Research on a China 6b Heavy-duty Diesel Vehicle Real-world Engine out NOx Emission Deterioration and NOx Correction for Humidity and Temperature using On-board Sensors and Big Data Approach

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Research Article

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Research on a China 6b heavy-duty diesel vehicle real-world engine out NOx emission deterioration and NOx correction for humidity and temperature using on-board sensors and big data approach

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Abstract

China VI standard proposed higher requirements for durability of heavy-duty diesel vehicles emissions. **Previous research** which took advantages of both on-board sensors and big data approach to get the NOx deterioration factor was rather scarce. **This paper** used big data approach to study the deterioration of engine out NOx emission based on 254,622 km operation data getting from the on-board sensors or ECUs. Meanwhile, a formula for on-board NOx correction for ambient humidity and temperature had been fitted. **The analyses revealed that** engine out NOx would not be deteriorated during the useful life or even longer (deterioration factor was 1.014 @700,000km). For a steady working condition, the engine out NOx mass flow (g/h) is negatively linearly correlated with absolute humidity (R^2= 0.997). If Ha was lower than 12g/kg, Ha almost had no effect on engine out NOx concentration (ppm). Otherwise, there was also a negatively linear relationship between them (R^2= 0.978). **It is hoped** that the methods and conclusions of this paper could provide some enlightenment for future NOx emission deterioration research.

Keywords

Heavy-duty diesel vehicle, engine out NOx emission, deterioration factor, NOx correction for humidity and temperature, big data

1 Introduction

On-road diesel vehicles produce a great amount of nitrogen oxides (NOx) worldwide, leading to deteriorating environment and increasing health issues **(Anenberg et al., 2017; Cheng et al., 2019)**. The second national (China) pollution source census statistical result showed that heavy duty diesel vehicles accounted for 2.04% of the total number of motor vehicles, but the NOx emission accounted for 61.84% of the total vehicle NOx emission, 34.56% of the total mobile pollution sources NOx emission **(China et al., 2017)**.

In the past few decades, increasingly stringent emission regulations have been adopted by many countries (e.g., Europe, US, Korea, Japan) **(Grange et al., 2017; Wu et al., 2017).** China had also issued "Limits and measurement methods for emissions from diesel fueled heavy-duty vehicles (CHINA VI)" numbered "GB17691-2018" in June, 2018. In China VI legislation, the requirement of useful life was increased, also for the first time the emissions warranty period was set. For instance, for the vehicles of category N3 with a maximum technically permissible mass exceeding 18,000kg, the useful life is 700,000km or seven years, the minimum emissions warranty period is 160,000km or five years, whichever is the sooner. Meanwhile, the minimum service accumulation period is 233,000km **(GB, 2018; Economic Commission, 2010; European Commission, 2011)**.

Manufacture generally verifies whether the emissions durability of the engine meets the requirements of the regulations through the durability test. Since a urea-SCR catalyst with high activity and durability is critical for the NOx emission control, most studies focus on the deterioration of SCR catalyst. Vehicle aging and oven aging are usually used for the research of SCR catalyst deterioration. The vehicle aging method provides realistic conditions, however the process requires long durability testing time. Thus, the oven aging approach has been used as an accelerated aging method with the purpose of reducing the total duration of the test by thermally stressing the catalyst in a high temperature environment **(De et al., 2017; De et al., 2018)**. In the aging process, periodically test was carried out on the engine bench to obtain the SCR conversion efficiency. Finally, a deterioration equation for SCR conversion efficiency was fitted **(Zhang et al., 2018; McCoy et al., 2014; Schmieg et al., 2012)**.

The deterioration equation of SCR conversion efficiency can characterize the deterioration of tailpipe NOx emission only if there is no deterioration of engine out NOx emission. However, few previous studies have been carried out on the deterioration of in-use vehicles engine out NOx emissions. If the engine out NOx deteriorates significantly, the tailpipe NOx may also fail to meet the regulatory requirements even if the SCR conversion efficiency remains the same as the original state. Therefore, the study of engine out NOx deterioration also makes sense for NOx emission control.

On the other hand, as the NOx emission depends on ambient air conditions, the NOx concentration shall be corrected for ambient air temperature and humidity before analyzing the deterioration of engine out NOx emissions by using the data from the on-board NOx sensors **(Krause et al., 1974; Hiromi et al., 1991; Pekula et al., 2003; Asad et al., 2012; Liu et al., 2015; Wang et al., 2018; Wang et al., 2019).** Since few in-use vehicles were equipped with ambient humidity sensor， almost no study takes advantage of vehicle operation data to analyze the influence of ambient factors on engine out NOx emission. Furthermore, no study had given out a formula suitable for on-board NOx sensor for NOx correction for ambient air temperature and humidity.

In view of the abovementioned problems, before the durability test, ambient air temperature and humidity sensors were installed at the engine air filter on the tested vehicle. The real-time data was uploaded (1Hz) to the cloud platform via telematics box (T-box). Based on the second-by-second data obtained from the 254,622 km durability test, by using big data approach, this work was going to achieve the following goals:

- Getting the deterioration equation and the useful life deterioration factor (DF) of the engine out NOx for the tested vehicle;
- Fitting an ambient air temperature and humidity correction formula for NOx sensor.

2 Materials

2.1 Tested vehicle

A N3 category heavy-duty diesel vehicle **(Figure 1(a)**) which was type approved to the China VI (step B) standard and registered in August 2019 was used to perform the on-road durability test.

There are two on-board NOx sensors located at diesel oxidation catalysts (DOC) inlet for engine out NOx measurement and ammonia slip catalyst (ASC) outlet for tailpipe NOx measurement, respectively (**Figure 1(b)**，**Figure 1(c)**). The main characteristics of the tested vehicle are summarized in **Table 1.**

The main operating route of the tested vehicle was the expressway between several cities (Shanghai, Suzhou, Hefei, Guangzhou, Shenzhen, etc.) in Southeast China (**Figure 2**).

(a) (b) (c)

Figure 1. (**a**) Tested vehicle; (**b**) aftertreatment configuration (picture of real products); (**c**) NOx sensors location and aftertreatment configuration (schematic plot).

Table 1 Summary of vehicle, engine, aftertreatment, fuel and DEF specifications.

Type of Vehicle	**N3 (Long–Haul)**
Year of production	7/2019
Type of engine	XX13600-60
Maximum technically permissible mass	48,800kg
Engine rated power	441kW
Reference torque	3000 Nm
WHTC cycle work	38.72 kWh
Emission standard	China VI (step B)
Aftertreatment system	DOC+DPF+SCR+ASC
Fuel	China VI Standard
Diesel exhaust fluid (DEF)	Adblue (32.5%)
Method of pressure charging	Turbocharging
Charge air cooling system	Intercooler

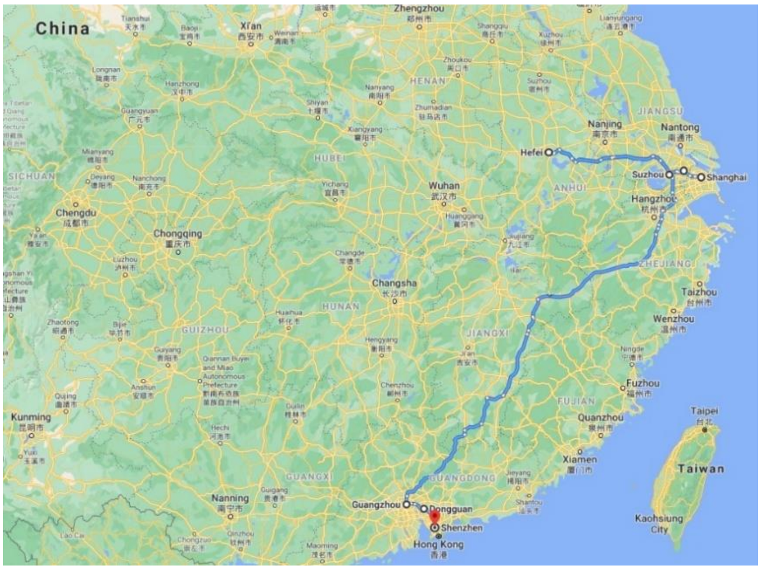


Figure 2 The main operating route of the tested vehicle

2.2 Data acquisition system

Data acquisition of durability test was based on the remote data acquisition system which included sensors (e.g. temperature sensors, pressure sensors), ECUs (e.g. EECU, VECU), telematics box (T-box) and cloud platform (**Figure3**). The communication between the ECUs and T-box was carried out through CAN (Controller Area Network) bus. T-Box encrypts and packs the data, then uploads the data packets to the cloud platform with 1Hz frequency based on https protocol through its built-in wireless communication module. After receiving the data packet, the cloud platform analyzes, stores and visualizes it. Meanwhile, the cloud platform provides functions such as data retrieval, download, statistical analysis, API (Application Programming Interface) and so on.

The Parameters collected in the durability test including ambient parameters, vehicle parameters, engine parameters and aftertreatment system parameters were shown in **Table 2**.

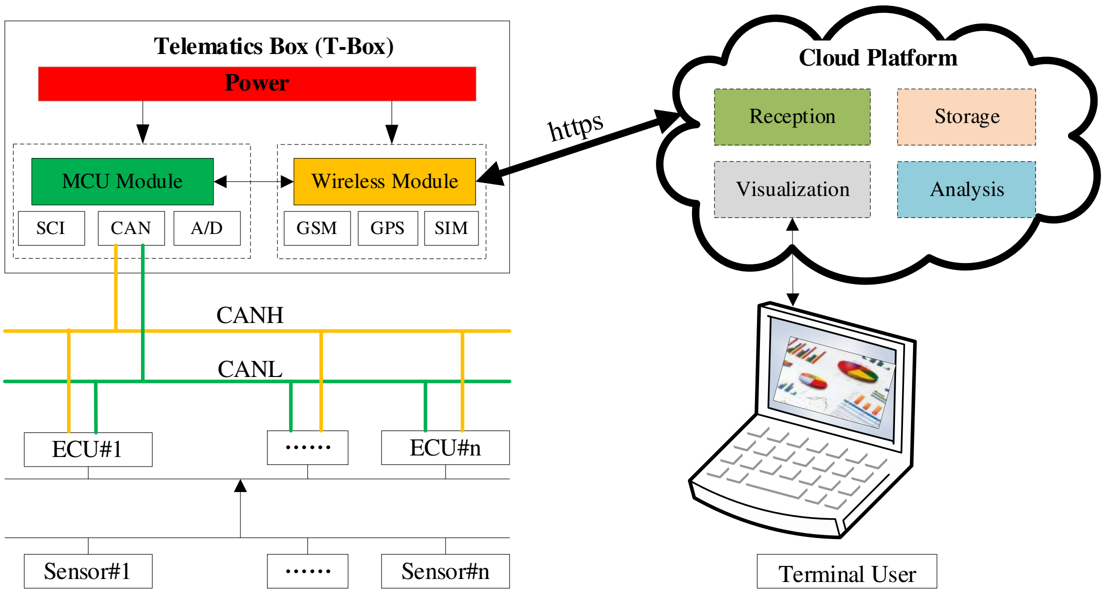


Figure 3 Data Acquisition System (schematic plot)

Table2 Durability test direct measurement parameters

	Parameter	**Unit**	**Source**	**Label**
	Ambient Temperature	℃	Sensor	"T_Air"
Ambient	Ambient Relative Humidity	%	Sensor	"RH_Air"
	Atmospheric Pressure	kPa	EECU	"P_Air"
	Vehicle Longitude	°	GPS	"Longitude"
	Vehicle Latitude	°	GPS	"Latitude"
Vehicle	Vehicle Speed	km/h	VECU	"Veh_Speed"
	Odometer	km	VECU	"Odometer"
	Gear	——	VECU	"Gear"
	Engine Speed	rpm	EECU	"Eng_Speed"
Engine	Actual Engine Percent Torque	%	EECU	"Act_Eng_Tor"
	Nominal Friction Percent Torque	%	EECU	"Fric_Tor"

	Throttle Opening	%	EECU	"Throttle_Opening"
	Rail Pressure	hPa	EECU	"P_Rail"
	Injection Timing	°CA	EECU	"Inj_Timing "
	Fuel Consumption Rate	kg/h	EECU	"Fuel_mRate"
	Accumulative Fuel Consumption	L	EECU	"Acc_Fuel_Cons"
	Fuel Tank Level	%	EECU	"Fuel_Level"
	Intercooler Outlet Temperature	°C	EECU	"T_AirC_O"
	Intercooler Outlet Pressure	kPa	EECU	"P_AirC_O"
	Intake air Mass Flow	kg/h	EECU	"Int_MassFlow"
	Intake Valve Opening	%	EECU	"Int_Valve_Opening"
	Coolant Temperature	°C	EECU	"T_Coolant"
	Oil Temperature	°C	EECU	"T_Oil"
	Oil Pressure	kPa	EECU	"P_Oil"
	Engine Out NOx	ppm	Sensor	"EngOut_NOx"
Aftertreatment system	DOC Inlet Temperature	°C	EECU	"T_DOC_In"
	DPF Inlet Temperature	°C	EECU	"T_DPF_In"
	DPF Pressure Drop	kPa	EECU	"P_Drop_DPF"
	SCR Inlet Temperature	°C	EECU	"T_SCR_In"
	SCR Outlet Temperature	°C	EECU	"T_SCR_Out"
	Urea Injection Temperature	°C	EECU	"T_Urea_Inj"
	Urea Consumption Rate	mg/s	EECU	"Urea_Inj_Rate"
	Urea Pump Pressure	hPa	EECU	"P_Urea_Pump"

Urea Tank Level	%	EECU	"Urea_Level"
Urea Tank Temperature	℃	EECU	"T_Urea"
Urea Concentration	%	EECU	"Urea_Conc"
Tail Pipe NOx	ppm	Sensor	"Tailpipe_NOx"

3 Method

3.1 Method of engine out NOx deterioration analysis

This paper used the method shown in **Figure 4** to carry out the research. Firstly, we should get the “Clean Dataset”, “Basic Dataset” and “Analysis Dataset”. Then, get the maximum odometer (Odo_Max) without deterioration of engine out NOx. Finally, in the range of “Odo_Max”, based on the NOx sensor and ambient air temperature and humidity sensors, accomplished NOx correction for ambient temperature and humidity and forecasted the deterioration factor (DF) of engine out NOx throughout the useful life of the tested vehicle.

