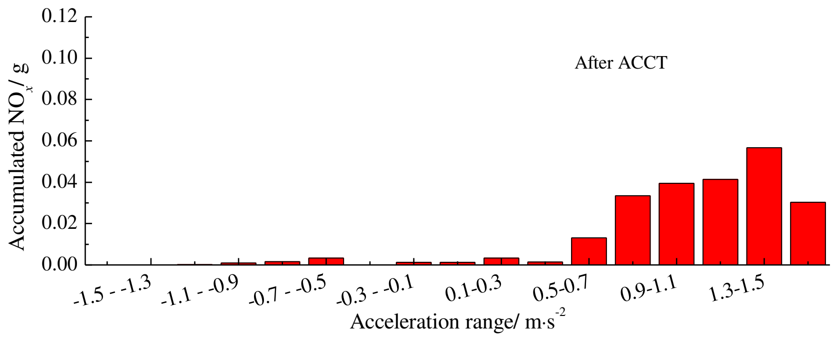

(a) Accumulated $NO_x$ emissions over various speed ranges



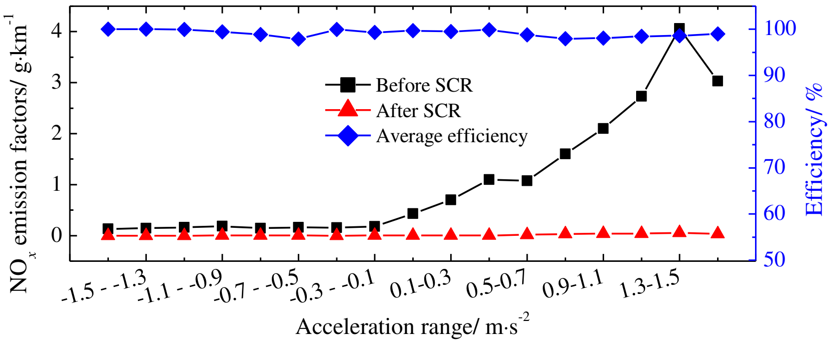

(b) Average $NO_x$ emission factors and ACCT efficiency over various speed ranges

Figure 17 Accumulated $NO_x$ emissions, average $NO_x$ emission factors and ACCT efficiency over various speed ranges

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 Figure 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 0.7 m/s$^2$ despite that the accumulation of $NO_x$ emissions at high acceleration dropped significantly. Figure 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.




(a) Accumulated $NO_x$ emissions over various acceleration ranges




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

Figure 18 Accumulated $NO_x$ emissions, average $NO_x$ emission factors and ACCT efficiency over various acceleration ranges

## 4. Discussion

Pathak et al. (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. (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 steering. Meseguer et al. (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. (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. (Varella et al., 2019). Sileghem et al. (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 (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. (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 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 pproaches 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 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.

## 6. CRediT authorship contribution statement

Jianbing Gao: Formal analysis, Investigation, Methodology, Resources, Validation, Visualization, Writing - original draft, Writing - 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. Biao Liang: Writing - review & editing; Ran Tu- review & editing; Chaochen, Ma- review & editing

## 7. Acknowledgement

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