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Fuel consumption and exhaust emissions of diesel vehicles in worldwide harmonized light vehicles test cycles and their sensitivities to eco-driving factors

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Abstract: Large amounts of fossil fuels are consumed by motor vehicles annually, and hazardous exhaust emissions from the motor vehicles have caused serious problems to environment and human health. Eco-driving can effectively improve the fuel economy and decrease the exhaust emissions, which makes it vital to analyze the fuel consumption and exhaust emissions at given driving cycle, and investigate their sensitivities to eco-driving factors. In this paper, the fuel consumption and exhaust emissions of a Euro-6 compliant light-duty diesel vehicle were tested in Worldwide Harmonized Light Vehicles Test Cycles on a chassis dynamometer; further, the sensitivities of the eco-driving factors that influence the fuel economy and exhaust emissions were analyzed using validated vehicle model. For the vehicle model simulation, the effect of the coolant temperature on fuel consumption and exhaust emission only considered its effect on lubricating oil viscosity. The results showed that vehicle acceleration and velocity dominates the fuel consumption rates in Worldwide Harmonized Light Vehicles Test Cycles, where more than 50% of the exhaust emissions was emitted in the first 300 seconds; also, fuel economy and exhaust emission factors showed a significant dependency on the road grade, coolant temperature, vehicle velocity and mass. For the driver-controllable factors, high vehicle velocity and low road grade (via route-choice) were recommended to achieve low fuel consumption and exhaust emissions.

Keywords: Diesel vehicles; Fuel consumption; exhaust emissions; sensitivities; eco-driving factors

1. Introduction

Toxic exhaust emissions from automotive vehicles have drawn much attention due to their negative effects on human health and environment [1]; also, plenty of fossil fuel is consumed by vehicles. Hao et. al [2] investigated the energy consumption and greenhouse gas emission from passenger vehicles, and the results showed that the greenhouse gas emission from passenger vehicles accounted for ~5% of the national total carbon dioxide (CO_2) emission in 2014, and the percentage was increasing these years. Restrict CO_2 emission standard was legislated, with the purpose of achieving 95 g/km CO_2 emission factor in 2020. In addition, Worldwide Harmonized Light Vehicles Test Cycles (WLTC) were used to test the vehicle emissions in laboratory level to overcome the issues in the New European Driving Cycle (NEDC), which be consisted of four repeated urban driving cycles (UDC) and one Extra-Urban driving cycle (EUDC) [3]. The WLTC for a class 3 vehicle (power/weight ratio >34) was divided in four parts based on vehicle velocity, such as low, medium, high, and extra-high vehicle velocity, which represented real world vehicle operations on urban and extra-urban roads, motorways, and freeways, respectively. As shown in reference [4], NEDC was far from the real driving due to its low acceleration, constant cruising velocity and many idle events. The fuel consumption produced under NEDC was 12%~30% lower than the real driving conditions [5], and the differences of the CO_2 emission between NEDC and WLTC ranged from 4.7 g/km to 29.2 g/km by testing 20 vehicles [3]. In addition, the cold start CO_2 emission in WLTC was ~14% higher than that of NEDC [6]. Ko et.al [7] compared the nitrogen oxide (NO_x) emission characteristics of a Euro 6-compliant diesel passenger car over NEDC and WLTC. The results showed that the NO_x conversion rate was higher for NEDC than that of WLTC due to better thermal conditions. The implementations of WLTC resulted of a huge challenge for diesel vehicle emission control, especially for NO_x emission. As indicated in reference [8], diesel cars for sale in Korea were selected, and the exhaust was tested under WLTC, NO_x emission from part of the vehicles exceeded Euro 6 limitation although lean NO_x trap (LNT) after-treatment was installed on the vehicles.