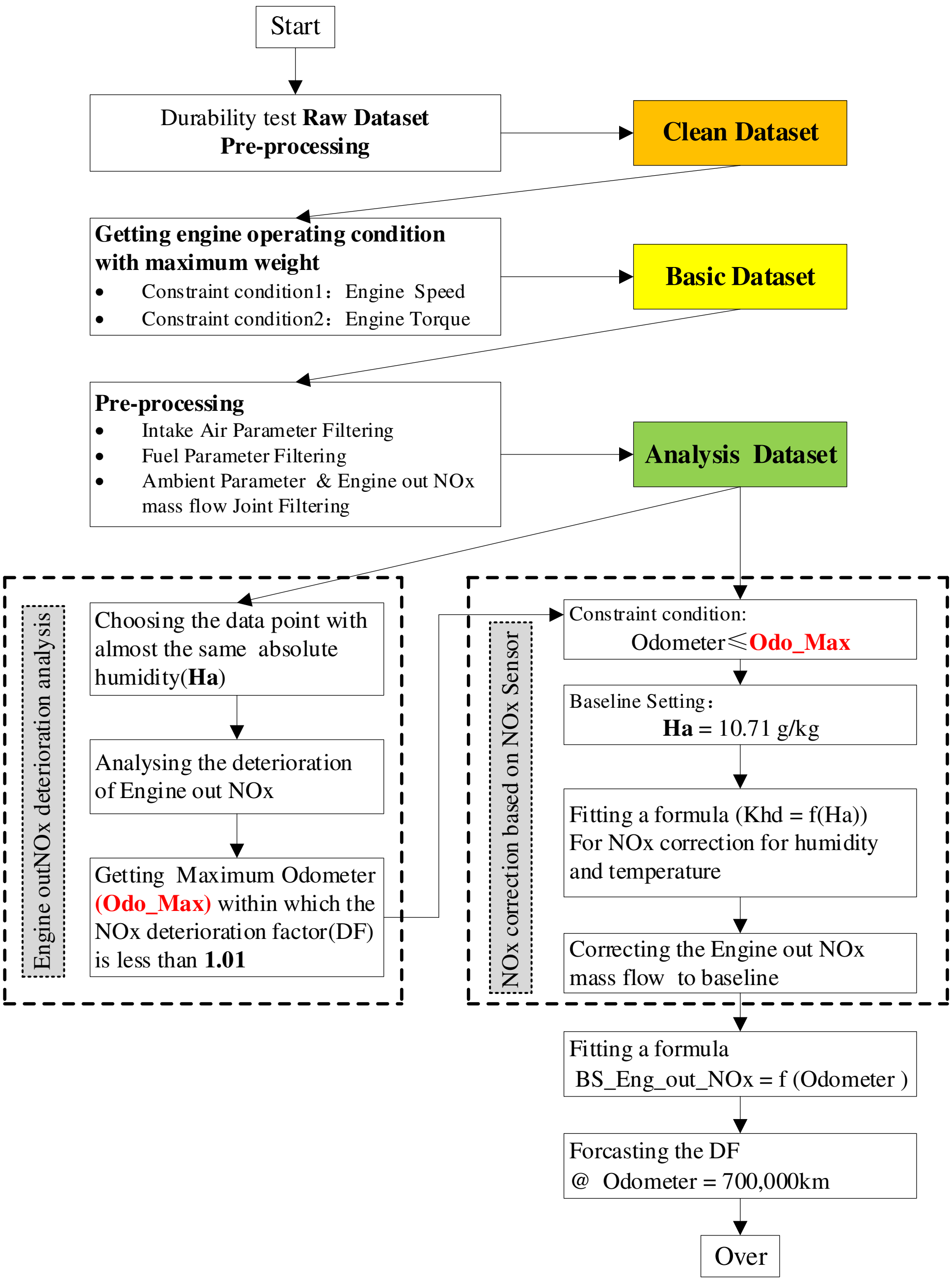


Figure 4 Method of engine out NOx deterioration analysis

3.2 Data preprocessing

Volume, velocity, variety, value, and veracity are the '5V' attributes of big data. Due to the low value density of big data, it is necessary to preprocess the data before analyzing a specific issue. Typically, data preprocessing includes duplicates drop, NaN filling, outliers handling, derived parameter calculation, normalization, feature selection, and so on **(Luengo et al., 2020; Steffen et al., 2020; Deng et al., 2020; Ma et al., 2020)**.

The "Raw Dataset" used in this paper consisted of **11,250,364** lines (observed value) and **37** columns (features), which belonged to the tall skinny dataset. The "Raw Dataset" preprocessing for engine out NOx deterioration analysis mainly included outliers handling, derived parameter calculation and feature selection.

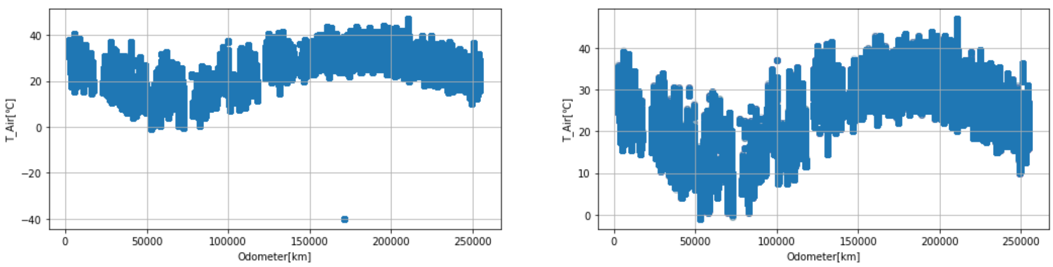
3.2.1 Outliers handling

The outliers of the datasets used in this paper can be classified into modifiable outliers and unmodifiable outliers.

- **Modifiable outliers**

Figure 5(a) shows the ambient temperature in the "Raw Dataset" with abnormal points. **Figure 5(b)** shows the modified ambient temperature. As we know, generally, ambient temperature would not suddenly severe change in a short time, so the pre-value or post-value both can be used as an alternative**.**

In this paper, the previous value fill method ("ffill" method in python) is used to deal with the modifiable outliers. In the same way, this method was also fit for the outliers of other signals which would not suddenly severe change in a short time, such as atmospheric pressure, longitude/latitude, fuel/urea level, odometer, etc.



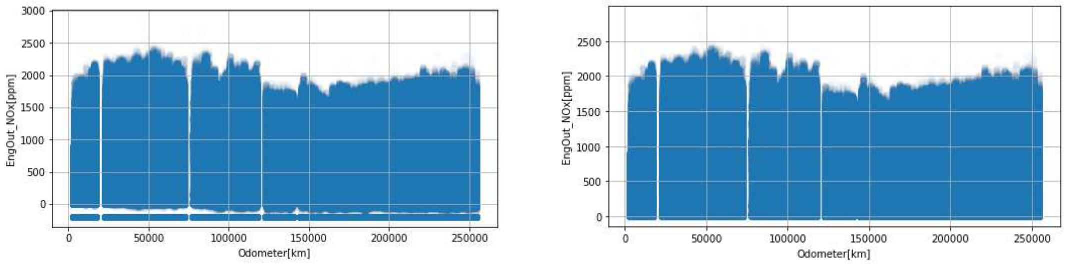
(a) Before preprocessing (b) After preprocessing

Figure 5 Demo for modifiable outliers preprocessing

- **Unmodifiable outliers**

As shown in **Figure 6(a)**, the engine out NOx concentration in the "Raw Dataset" has many abnormal points which were less than zero. Since the engine out NOx concentration was related to the engine working condition, and for in-use vehicles, the engines usually operate in transient conditions, it is impossible to replace the abnormal points with the pre-value or post-value. Generally, for the high-thin datasets, the unmodifiable outliers can be directly deleted. **Figure 6(b)** shows the engine out NOx concentration without abnormal values.

Other abnormal points of signals related to engine working conditions in the "Raw Dataset" (such as fuel injection timing, fuel consumption, throttle opening, urea consumption rate, etc.) can be handled by the same way.



(a) Before preprocessing (b) After preprocessing

Figure 6 Demo for unmodifiable outliers preprocessing

3.2.2 Derived Parameter Calculation

- **NOx Dry/wet correction**

Due to the concentration was measured on a dry basis for the on-board NOx sensor, the measured concentration shall be converted to a wet basis according to the following **Equations (1-5)**:

$$c_{NOx(wet)} = c_{NOx(dry)} * k_w \tag{1}$$

$$k_w = (1 - \frac{1.2442 * H_a + 111.19 * \omega_{ALF} * q_{mf,i} / q_{mad,i}}{773.4 + 1.2442 * H_a + q_{mf,i} / q_{mad,i} * k_{f,w} * 1000}) * 1.008 \tag{2}$$

$$k_{f,w} = 0.055594 * w_{ALF} + 0.0080021 * w_{DEL} + 0.0070046 * w_{EPS} \tag{3}$$

$$H_a = \frac{6.220 * R_a * P_a}{P_B - P_a * R_a * 100} \tag{4}$$

$$\begin{aligned} P_a = (&4.856884 + 0.2660089 * T_a + 0.01688919 * T_a^2 - 7.477123 * 10^{-5} * T_a^3 \\ &+ 8.10525 * 10^{-6} * T_a^4 - 3.115221 * 10^{-8} * T_a^5) * (101.32 / 760) \end{aligned} \tag{5}$$

where:

$c_{NOx(wet)}$ is the wet concentration in ppm;

$c_{NOx(dry)}$ is the dry concentration in ppm (NOx sensor observed value);

k_w is the dry/wet correction factor;

H_a is the intake air humidity, g water per kg dry air;

$q_{mf,i}$ is the instantaneous fuel mass flow rate, kg/h;

$q_{mad,i}$ is the instantaneous dry intake air mass flow rate, kg/h;

ω_{ALF} is the hydrogen content of the fuel, percent mass;

w_{DEL} is the nitrogen content of the fuel, percent mass;

w_{EPS} is the oxygen content of the fuel, percent mass;

T_a is temperature of the intake air,°C;

R_a is relative humidity of the intake air,%;

P_a is saturation vapour pressure of the intake air, kPa;

P_B is total barometric pressure, kPa.

- **NOx mass flow**

The calculation of the instantaneous NOx mass flow shall be according to the following **Equations (6-7)**:

$$q_{mNOx,i} = 0.001587 * q_{mew,i} * c_{NOx(wet),i} \tag{6}$$

$$q_{mew,i} = q_{maw,i} + q_{mf,i} \tag{7}$$

where:

$q_{mNOx,i}$ is the instantaneous NOx mass flow rate, g/h

$c_{NOx(wet),i}$ is the instantaneous wet concentration in ppm

$q_{mew,i}$ is the instantaneous exhaust mass flow rate, kg/h

$q_{maw,i}$ is the instantaneous intake air mass flow rate, kg/h

$q_{mf,i}$ is the instantaneous fuel mass flow rate, kg/h

- **Engine Power**

The calculation of the engine power shall be according to the following **Equations (8-9)**:

$$Eng\_Power = \frac{Eng\_Speed * Eng\_Tor / 100 * Torque\_refer}{9550} \tag{8}$$

$$Eng\_Tor = Tor_{Act,Eng} - Tor_{Fric} \tag{9}$$

Where:

$Tor_{Act,Eng}$ is actual engine percent torque,%

Tor_{Fric} is friction percent torque,%

$Torque\_refer$ is 3000 N.m

- **Instantaneous NOx brake specific emission**

The calculation of the instantaneous NOx brake specific emission (g/kW.h) shall be according to the following **Equation (10)**:

$$BSNOx_i = \frac{q_{mNOx,i}}{Eng\_Power_i} \tag{10}$$

3.2.3 Feature selection

In this paper, we mainly focused on engine out NOx. However, the vehicle location parameters, aftertreatment system parameters, and some indicative parameters (e.g. fuel level) didn't directly affect the engine out NOx emission. These features can be dropped during data preprocessing.

Moreover, the derived parameters obtained in section 3.1.2 can be incorporated into the dataset for engine out NOx analysis.

After the above data preprocessing, we can get the "Clean Dataset", and the parameters of "Clean Dataset" were shown in **Table 3**.

Table3 Parameters in Clean Dataset

	Parameter	Unit	Source	Label
Ambient	Ambient Temperature	℃	Sensor	"T_Air"
	Ambient Relative Humidity	%	Sensor	"RH_Air"
	Atmospheric Pressure	kPa	EECU	"P_Air"
Vehicle	Vehicle Speed	km/h	VECU	"Veh_Speed"
	Odometer	km	VECU	"Odometer"
	Gear	——	VECU	"Gear"
Engine	Engine Speed	rpm	EECU	"Eng_Speed"
	Actual Engine Percent Torque	%	EECU	"Act_Eng_Tor"
	Nominal Friction Percent Torque	%	EECU	"Fric_Tor"
	Throttle Opening	%	EECU	"Throttle_Opening"
	Rail Pressure	hPa	EECU	"P_Rail"
	Injection Timing	°CA	EECU	"Inj_Timing "
	Fuel Consumption Rate	kg/h	EECU	"Fuel_mRate"
	Accumulative Fuel Consumption	L	EECU	"Acc_Fuel_Cons"
	Intercooler Outlet Temperature	℃	EECU	"T_AirC_O"
	Intercooler Outlet Pressure	kPa	EECU	"P_AirC_O"
	Intake Mass Flow	kg/h	EECU	"Int_MassFlow"
	Intake Valve Opening	%	EECU	"Int_Valve_Opening"
	Coolant Temperature	℃	EECU	"T_Coolant"
	Oil Temperature	℃	EECU	"T_Oil"

	Oil Pressure	kPa	EECU	"P_Oil"
Deprived Parameters	Engine Out NOx(wet)	ppm	Calculation	"EngOut_NOx_wet"
	Engine Out Mass Flow	g/h	Calculation	"EngOut_NOx_MF"
	Net Percent Torque	%	Calculation	"Eng _Tor"
	Engine Power	kW	Calculation	"Eng_Power"
	Brake Specific Engine Out NOx	g/kW.h	Calculation	"BSEngOut_NOx"
	Absolute Humidity	g/kg	Calculation	"Ha"

4. Results and Discussion

Based on the data getting from 254,622 km durability test of the tested vehicle, we carried out the research for engine out NOx emission deterioration, at the same time, completed the NOx correction for ambient air temperature and humidity.

4.1 Results

In this paper, the “Clean Dataset”, “Basic Dataset” and “Analysis Dataset” were obtained according to the methods shown in Section 3.1, the datasets scale， specific methods and constraint conditions were shown in the **Table 4**.

The “Raw Dateset” in **Table 4** was the data of 254,622 km durability test. The “Clean Dataset” was got by data preprocessing described in Section 3.2 in this paper.

Table 4 Scale of Datasets and Method/Constraint Condition

Input Dataset			Method / Constraint Condition	Output Dataset
Name	**Rows**	**Columns**		
Raw Dataset	11,250,364	37	Data Preprocessing	**Clean Dataset**
Clean Dataset	9,962,537	27	Getting Eng_Speed max Weight Bin/	Dataset_A

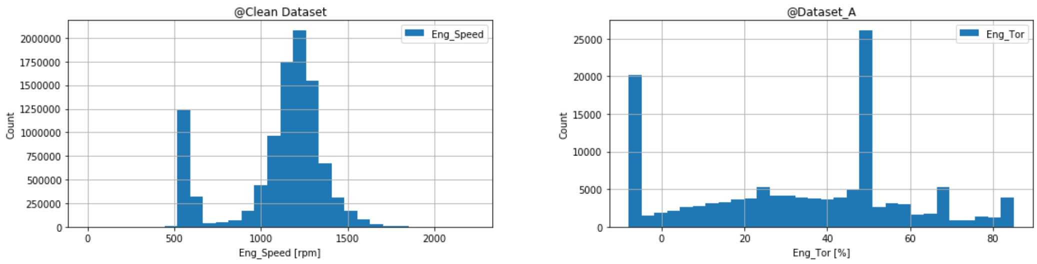
			Eng_Speed = 1200±2 [rpm]	
Dataset_A	130,135	27	Getting Eng_Tor max Weight Bin / Eng_Tor = 50±1 [%]	**Basic Dataset**
Basic Dataset	25,417	27	Intake Air Parameter Filtering/ Int_MassFlow IQR	Dataset_B
Dataset_B	23,825	27	Fuel injection Parameters Filtering/ Fuel_Rate IQR	Dataset_C
Dataset_C	21,348	27	Fuel injection Parameters Filtering/ Injection Timing IQR	Dataset_D
Dataset_D	19,733	27	Ambient Parameter Joint Filtering/ EngOut_NOx_MF vs Ha (linear)	**Analysis Dataset**
Analysis Dataset	12,144	27	Ha =15±0.5 [g/kg]	Dataset_E

IQR: Interquartile range

4.1.1 Basic Dataset acquisition

Figure 7(a) shows the frequency distribution (bins=30) of engine speed on "Clean Dataset". Within its maximum weight range ***[1185, 1259] rpm***, we had taken 1200±2 rpm as the constraint condition to get a new dataset named "Dataset_A", where,±2 is the tolerance range of engine speed, so as to avoid the scale of the dataset being too small, similarly hereinafter.

Figure 7(b) shows the frequency distribution (bins=30) of net percent torque on "Dataset_A", and within its maximum weight range ***[48, 51] %***, we had taken 50±1 % as the constraint condition, then we got the "Basic Dataset" for the following research.



(a) (b)

Figure7 (a) Eng_Speed distribution @ Clean Dataset; (b) Eng_Tor distribution @ Dataset_A

4.1.2 Basic Dataset preprocessing

The analysis of the deterioration of engine out NOx shall be carried out on a certain steady working condition (for in-use vehicles) or established cycles (for engine bench, whether transient or steady). Therefore, for the tested vehicle, before the engine out NOx deterioration research, we should ensure the dataset used for the research was a “steady” one.

On the “Basic Dataset”, although the engine speed and engine torque were almost the same, the dataset contained many transition operating points, some outliers, and shot noise, etc. Therefore, in order to obtain the dataset of a certain steady working condition as accurate as possible, it is necessary to filter the “Basic Dataset” to eliminate the influence of transition working conditions and noise points on the final results.

For a given diesel engine and a given working condition, engine out NOx is mainly affected by intake air parameters and fuel injection parameters. The intake air parameters are main affected by ambient air parameters. So, we could use these parameters to filter the “Basic Dataset”, then we would get the “Analysis Dataset”.

- **Intake air parameter filtering**

Figure 8(a) shows the intake air mass flow versus odometer on “**Basic Dataset**”. As it can be seen, there were many outliers and shot noise points, which were basically generated by transition working conditions.

Figure 8(b) shows the frequency distribution of the intake air mass flow. As it can be seen, the intake air mass flow distribution was relatively concentrated, so interquartile range (IQR) can be used for filtering. If the value was less than the minimum or greater than the maximum showed in **Figure 9,** it would be dropped.

Figure 8(c) shows the box-plot of the intake air mass flow (the minimum is 835.0 kg/h, the maximum is 1071.0 kg/h)

Figure 8(d) shows the result of the intake air mass flow that had been filtered by IQR. Compared to **Figure 8(a)**, we could find that a large number of outliers had been filtered out. After the filtering of intake air mass flow, we got "Dataset_B".

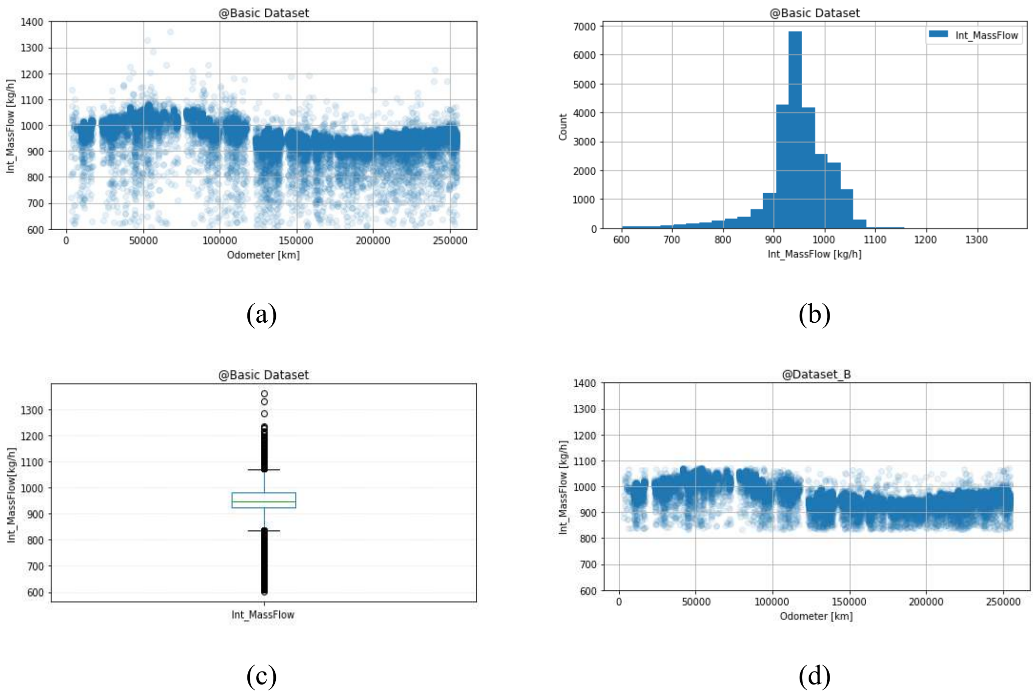


Figure 8 Intake air parameter filtering. (a) Int_MassFlow vs odometer @ Basic Dataset; (b) Int_MassFlow frequency distribution @ Basic Dataset; (c) Int_MassFlow box-plot @ Basic Dataset; (d) Int_MassFlow vs odometer @ Dataset_B;

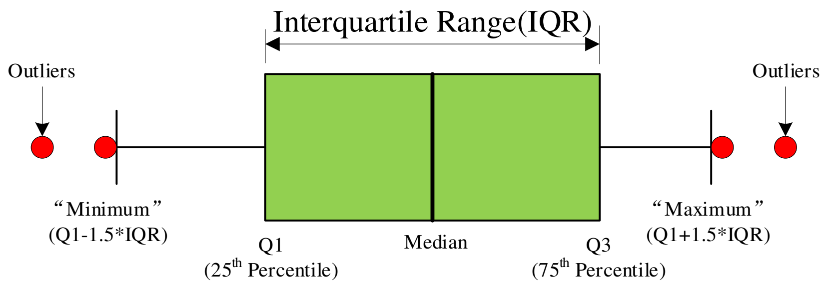


Figure 9 IQR (box-plot) filtering schematic plot

- **Fuel injection parameters filtering**

Figure 10(a) shows the fuel consumption rate versus odometer on "Dataset_B". **Figure 10(b)** shows the box-plot of the fuel consumption rate (the minimum is 34.78 kg/h, the maximum is 35.45 kg/h). We got "Dataset_C" after filtering fuel consumption rate by IQR.

Figure 10(c) shows the injection timing versus odometer on "Dataset_C". **Figure 10(d)** shows the box-plot of injection timing (the minimum is 5.83 BTDC°CA, the maximum is 5.99 BTDC°CA). We got "Dataset_D" after filtering injection timing by IQR.

Figure 10(e) shows the fuel consumption rate versus injection timing on "Dataset_B". As it can be seen, for a given operation condition of the tested vehicle, the larger the injection timing is, the higher the fuel consumption is. As we know, the larger the injection timing is, the higher the combustion temperature is, the higher combustion temperature would lead to higher engine out NOx emission. So, we had taken both fuel consumption rate and injection timing as the constraint conditions to ensure the consistency of the injection parameters.

Figure 10(f) shows the fuel consumption rate versus injection timing that had been filtered by IQR, then, we got "Dataset_D".

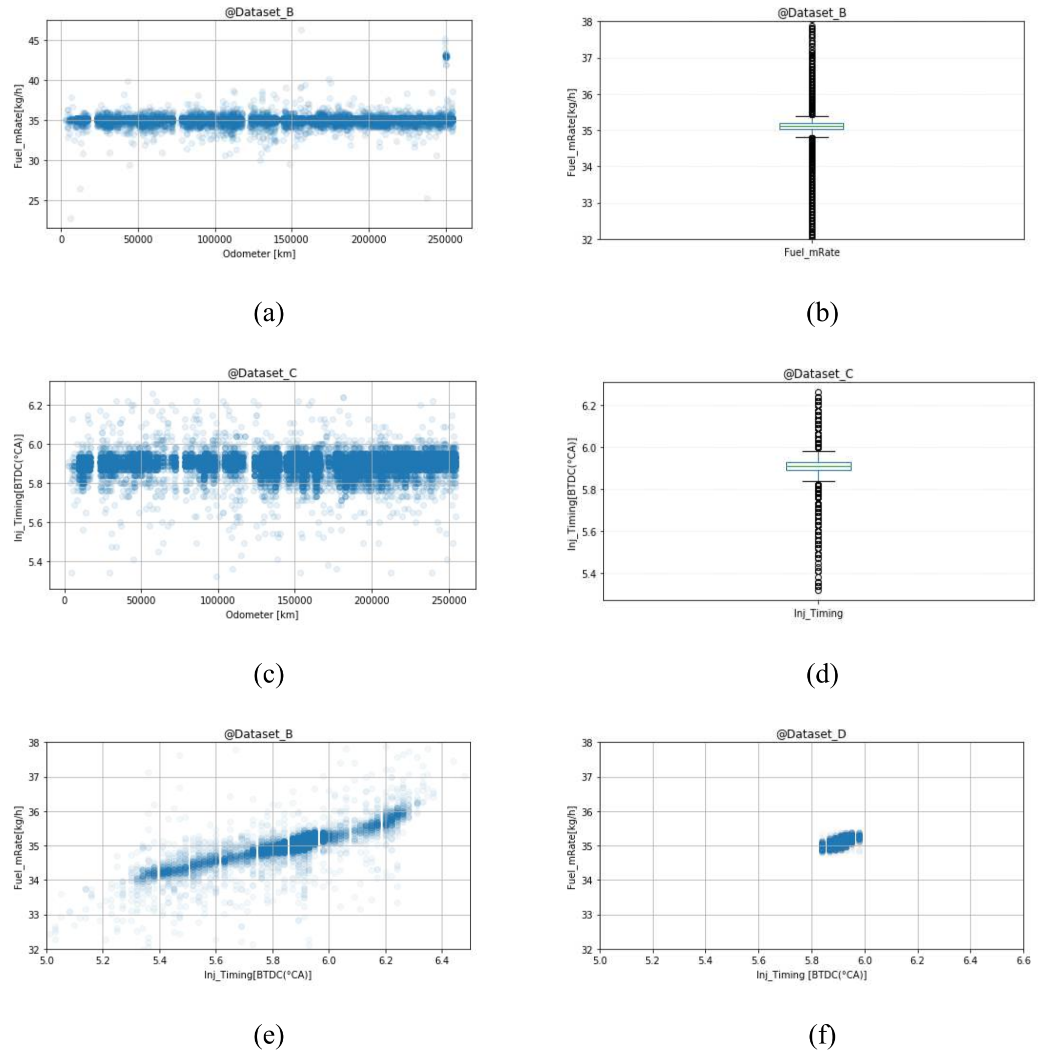
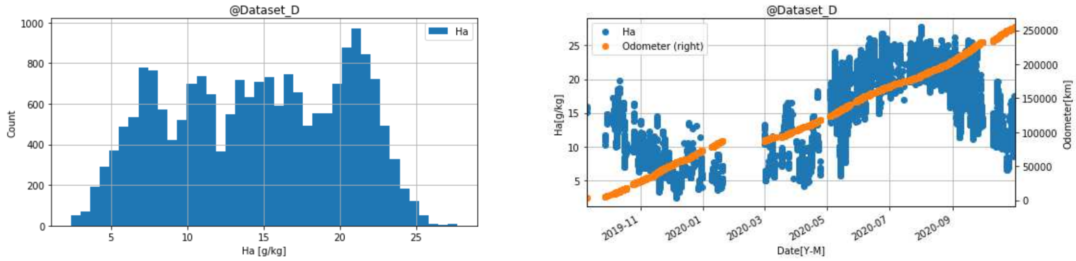


Figure 10 Fuel injection parameters filtering (a) Fuel_mRate vs odometer @ Dataset_B; (b) Fuel_mRate box-plot @ Dataset_B; (c) Inj_Timing vs odometer @ Dataset_C; (d) Inj_Timing box-plot @ Dataset_C ; (e) Inj_Timing vs Fuel_mRate @ Dataset_B; (f) Inj_Timing vs Fuel_mRate @ Dataset_D;

- **Ambient parameters and engine out NOx mass flow joint filtering**

Figure 11(a) shows the frequency distribution of absolute humidity (Ha) on "Dataset_D". The distribution of Ha is relatively dispersed. Therefore, IQR filtering method can no longer be suitable for filtering ambient parameters.

Figure 11(b) shows Ha distribution in different seasons on "Dataset_D". As it can be seen, Ha was significantly affected by seasons in Southeast China, for instance, usually Ha is lower (5-10 g/kg) in winter and higher (20-25 g/kg) in summer.



(a) (b)

Figure 11 (a) Ha distribution@ Dataset_D; (b) Ha & odometer vs Date @ Dataset_D

After the intake air parameter and fuel injection parameters filtering, absolute humidity (Ha), was the most related ambient parameter to engine out NOx mass flow. The Pearson correlation coefficient between engine out NOx mass flow and Ha changed from **-0.359** (on “Clean Dataset”) to **-0.587** (on “Dataset_D”).

As it was shown in **Figure 12(a)**, on the whole, there was a good linear relationship (fitting function: $y = -16.444*x + 1562.7$) between engine out NOx mass flow and Ha. But, there were still many shot noise points which may lead to a lower Pearson correlation coefficient and relatively big error for the final results or conclusions. Therefore, before the quantitative analysis of the impact of ambient factors on engine out NOx emission, these shot noise points should be filtered out. The specific filtering steps were as follows:

Step1: Fitting a function f **(Equation 11)**, then getting k and b;

$$EngOut\_NOx\_MF = f(Ha) = k * Ha + b \tag{11}$$

Step2: Calculating the instantaneous engine out NOx mass flow at the observed Ha by using k and b in step 1 **(Equation 12)**

$$Eng\_Out\_NOx\_Cal_i = k * Ha_i + b \tag{12}$$

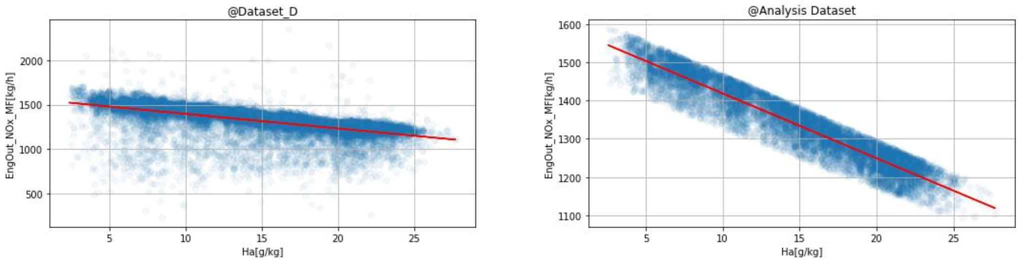
Step3: Calculating the ratio of each observed point by using the following **Equation 13**

$$Ratio_i = EngOut\_NOx\_MF_i \;/\; Eng\_Out\_NOx\_Cal_i \tag{13}$$

Step4: Setting a range ***[0.95, 1.05]*** for ratio, filtering by the ratio, then getting a new dataset.

Step5: Repeating step1-4 until the difference of two successive iterations k is less than 1%.

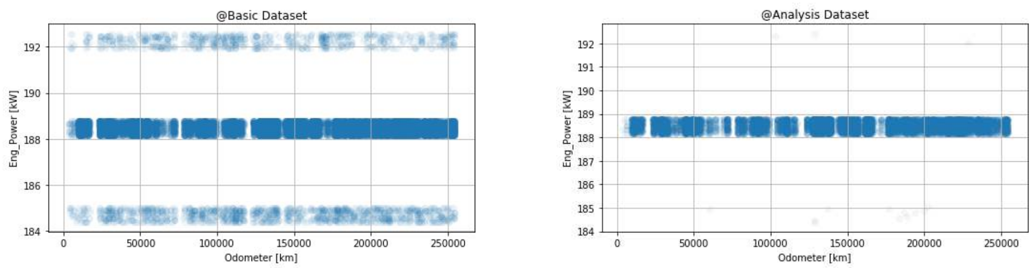
Figure 12(b) shows the result of the Ha and engine out NOx mass flow joint filtering on "Dataset_D". The fitting function is *y = -16.963*x + 1588.7*, then we got "Analysis Dataset".



(a) (b)

Figure 12 Ambient parameters and engine out NOx mass flow joint filtering; (a) Ha vs EngOut_NOx_MF@ Dataset_D; (b) Ha vs EngOut_NOx_MF@ Analysis Dataset;

Figure 13(a) and **Figure 13(b)** show engine power vs odometer on "Basic Dataset" and "Analysis Dataset" respectively, as it can be seen, after the abovementioned filtering, the engine power on "Analysis Dataset" was all almost the same in 254,622 km durability test. So "Analysis Dataset" could be considered as a "steady" dataset.