Exhaust emissions and fuel consumption decreased greatly after adopting advanced technologies in engine levels, Table 1 summarizes the technologies decreasing engine emissions and fuel consumption. Meantime, they were further improved in vehicle level by improving maneuvers [9], adopting lightweight materials [10], and optimizing vehicle bodies [11]. Reference [12] reviewed the catalyst thermal management during engine cold start and warm up to decrease the exhaust emissions and drop fuel penalty. Biodiesel fuel [13] was a practical approach to decrease the exhaust emissions due to its higher oxygen and lower sulphur content, also, it alleviated the dependence of the automotive market on the fossil fuels. Organic Rankine cycle (ORC) [14] was an effective method to enhance the overall thermal efficiency by recycling the waste heat from exhaust and coolant, and the maximum heat recovery efficiency was 8.5%; the energy power output increased by 10.63% in reference [15]. Electric pumps of coolant [16] and lubricating oil [17] were used to increase the coolant and oil temperature aiming at dropping the friction loss caused by the huge oil viscosity. As tested by Chanfreau et al. [18], it reduced 2%~5% fuel consumption, 10% tailpipe hydrocarbon (HC) and 20% carbon monoxide (CO) emissions by increasing the coolant temperature from 90 °C to 110 °C. The smoke emission also reduced drastically from 1.14 Filter Smoke Number (FSN) to 0.068 FSN when the coolant temperature increased from 45 °C to 90 °C [19], which implied that fuel films may be a major source of PM emission under cold operating conditions. Mohammad et.al [20] showed that ~25% energy was lost in lubricating oil under −20 °C atmosphere temperature, which directly resulted from high viscosity.

Table 1 Technologies used for decreasing exhaust emissions and fuel consumption in engine levels

Technologies	Ref.
Emulsion + anti-oxidant additive	Ref. [21]
High-pressure methanol steam reforming	Ref. [22]
Fuel injection strategies	Ref. [23]
Non-thermal plasma	Ref. [24]
Emulsion of nerium oleander biofuel	Ref. [25]
Spark timing	Ref. [26]
Catalyst thermal management	Ref. [12]

Organic rankine cycle	Ref. [27]
Double swirl combustion system	Ref. [28]
Fuel injection timing	Ref. [29]
Cerium oxide nano additive	Ref. [30]
Diesel oxidation catalyst (DOC)	Ref. [31]
High pressure common rail	Ref. [32]
Turbocharger	Ref. [33]
Diesel particulate matter (DPF)	Ref. [34]
Diesel + water + surfactant	Ref. [35]
Selective catalytic reduction (SCR)	Ref. [36]

Although the technologies in engine and vehicle levels had improved significantly for reducing the fuel consumption and emissions, the fuel economy and exhaust emission factors of the vehicles were greatly dependant on drivers, weather, road and traffic conditions. The further improvement of the fuel economy and exhaust emissions should be focused on eco-driving, from the points of the driver behaviors and route-choice, which were human-controllable factors. Reference [37] showed that the vehicles should be avoided the frequent acceleration and deceleration to enhance the fuel economy. Mensing et. al [38] optimized the vehicle trajectories for eco-driving, and the potential gains in fuel economy were discussed. The theory improvement of the fuel economy was ~34% for a free flow urban setting in eco-driving, while the value decreased by 16%~54% after considering the safe driving. In addition, 47% fuel consumption drop was achieved by predicting the cruise control after driving through a sequence of 9 traffic lights to avoid long time stops at the traffic lights [39]. While the technology needed the communications between the vehicles and traffic lights, meantime, safe following distance should be ensured. Saboohi et. al [40] also performed the eco-driving by adjusting the vehicle speed and gear shift timing, from which the potential of fuel saving was ~1.5L/100 km. In eco-driving, drivers also played an extremely important effect on fuel economy and exhaust emissions, which made driver trainings an necessity. In reference [41], 203 drivers were monitored in a real world setting of Australia after five training interventions that 4.6% fuel consumption drop was achieved compared with pre-training. Wang et. al [42] quantitatively investigated the effects of vehicle parameters on fuel consumption of a heavy-duty vehicle. The fuel consumption decreased by 8% when the vehicle weight decreased by 20% at given conditions. Meantime, 10% aerodynamic drag reduction had an effect of reducing 7% rolling resistance reduction, and it was indicated that it may be more cost effective to reduce aerodynamic drag coefficient or rolling resistance coefficient to reduce fuel consumption. It was shown by the reference [43] that the rolling resistance accounted for up to 20% of fuel consumption from cars, and 30%~40% from trucks. Also, 10% reduction in rolling resistance for passenger cars would brought about 1%~2% improvement for fuel economy.

Eco-driving could effectively decrease the fuel consumption, however, to the authors' knowledge, majority of the eco-driving investigations were only focused on improving the vehicle fuel economy or decreasing exhaust emissions. In fact, the eco-driving included both the fuel economy improvement and exhaust emission decrease; a compromise should be made in some cases. In this paper, exhaust emissions and fuel consumption rates of a diesel vehicle were tested in WLTC through chassis dynamometers. Meantime, the sensitivities of the fuel economy and exhaust emission factors to the eco-driving factors were investigated, e.g. drag coefficient, road grade, wind velocity, gear shift perfection, coolant temperature, rolling resistance coefficient, vehicle velocity and mass. Further, the principles for eco-driving were given, taken the fuel economy and emission factors into consideration.