(a) (b)

Figure 13 (a) Eng_Power vs Odometer @ Basic Dataset; (b) Eng_Power vs Odometer@ Analysis

Dataset;

4.2 Analysis of engine out NOx emission deterioration

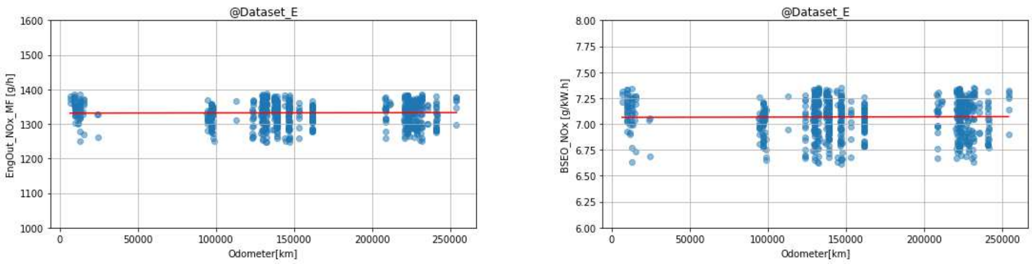
On “Analysis Dataset”，the Pearson correlation coefficient between engine out NOx mass flow and Ha was **-0.947** (**Table 5**), without considering the deterioration , engine out NOx mass flow was most related to Ha.

Table 5 Pearson correlation coefficient for EngOut_NOx_MF @ Analysis Dataset

EngOut_NOx_MF	1.000	Fuel_mRate	0.047	T_Coolant	-0.061
BSEO_NOx	1.000	Eng_Tor	0.018	RH_Air	-0.082
EngOut_NOx_wet	0.898	Act_Eng_Tor	0.018	T_Oil	-0.350
Int_MassFlow	0.859	Eng_Power	0.016	Odometer	-0.534
P_AirC_O	0.777	P_Rail	0.009	Acc_Fuel_Cons	-0.541
P_Air	0.569	Eng_Speed	0.007	T_AirC_O	-0.859
P_Oil	0.080	Int_Valve_Opening	-0.021	T_Air	-0.863
Throttle_Opening	0.064	Gear	-0.045	**Ha**	**-0.947**
Inj_Timing	0.060	Veh_Speed	-0.045	Fric_Tor	——

Therefore, further taking Ha = 15±0.5 g/kg which could cover a wider range of mileage or seasons **(Figure 11(b))** as a constraint condition, we can got a new dataset named “Dataset_E” on which we could analyse the deterioration of engine out NOx emission.

Figure 14(a) shows the deterioration of engine out NOx mass flow (g/h) and **Figure 14(b)** shows the deterioration of the engine out NOx brake specific emission (g/kW.h) on “Dataset_E”.



(a) (b)

Figure 14 (a) EngOut_NOx_MF vs Odometer @ Dataset_E; (b) BSEngOut_NOx vs Odometer@ Dataset_E;

The deterioration function and deterioration factor were shown in **Table 6**. As it can be seen, within 254,622 km, for the maximum weight working condition (including ambient condition) of the tested vehicle, the deterioration factors of engine out NOx mass flow and engine out NOx brake specific emission were 1.001 and 1.001, respectively

Table 6 The deterioration information for engine out NOx@ Dataset_E

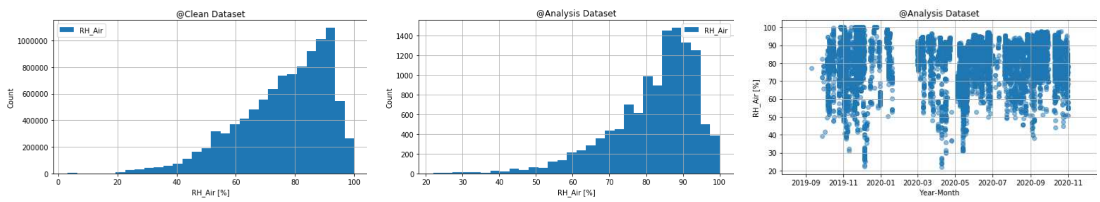
		Eng_Out NOx [g/h]	Eng_Out NOx [g/kW.h]
Deterioration Equation	k	6.102E-06	2.770E-08
	b	1331.3	7.063
Odometer [km]	0	1331.3	7.063
	254,622	1332.9	7.070
	700,000	1335.6	7.083
Deterioration Factor (DF) @254,622 km		1.001	1.001
Deterioration Factor (DF) @700,000 km		1.003	1.003

Therefore, within the durability test mileage, we could consider that the engine out NOx emission of the tested vehicle did not deteriorate. That's to say, a study based on on-board sensors for NOx correction for ambient air temperature and humidity can be carried out on "Analysis Dataset".

4.3 On-board NOx correction for ambient air temperature and humidity

4.3.1 Distribution of ambient air factors

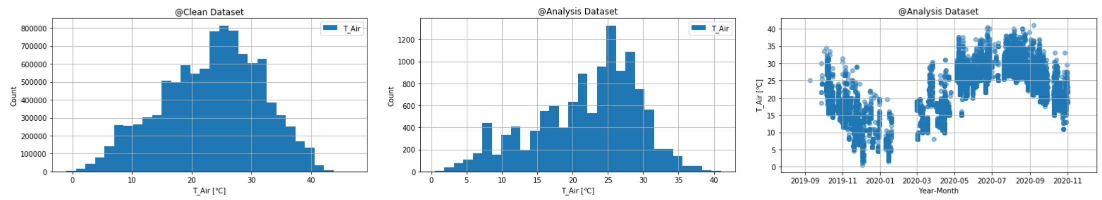
Figure 15(a) shows the distribution of relative humidity in the operation area (Southeast China, see Figure 2) of the tested vehicle from September 2019 to November 2020 on "Clean Dataset", the ratio of relative humidity greater than 50% was 93.5%, and that greater than 60% was 84.5%. **Figure 15(b)** shows the distribution of relative humidity on "Analysis Dataset", the ratio of relative humidity greater than 50% is 97.8%, and that greater than 60% is 93.4%. **Figure 15(c)** shows the distribution of relative humidity in different months on "Analysis Dataset". "Analysis Dataset" can basically represent the distribution of relative humidity in the Southeast China throughout a year.



(a) (b) (c)

Figure 15 (a) RH_Air distribution @Clean Dataset; (b) RH_Air distribution @Analysis Dataset; (c) RH_Air vs Date @ Analysis Dataset

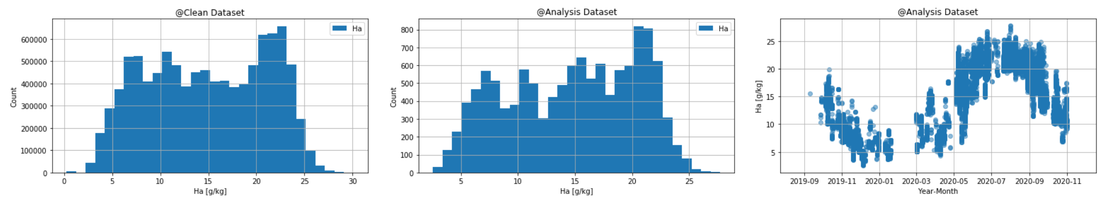
Figure 16(a) and **Figure 16(b)** showed the distribution of ambient temperature on "Clean Dataset" and "Analysis Dataset" respectively. As it can be seen, the ambient temperature is mainly affected by the season (**Figure 16(c)**), and the ambient temperature is almost above 0℃ in Southeast China all the year round.



(a) (b) (c)

Figure16 (a) T_Air distribution @Clean Dataset; (b) T_Air distribution @Analysis Dataset; (c) T_Air vs Date @ Analysis Dataset

Figure 17(a) and Figure **17(b)** showed the distribution of Ha on "Clean Dataset" and "Analysis Dataset" respectively. As it can be seen, the trend of Ha changing with the season was almost the same as that of the ambient temperature (**Figure 16(c), Figure 17(c)**).



(a) (b) (c)

Figure17 (a) Ha distribution @Clean Dataset; (b) Ha distribution @Analysis Dataset; (c) Ha vs Date @ Analysis Dataset

Figure 18 shows the relationship between Ha and ambient temperature/relative humidity. The functional relationship can be described by **Equation 14**.

$$Ha = (0.0372 * RHa + 0.5212) * e^{0.063*Ta} \tag{14}$$

Where: RHa is relative humidity, %;Ta is ambient temperature,℃.

If the relative humidity remained the same or varied in a small range, Ha had an exponential relationship with the ambient temperature.

When the ambient temperature was at a low level, the variety of relative humidity has little effect on Ha, in other words, the lower ambient temperature would directly lead to lower Ha in winter.

The larger the Ha is, the larger the specific heat capacity of the intake air is. Larger Ha would lead to lower combustion temperature and lower engine out NOx emission. So, Ha has a significant effect on engine out NOx emission.

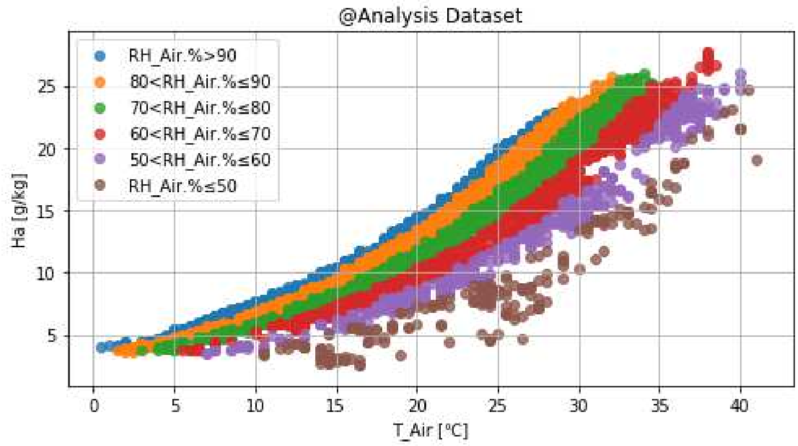


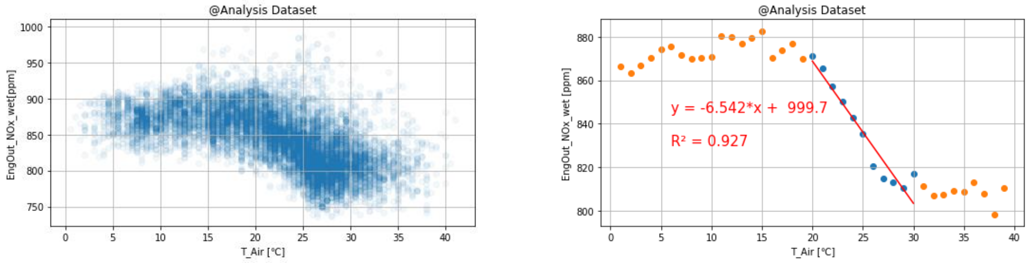
Figure 18 The relationship between Ha and ambient temperature/relative humidity

4.3.2 The effect of ambient factors to engine out NOx emission

In this section, we mainly discuss the effect of ambient factors (ambient temperature and absolute humidity(Ha)) on engine out NOx concentration (ppm) and engine out NOx mass flow (g/h).

- **Ambient temperature vs engine out NOx (ppm)**

Figure 19(a) shows ambient temperature vs engine out NOx concentration (ppm, wet basis) on “Analysis Dataset” ; **Figure 19(b)** shows the average value of engine out NOx concentration (ppm, wet basis) at different ambient temperature (step = 1℃) . As it can be seen, when the ambient temperature is within the range of 20~30℃, there is a negative linear relationship between ambient temperature and engine out NOx concentration (R^2= 0.927). But, when the ambient temperature is lower than 20 ℃ or higher than 30 ℃, the change of ambient temperature has little effect on engine out NOx concentration (within 20ppm).

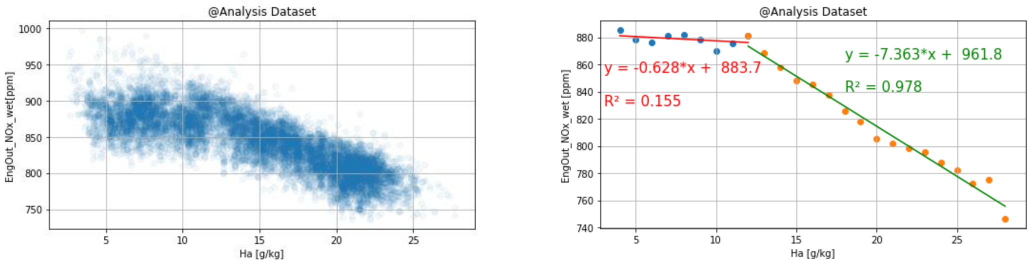


(a) (b)

Figure 19 (a) T_Air vs EngOut_NOx_wet @ Analysis Dataset; (b) T_Air vs EngOut_NOx_wet (mean) @ Analysis Dataset;

- **Ha vs engine out NOx (ppm)**

Figure 20(a) shows Ha vs engine out NOx concentration (ppm, wet basis) on "Analysis Dataset"; **Figure 20(b)** shows the average value of engine out NOx concentration (ppm, wet basis) at different Ha (step = 1 g/kg). As it can be seen, when Ha is lower than 12 g/kg, the change of Ha had little effect on engine out NOx concentration (within 20ppm), otherwise, engine out NOx concentration had a good negative linear relationship with Ha (R^2= 0.978).



(a) (b)

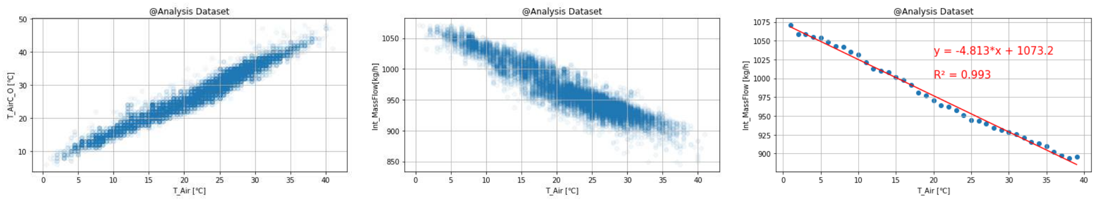
Figure 20 (a) T_Air vs EngOut_NOx_wet @ Analysis Dataset; (b) T_Air vs EngOut_NOx_wet (mean) @ Analysis Dataset;

- **Ambient temperature vs intake air mass flow**

According to **Equation 6** and **Equation 7**, the engine out NOx mass flow is affected by the exhaust mass flow and engine out NOx concentration (wet basis, ppm). On "Analysis Dataset", the exhaust mass flow is mainly affected by the intake air mass flow because the fuel consumption rate is almost the same.

For a given steady working condition (e.g. “Analysis Dataset”), according to ideal gas law PV= nRT, the intake air mass flow will be affected by intercooler outlet temperature.

Figure 21(a) shows intercooler outlet temperature versus ambient temperature; **Figure 21(b)** shows intake air mass flow versus ambient temperature; **Figure 21(c)** shows ambient temperature versus the average value of intake air mass flow at different ambient temperature (step = 1℃). As it can be seen , the intake air mass flow had a good negative linear relationship with ambient temperature(R^2= 0.993).

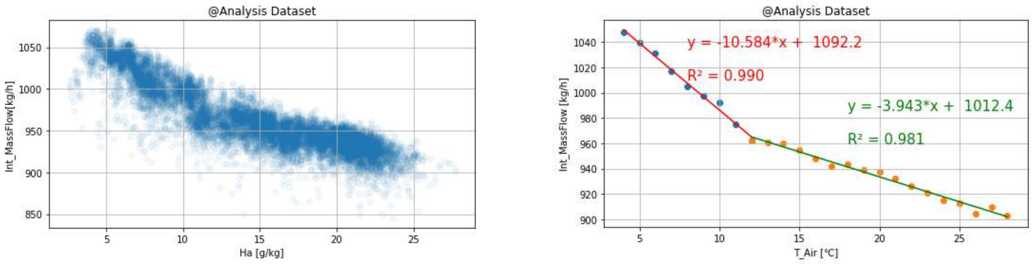


(a) (b) (c)

Figure 21 (a) T_Air vs T_AirC_O @ Analysis Dataset; (b) T_Air vs Int_MassFlow @ Analysis Dataset; (c) T_Air vs Int_MassFlow (mean) @ Analysis Dataset

- **Ha vs intake air mass flow**

Figure 22(a) shows intake air mass flow versus Ha on “Analysis Dataset”; **Figure 22(b)** shows the average value of intake air mass flow at different Ha (step = 1 g/kg) .As it can be seen, Ha lower than12 g/kg (***k* = *-10.584***) had a greater effect on intake air mass flow than that of Ha higher than12 g/kg (***k* = *-3.943***).

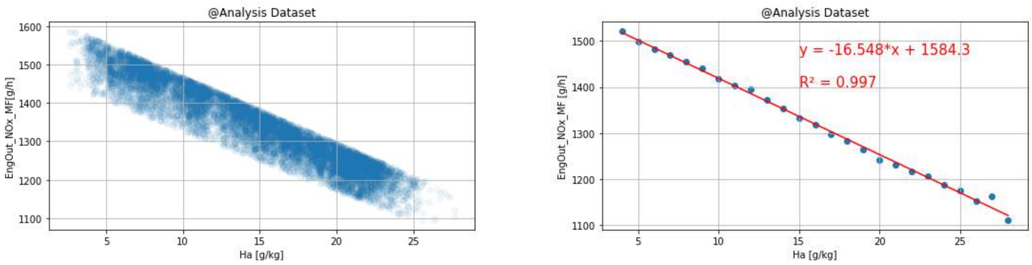


(a) (b)

Figure 22 (a) Ha vs Int_MassFlow @ Analysis Dataset; (b) Ha vs Int_MassFlow (mean) @ Analysis Dataset.

- **Ha vs engine out NOx (g/h)**

Figure 23(a) shows Ha vs engine out NOx mass flow (g/h) on Analysis Dataset; **Figure 23(b)** shows the average value of engine out NOx mass flow (g/h) at different Ha (step = 1 g/kg) .Engine out NOx mass flow had a good negative linear relationship with Ha (R^2= 0.997).



(a) (b)

Figure 23 (a) Ha vs EngOut_NOx_MF@ Analysis Dataset; (b) Ha vs EngOut_NOx_MF (mean) @ Analysis Dataset;

To sum up, for a given steady working condition, whether ambient temperature or Ha, they had different effect on engine out NOx concentration (ppm) at different sections; the exhaust mass flow rate was mainly affected by the ambient temperature; engine out NOx mass flow (g/h) was mainly affected by Ha. So, we can take the engine out NOx mass flow (g/h) as the correction target, Ha as the independent variable to study a formula for NOx correction for ambient air temperature and humidity based on on-board sensors.

4.3.3 NOx correction for temperature and humidity

According to the results of section 4.3.2 in this paper, based on on-board sensors, we had carried out the NOx correction for ambient temperature and humidity as following steps:

Step1: NOx Dry-Wet correction (It had been done in data preprocessing).

Step2: Setting Ha = 10.71 g/kg as the reference, that is to say $K_{h,d}$ = 1 @ Ha = 10.71 g/kg .

Step3: Calculating the average value of engine out NOx mass flow @ Ha = 10.71±0.5 g/kg by **Equation 15**.

$$EngOut\_NOx\_MF_{Base} = (\sum_{i}^{n} EngOut\_NOx\_MF_{Ha_i = 10.71\pm0.5}) / n \tag{15}$$

Step4: Calculating the real correction coefficient $K_{h,d}$_Real of each observation point by **Equation 16**.

$$K_{h,d}\_Real_i = EngOut\_NOx\_MF_{Base} / EngOut\_NOx\_MF_i \tag{16}$$

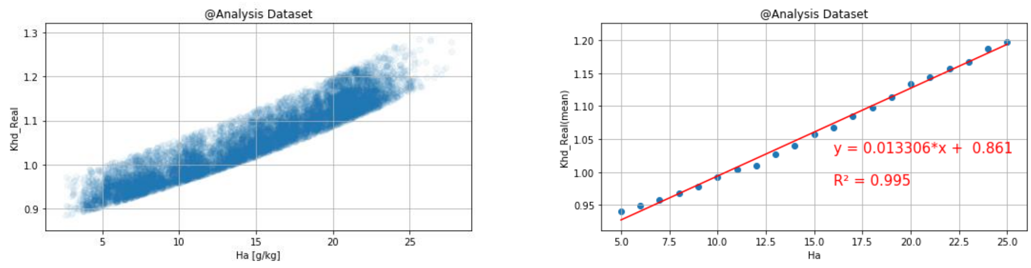
Step5: Fitting a formula for $K_{h,d}$ **(Equation 17)**, then getting k and b;

$$K_{h,d} = f\left(Ha\right) = k * Ha + b \tag{17}$$

Step6: Using k and b obtained in step 5 to correct engine out NOx mass flow.

Figure 24(a) shows Ha versus $K_{h,d}$_Real on Analysis Dataset; **Figure 24(b)** shows the average value of $K_{h,d}$_Real at different Ha (step = 1 g/kg, range= (5,25)). $K_{h,d}$_Real had a good positive linear relationship with Ha (y = 0.013306*x + 0.861 , R2= 0.995).

$$K_{h,d} = 0.013306 * Ha + 0.861 \tag{18}$$



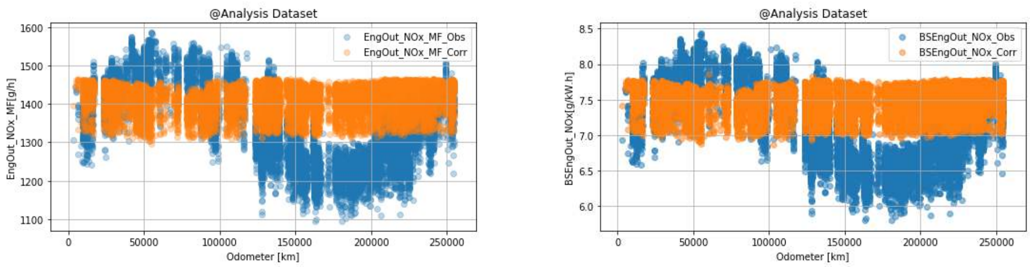
(a) (b)

Figure 24 (a) Ha vs $K_{h,d}$_Real @ Analysis Dataset; (b) Ha vs $K_{h,d}$_Real (mean) @ Analysis Dataset;

4.3.4 Verification of NOx correction formula

For the base point (Ha = 10.71g/kg), $K_{h,d}$ =1.004, The bias was merely 0.4%, So, we may conclude that the accuracy of **Equation 18** could be guaranteed for the base point.

Figure 25(a) shows the raw and corrected engine out NOx mass flow versus odometer on "Analysis Dataset". As it can be seen, after ambient temperature and humidity correction, engine out NOx mass flow was on the same level in different seasons, so as the engine out NOx brake specific emission (**Figure 25(b)**).



(a) (b)

Figure 25 (a) Odometer vs EngOut_NOx_MF @ Analysis Dataset; (b) Odometer vs BSEngOut_NOx @ Analysis Dataset;

Table7 shows the deterioration function (linear) of the corrected engine out NOx mass flow (g/h) and engine out NOx brake specific emission (g/kW.h).

Compared to T**able 6**, the deterioration factor (@254,622 km) of engine out NOx was 0.004

higher than that in **Table 6**, the deterioration factor (@700,000 km) of engine out NOx was 0.011 higher than that in **Table 6**. Generally, the different between the deterioration factor in **Table 6** and **Table7** was less than 1.1%.

So, we can conclude that the method used in this paper and the formula (**Equation 18**) for NOx correction for ambient air temperature and humidity were suitable for on-board sensors and could be used for the deterioration analysis for the in-use vehicle engine out NOx emission.

Table 7 The deterioration information for engine out NOx@ Analysis Dataset

		Eng_Out NOx [g/h]	Eng_Out NOx [g/kW.h]
Deterioration Equation	k	2.805E-05	1.489E-07
	b	1403.9	7.449
Odometer [km]	0	1403.9	7.449
	254,622	1411.1	7.487
	700,000	1423.6	7.553
Deterioration Factor (DF) @254,622 km		1.005	1.005
Deterioration Factor (DF) @700,000 km		1.014	1.014

5. Conclusion and Outlook

This study had analyzed the deterioration of the engine out NOx by using 254,622km durability test data and big data approach for the tested vehicle. Then, within the odometer that no engine out NOx deterioration had happened, we had completed the NOx correction for ambient temperature and humidity for NOx sensor. The main conclusions of our present study can be summarized to the following:

- After 254,622km durability test, the deterioration factor of engine out NOx is about 1.005, which basically indicated that the engine out NOx emission was not deteriorated.
- According to the deterioration function of the engine out NOx, we forecasted that the deterioration factor of engine out NOx would be 1.014 at the end of the useful life (700,000km) of the tested vehicle. That meant engine out NOx would not be deteriorated during the useful life or even longer.
- The engine out NOx concentration (ppm) would be affected by absolute humidity and ambient temperature. But, different range of absolute humidity or ambient temperature would have different effects on engine out NOx concentration (ppm).
- For a steady working condition, engine out NOx mass flow (g/h) had a good negative linear relationship with Ha (R^2= 0.997).
- The formula for NOx correction for ambient air temperature and humidity based on on-board sensors can be used for the deterioration analysis of the in-use vehicle engine out NOx emission.

In this work, we had only analyzed the working condition with maximum weight of the tested vehicle. Moreover, the ambient air temperature and humidity can merely represent the environmental conditions in Southeast China. As for other areas in China, the k and b in **Equation 18** for calculating $K_{h,d}$ may be not suitable, it need to be proved. Future studies should focus on the applicability of k and b for different environmental conditions.

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Availability of data and material

The datasets used during the current study are available from the corresponding author on reasonable request.

Competing interests

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.

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Authors' contributions

Peng Li: Conceptualization, Methodology, Formal analysis, Investigation, Data Curation, Writing - Original Draft, Visualization

Lin Lü: Conceptualization, Methodology, Investigation, Resources, Writing - Review & Editing, Supervision, Project administration, Funding acquisition

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Zhang, Y., et al., **2018**. Experimental study on the durability of biodiesel-powered engine equipped with a diesel oxidation catalyst and a selective catalytic reduction system. Energy. 159, 1024-1034.

Figures

Figure 1

(a) Tested vehicle; (b) aftertreatment configuration (picture of real products); (c) NOx sensors location and aftertreatment configuration (schematic plot).

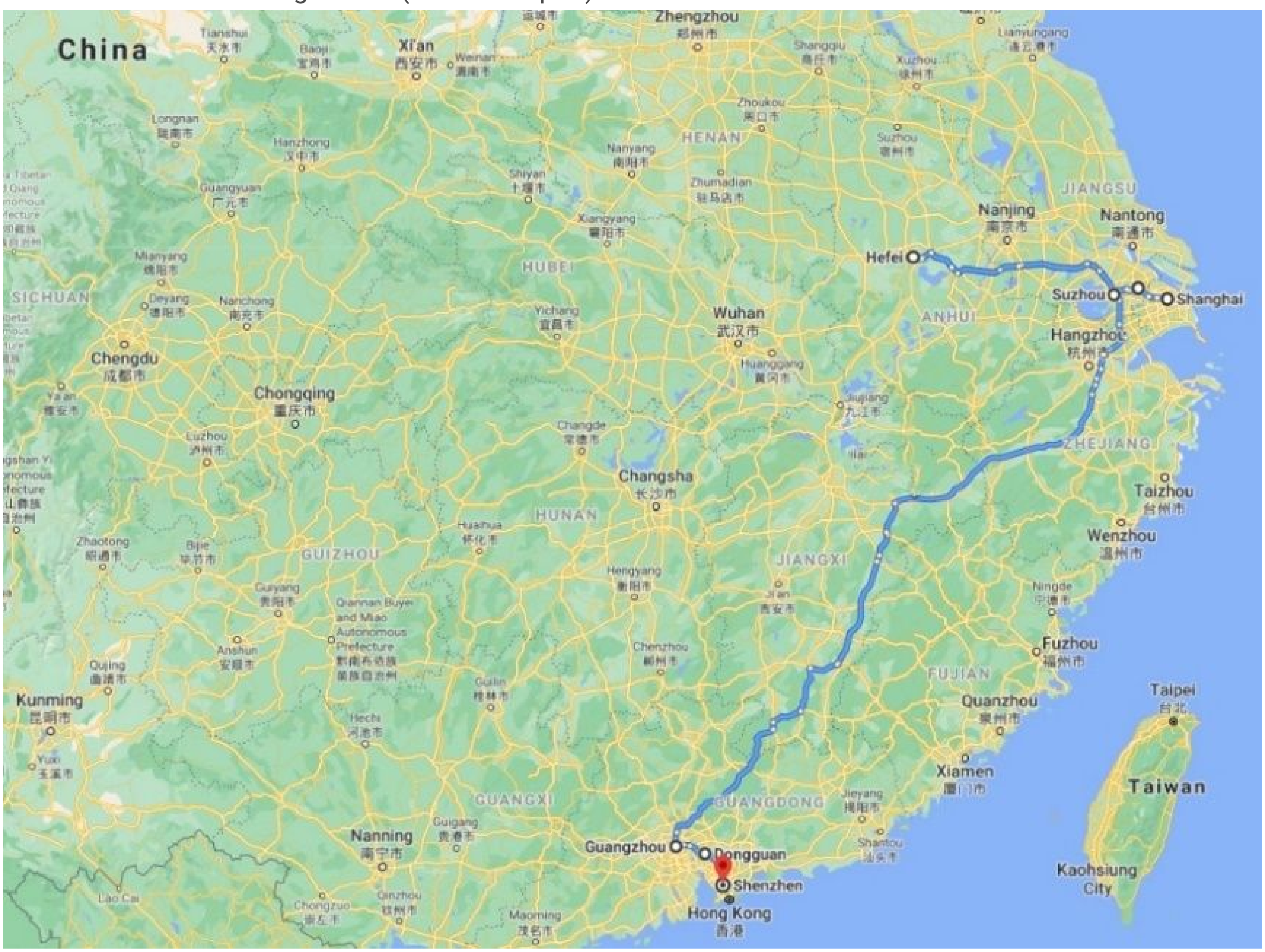


Figure 2

The main operating route of the tested vehicle Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

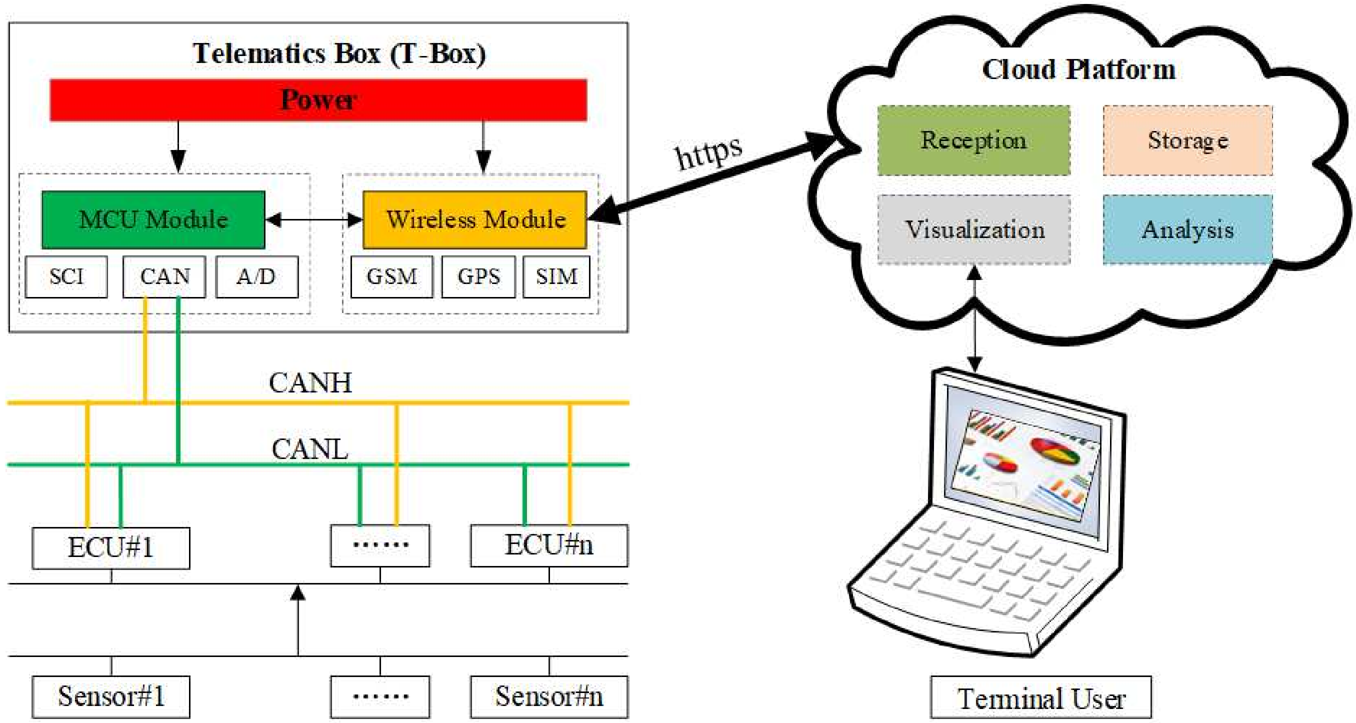


Figure 3

Data Acquisition System (schematic plot)

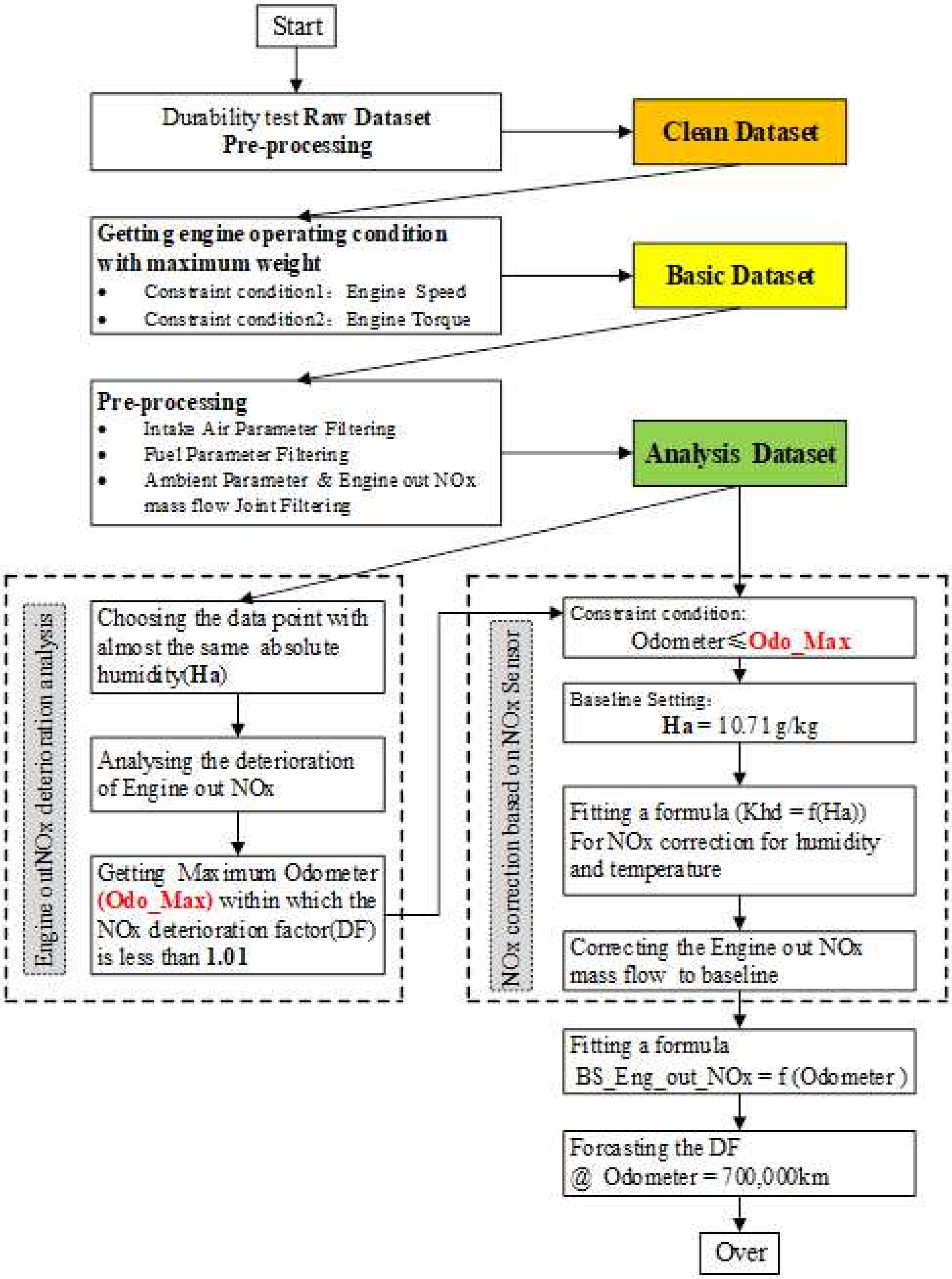
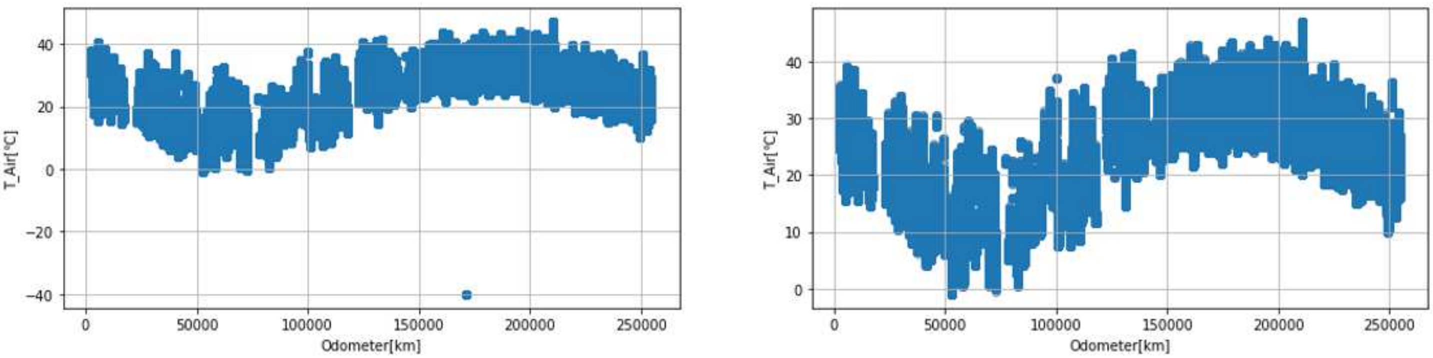


Figure 4

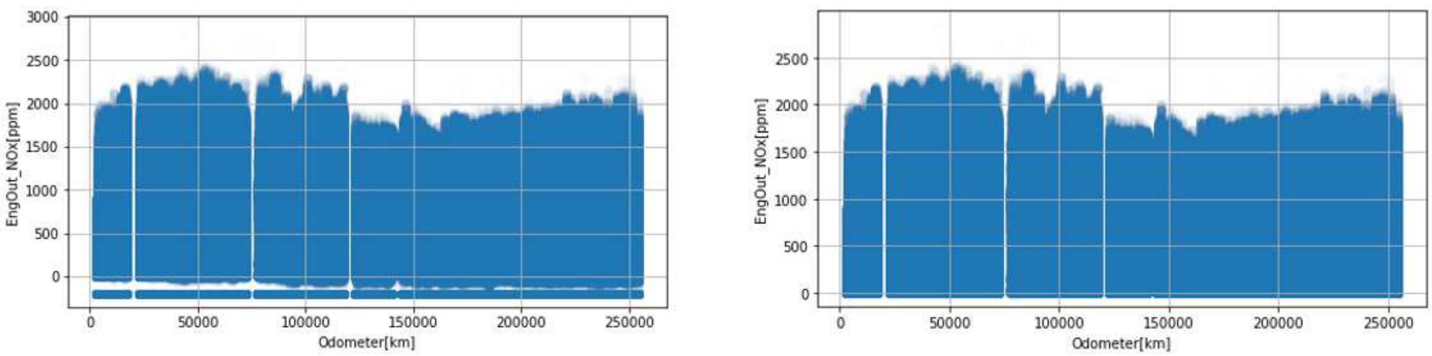
Method of engine out NOx deterioration analysis



(a) Before preprocessing (b) After preprocessing

Figure 5

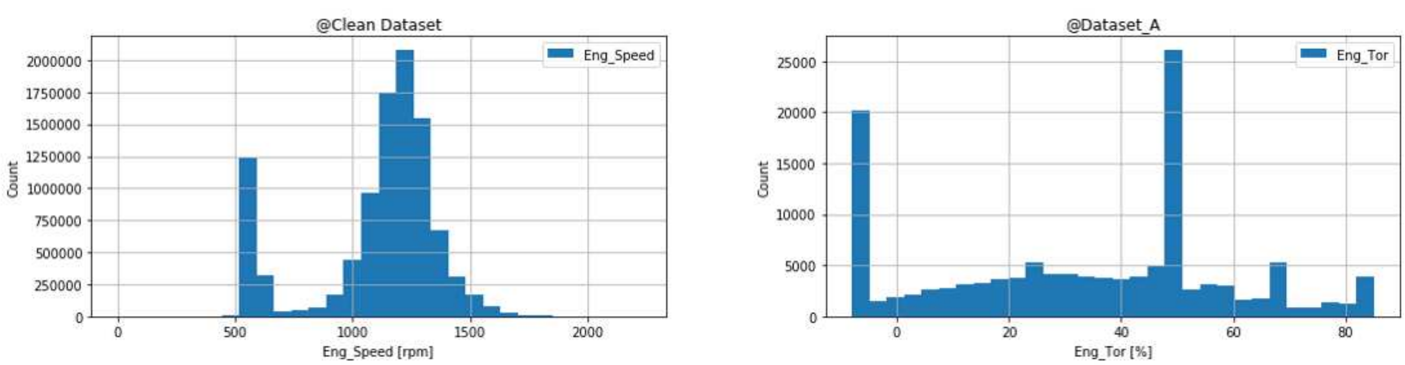
Method of engine out NOx deterioration analysis



(a) Before preprocessing (b) After preprocessing

Figure 6

Demo for unmodifiable outliers preprocessing



(a) (b)

Figure 7

(a) Eng_Speed distribution @ Clean Dataset; (b) Eng_Tor distribution @ Dataset_A

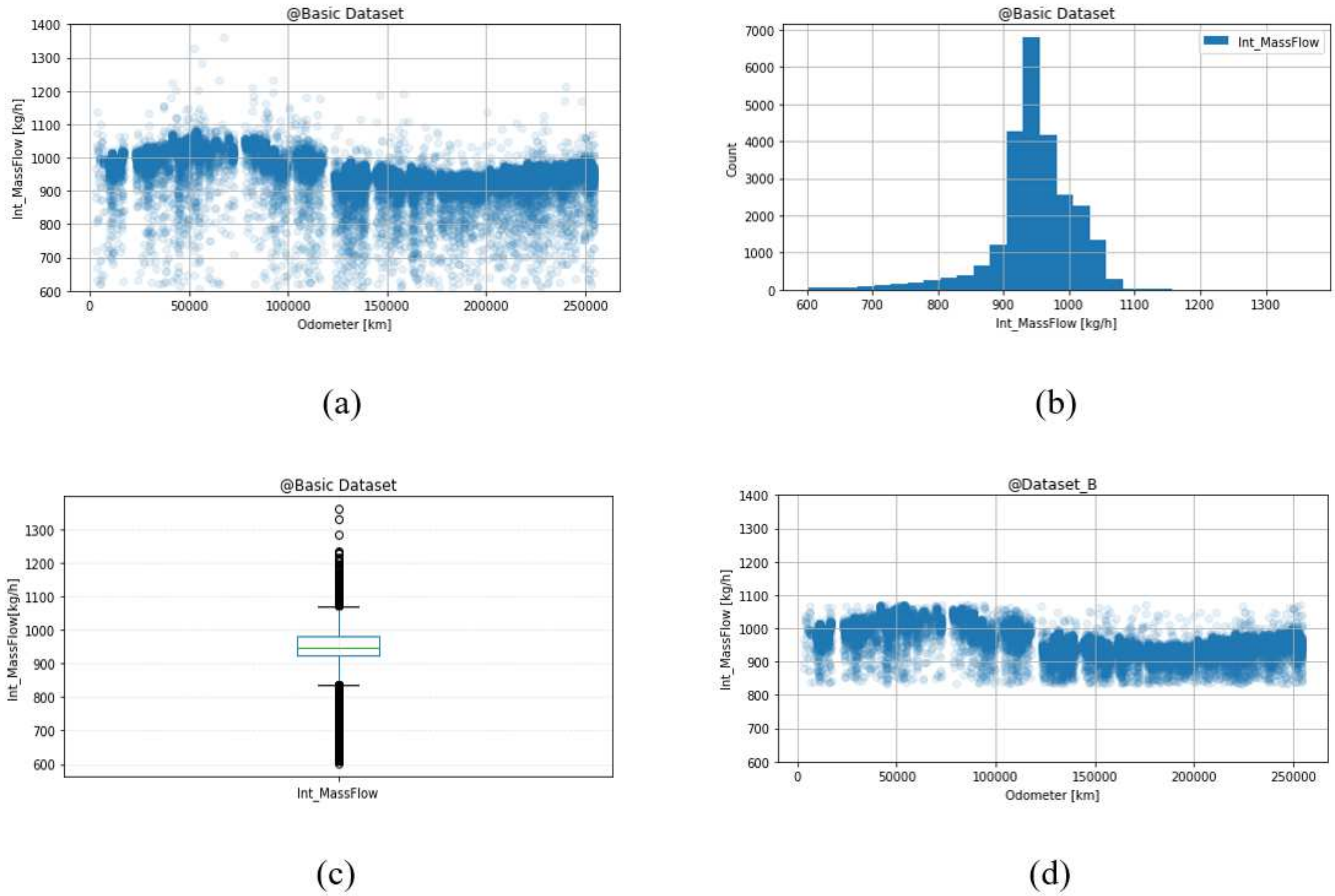


Figure 8

Intake air parameter filtering. (a) Int_MassFlow vs odometer @ Basic Dataset; (b) Int_MassFlow frequency distribution @ Basic Dataset; (c) Int_MassFlow box-plot @ Basic Dataset; (d) Int_MassFlow vs odometer @ Dataset_B;

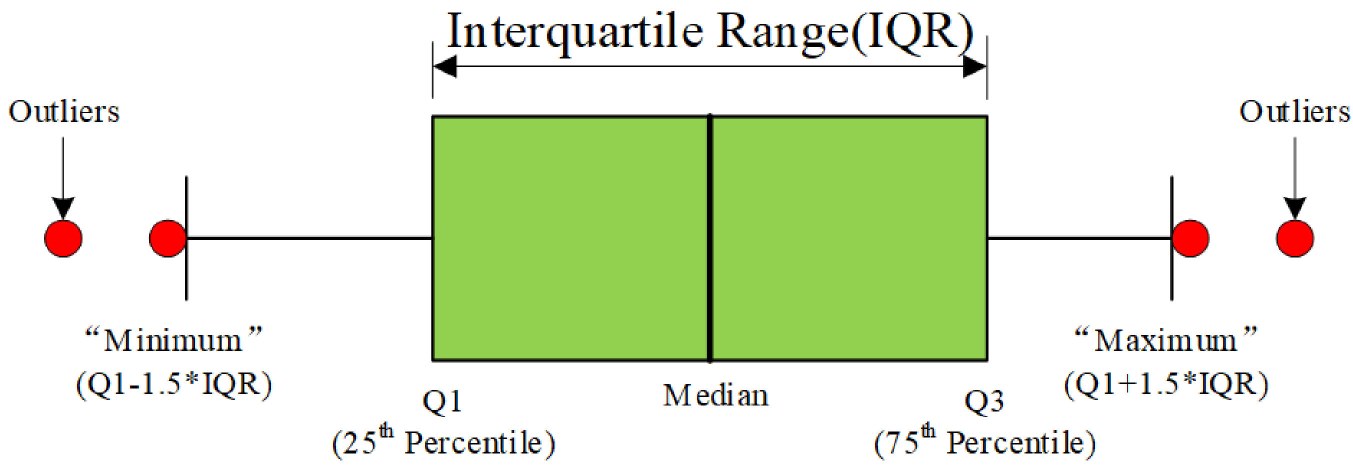


Figure 9

IQR (box-plot) filtering schematic plot

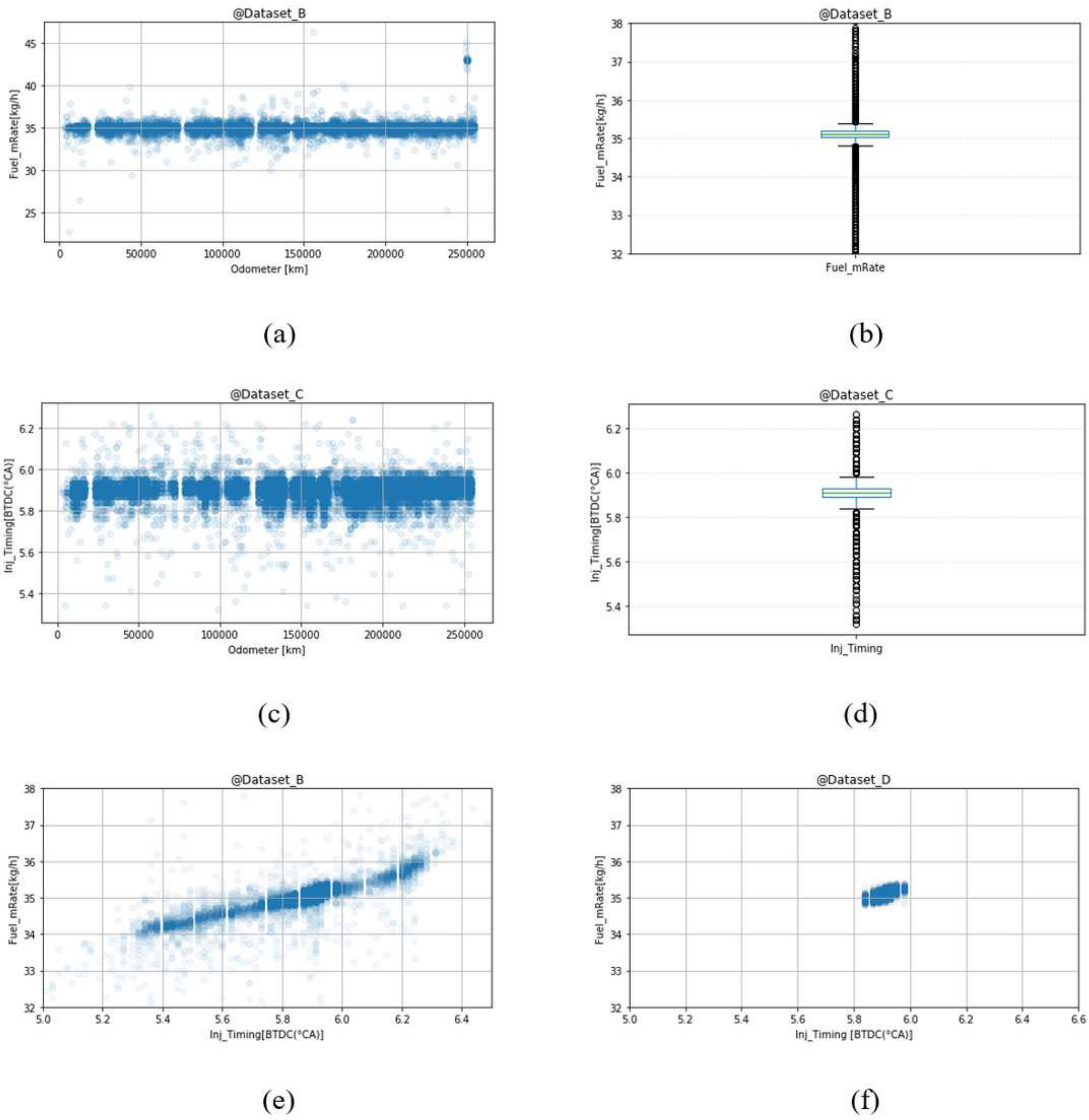
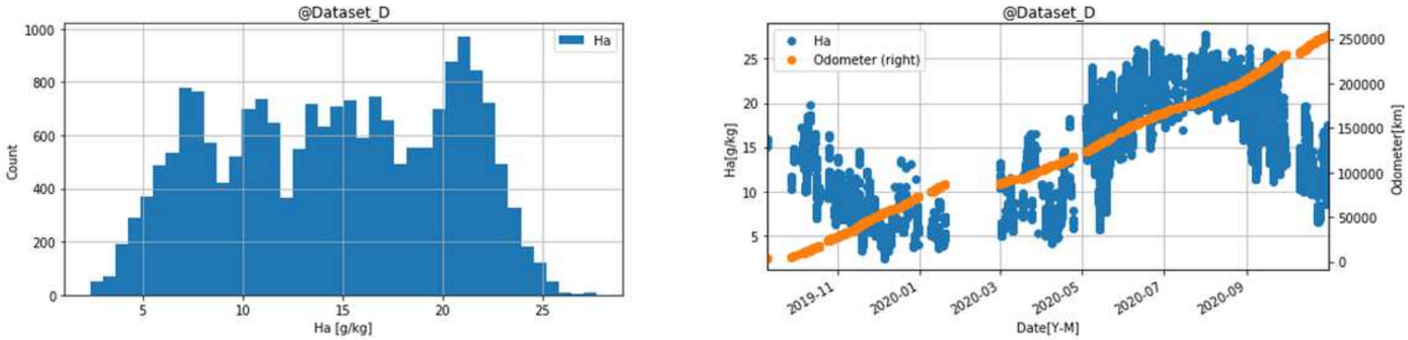


Figure 10

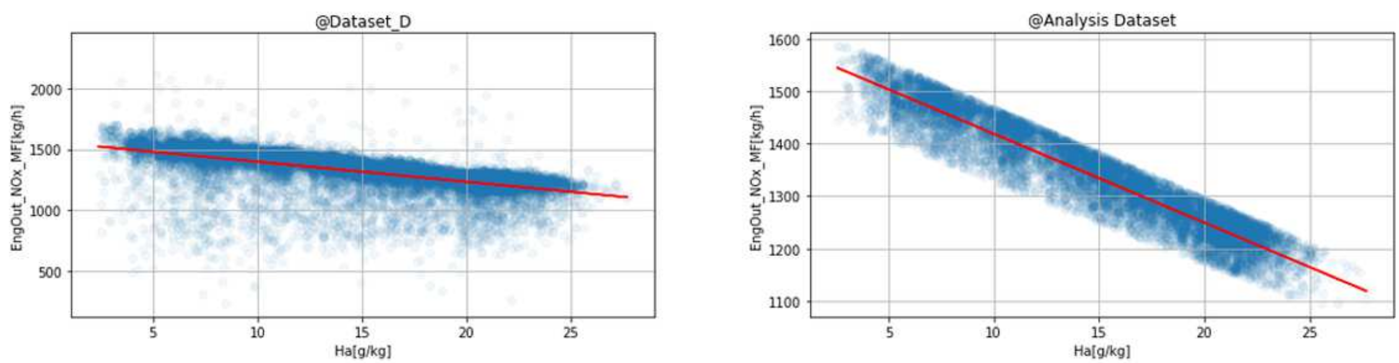
Fuel injection parameters filtering (a) Fuel_mRate vs odometer @ Dataset_B; (b) Fuel_mRate box-plot @ Dataset_B; (c) Inj_Timing vs odometer @ Dataset_C; (d) Inj_Timing box-plot @ Dataset_C ; (e) Inj_Timing vs Fuel_mRate @ Dataset_B; (f) Inj_Timing vs Fuel_mRate @ Dataset_D;



(a) (b)

Figure 11

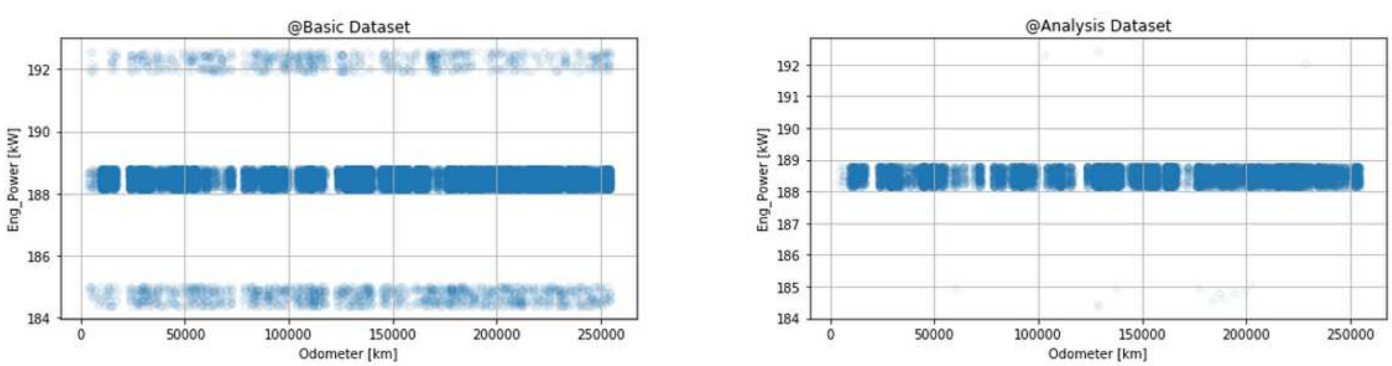
(a) Ha distribution@ Dataset_D; (b) Ha & odometer vs Date @ Dataset_D



(a) (b)

Figure 12

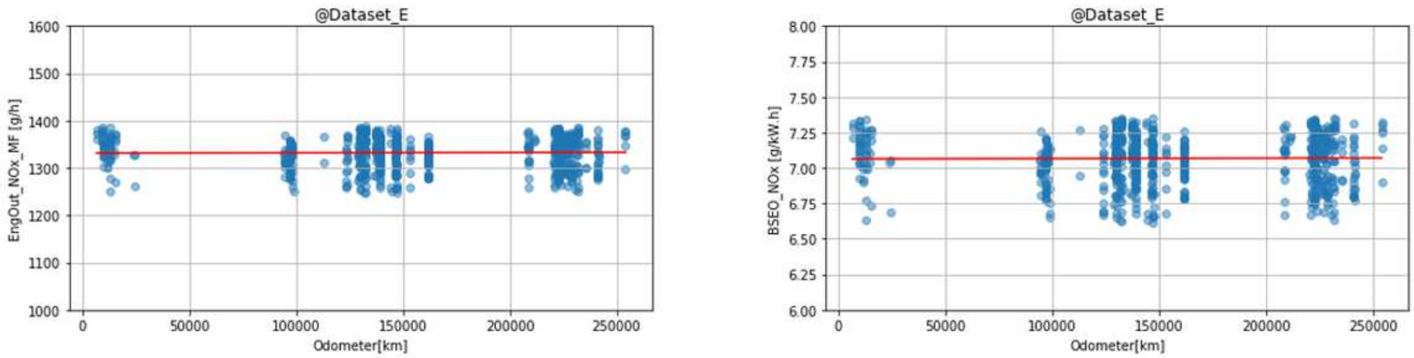
Ambient parameters and engine out NOx mass flow joint filtering; (a) Ha vs EngOut_NOx_MF@ Dataset_D; (b) Ha vs EngOut_NOx_MF@ Analysis Dataset;



(a) (b)

Figure 13

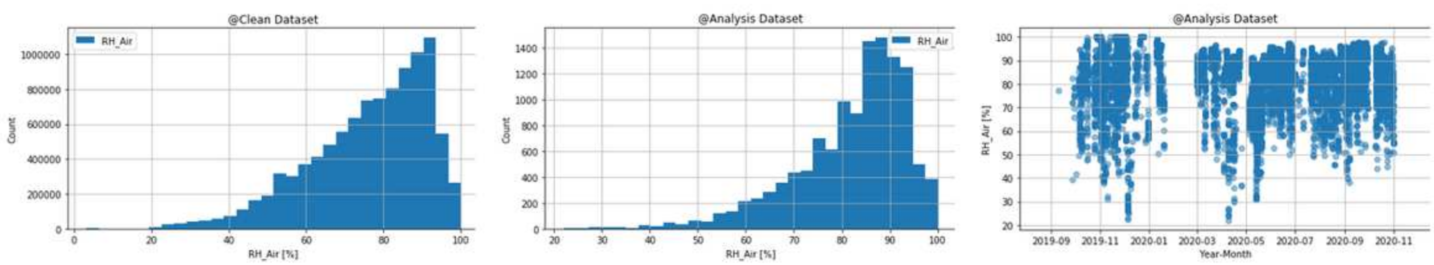
(a) Eng_Power vs Odometer @ Basic Dataset; (b) Eng_Power vs Odometer@ Analysis Dataset;



(a) (b)

Figure 14

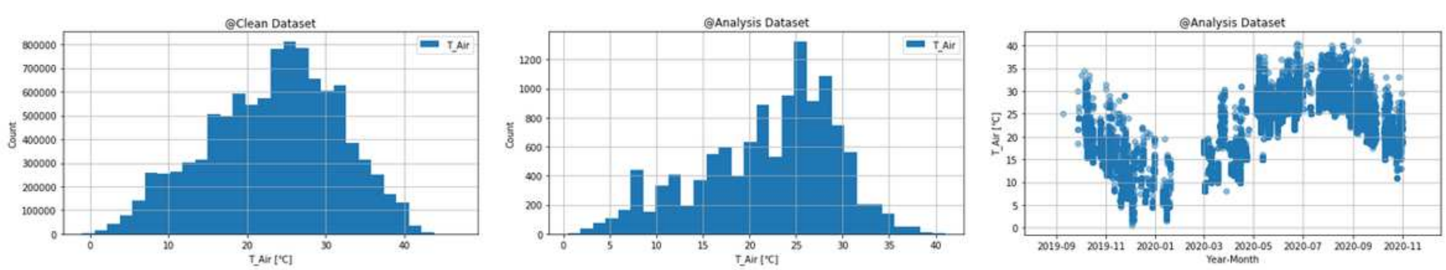
(a) EngOut_NOx_MF vs Odometer @ Dataset_E; (b) BSEngOut_NOx vs Odometer@ Dataset_E;



(a) (b) (c)

Figure 15

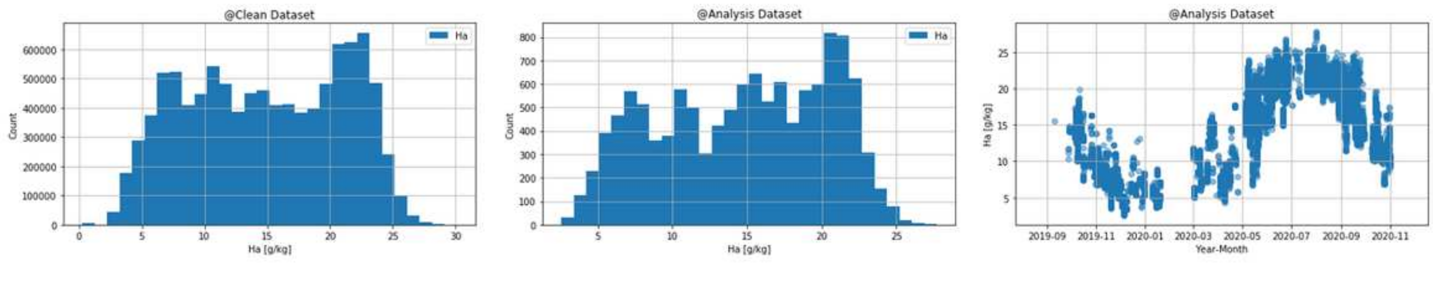
(a) RH_Air distribution @Clean Dataset; (b) RH_Air distribution @Analysis Dataset; (c) RH_Air vs Date @ Analysis Dataset



(a) (b) (c)

Figure 16

(a) T_Air distribution @Clean Dataset; (b) T_Air distribution @Analysis Dataset; (c) T_Air vs Date @ Analysis Dataset



(a) (b) (c)

Figure 17

(a) Ha distribution @Clean Dataset; (b) Ha distribution @Analysis Dataset; (c) Ha vs Date @ Analysis Dataset

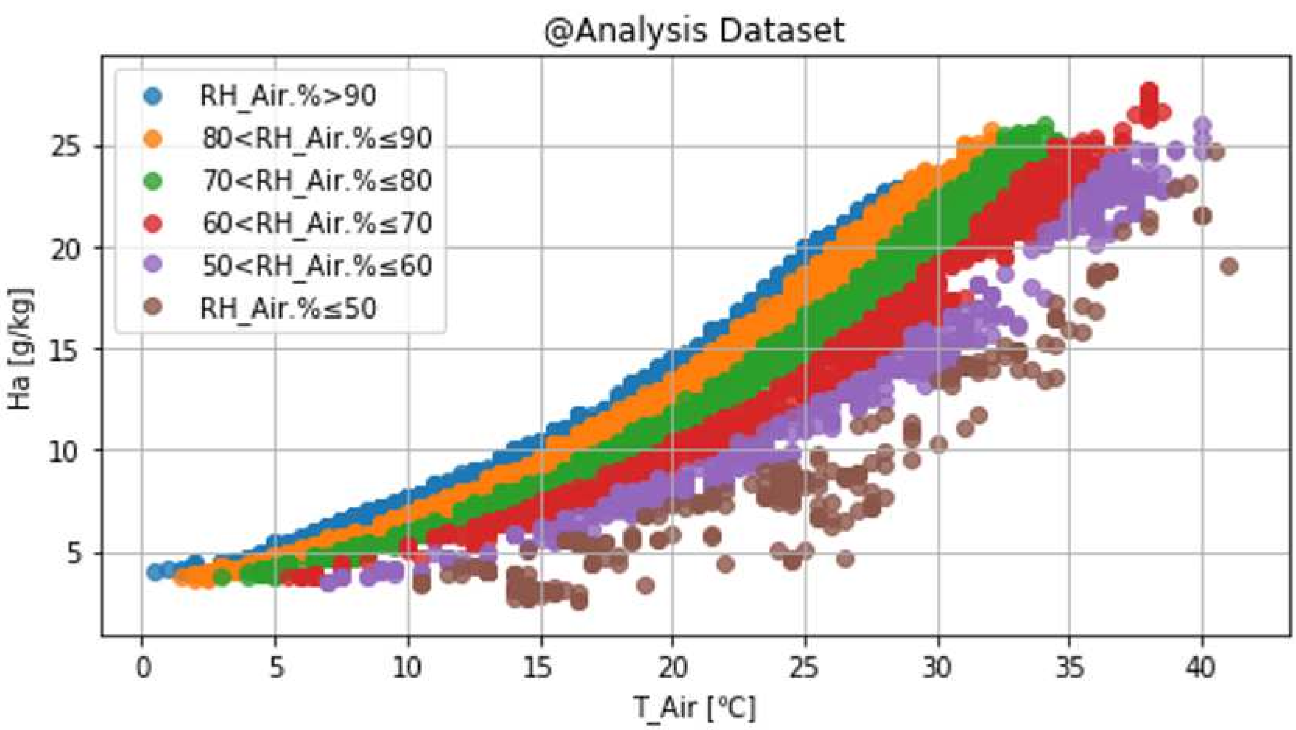
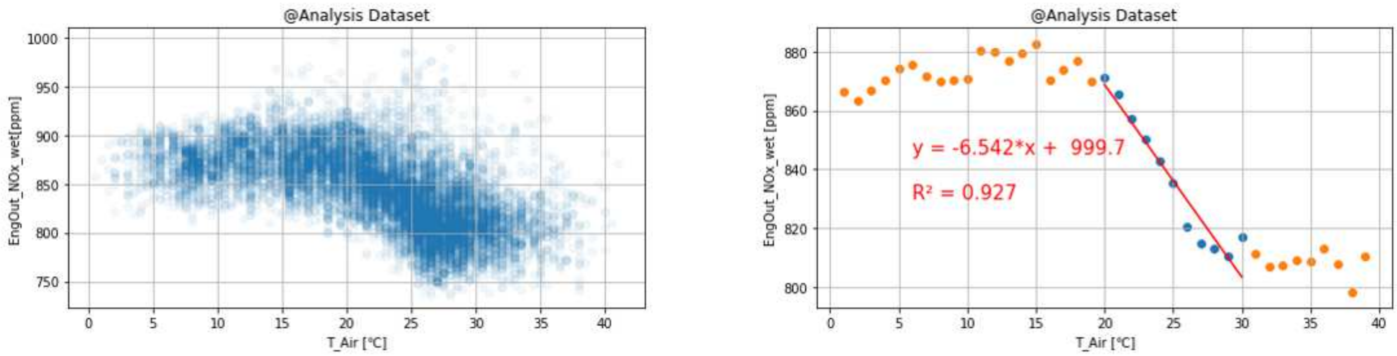


Figure 18

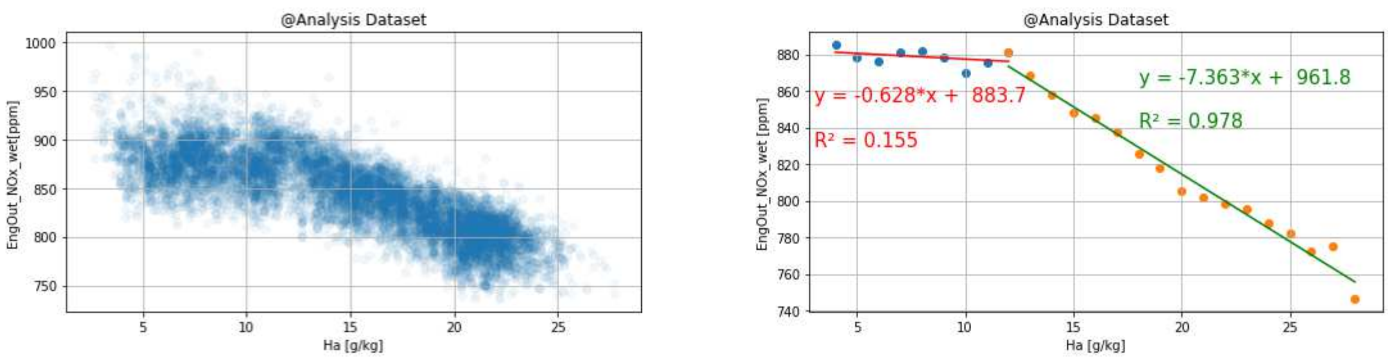
The relationship between Ha and ambient temperature/relative humidity



(a) (b)

Figure 19

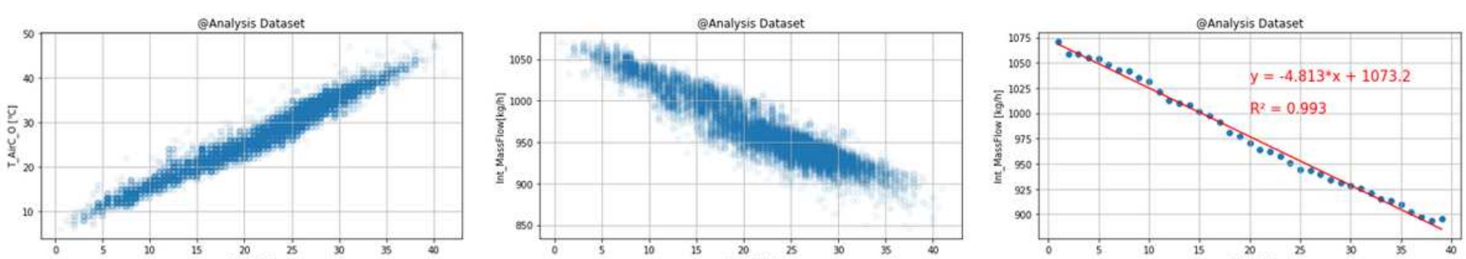
(a) T_Air vs EngOut_NOx_wet @ Analysis Dataset; (b) T_Air vs EngOut_NOx_wet (mean) @ Analysis Dataset;



(a) (b)

Figure 20

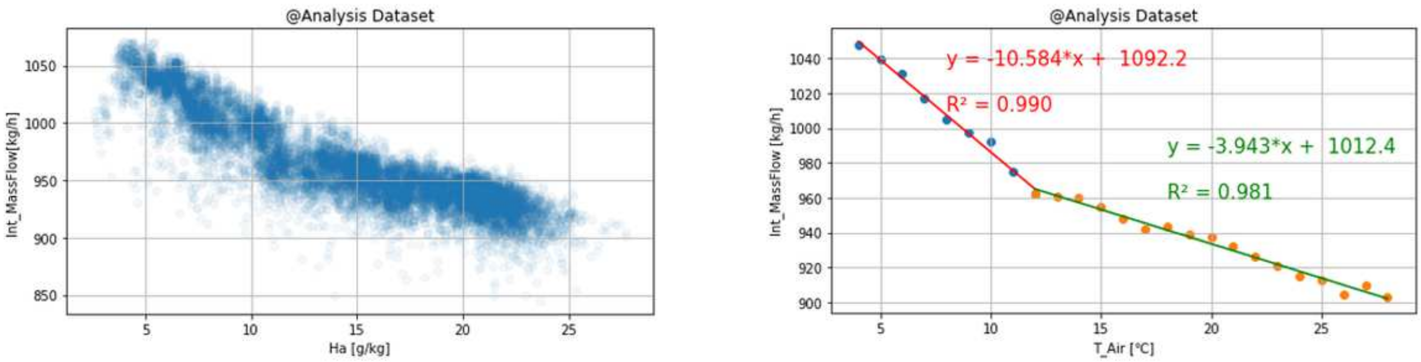
(a) T_Air vs EngOut_NOx_wet @ Analysis Dataset; (b) T_Air vs EngOut_NOx_wet (mean) @ Analysis Dataset;



(a) (b) (c)

Figure 21

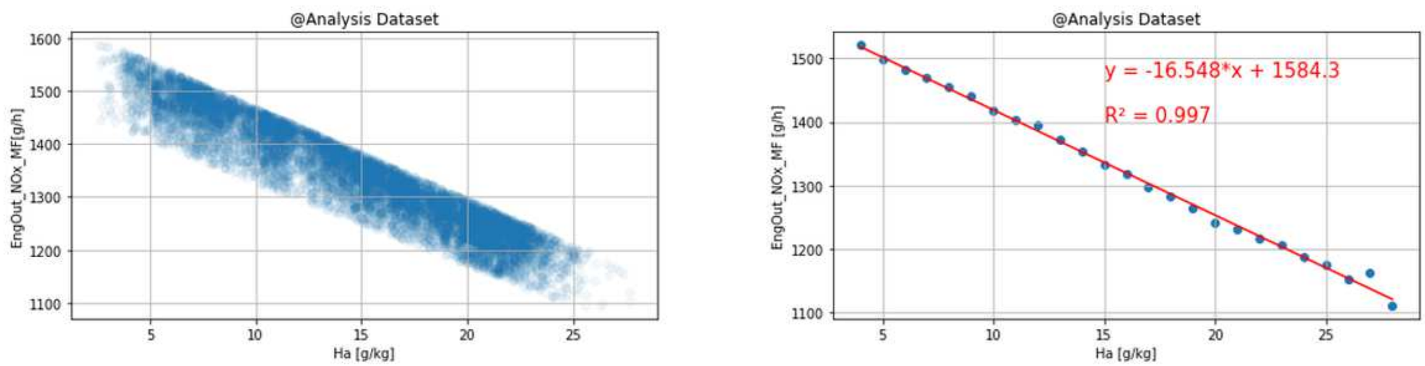
(a) T_Air vs T_AirC_O @ Analysis Dataset; (b) T_Air vs Int_MassFlow @ Analysis Dataset; (c) T_Air vs Int_MassFlow (mean) @ Analysis Dataset



(a) (b)

Figure 22

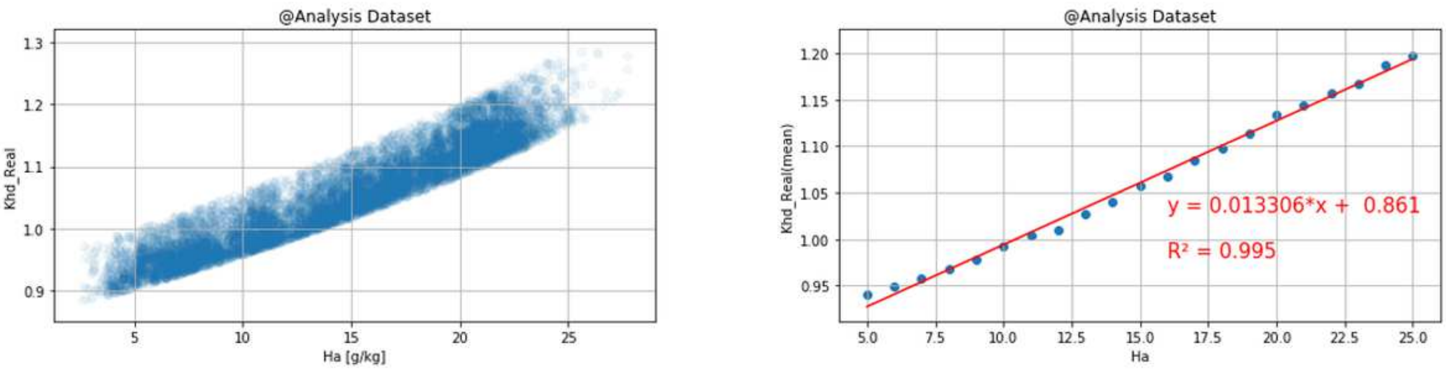
(a) Ha vs Int_MassFlow @ Analysis Dataset; (b) Ha vs Int_MassFlow (mean) @ Analysis Dataset.



(a) (b)

Figure 23

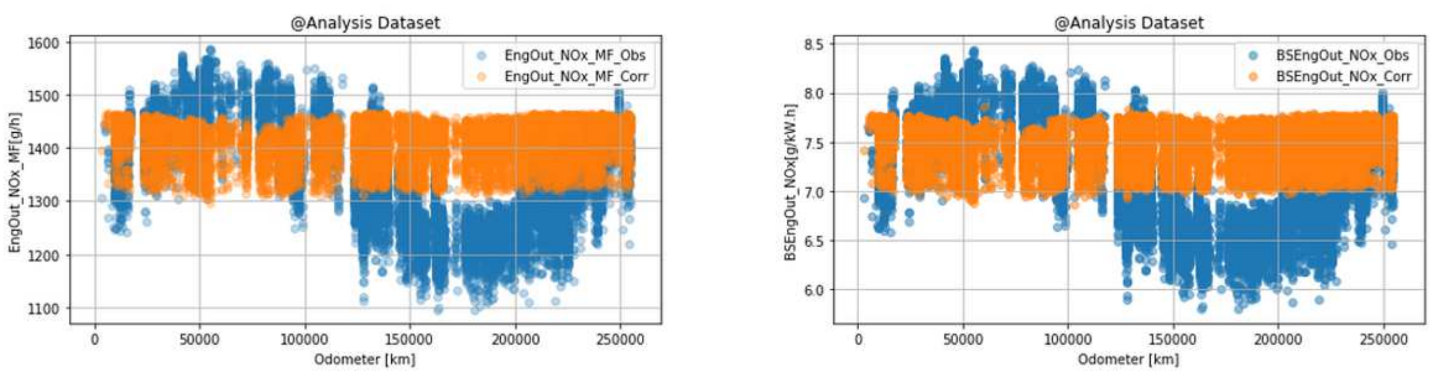
(a) Ha vs EngOut_NOx_MF@ Analysis Dataset; (b) Ha vs EngOut_NOx_MF (mean) @ Analysis Dataset;



(a) (b)

Figure 24

(a) Ha vs Kh,d_Real @ Analysis Dataset; (b) Ha vs Kh,d_Real (mean) @ Analysis Dataset;



(a) (b)

Figure 25

(a) Odometer vs EngOut_NOx_MF @ Analysis Dataset; (b) Odometer vs BSEngOut_NOx @ Analysis Dataset;