2. Materials and Methods

Table 2 shows the specifications of the tested diesel vehicle, whose power was a four cylinder, turbocharged, direct injection engine. The max power output and torque were 103 kW and 325 N·m, respectively. The test of fuel consumption and exhaust emissions in WLTC was based on the chassis dynamometer experiments. The sensitivity analysis of the eco-driving factors to the fuel economy and exhaust emission factors were conducted using the validated diesel vehicle model.

Table 2 Specifications of the diesel vehicle

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

2.1 Experimental section

The demonstrated vehicle was tested in a temperature and humidity controllable atmosphere after being soaked for at least 12 hours over WLTC. Regular emissions (CO, HC, NO$_x$, and soot) were measured using a constant volume sampling system connecting with a emission analyzer (HORIBA MEXA-7000). The performances of the engine, e.g. brake specific fuel consumption (BSFC), gaseous and soot emissions *vs*. engine speed and load which were basic input parameters of the diesel vehicle model, were tested in a engine test bench.

2.2 Simulation section

The diesel vehicle model was setup using a commercial software, and validated point by point over WLTC. The eco-driving factors, which were investigated in this paper, were drag coefficient, road grade, wind velocity, gear shift perfection, coolant temperature, rolling resistance coefficient, vehicle velocity and mass. The single variable method, where all the parameters were kept the same except for the target ones, was adopted to investigate the sensitivities of the target factors to the fuel economy and exhaust emission. The flowchart of the method using in the paper is shown in Figure 1.

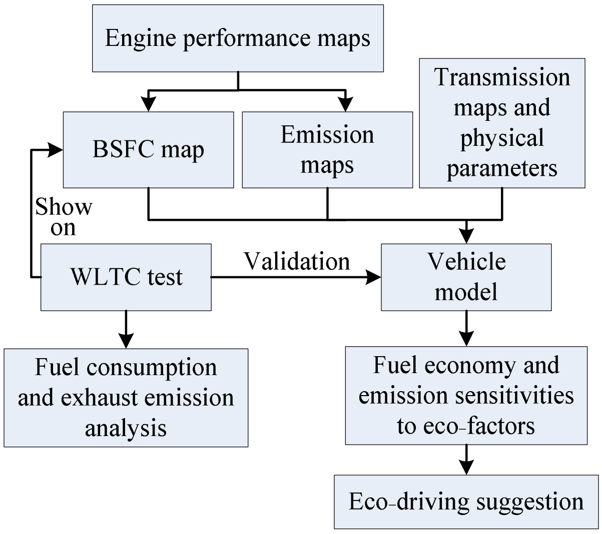

Figure 1 Flowchart of the method used in the research

3. Results and discussions

This section includes the following three parts: 1) test the fuel consumption and exhaust emissions in WLTC, where the emissions during cold start were addressed; 2) sensitivities of the fuel economy and exhaust emissions to eco-driving factors, which were investigated using simulation method; 3) the choice of vehicle operation for eco-driving, which was researched based on the results of section 3.2.

3.1 Test results of the fuel consumption and exhaust emissions

Figure 2 shows the locations of the engine operation points on BSFC map, which was obtained from the test data of the engine test bench. The minimum BSFC was ~225 $g/(kW\cdot h)^{-1}$, being in the range of 1500 RPM ~ 2500 RPM, and high engine loads. The engine operation points in WLTC were mainly located at low engine load regions, which would cause poor brake thermal efficiency in the engine level. Under the conditions of the same engine power output, shifts of the engine operation points to lower engine speed and higher engine load would result of lower fuel consumptions. However, the movement of the engine operation points was enslaved to the vehicle conditions, e.g. transmission system, vehicle velocity, road grade and cargo mass. Figure 3 shows the maps of CO, HC, NO_x, and soot emissions. The emissions were greatly dependant on the engine operation conditions, and the maximum emission concentration was thousands of times higher than the minimum value. The optimal engine points for CO and HC emissions were located in the region of medium engine speed and high engine load, however, they were under the low engine speed and load for NO_x and soot emissions. There should be some balance among different emissions in eco-driving. The NO_x emission is still a huge challenge to meet stricter emission regulations, so that more attentions should be focused on NO_x. Driver trainings were suggested to achieve the eco-driving, where the engine was avoided operating at the “red zone”.

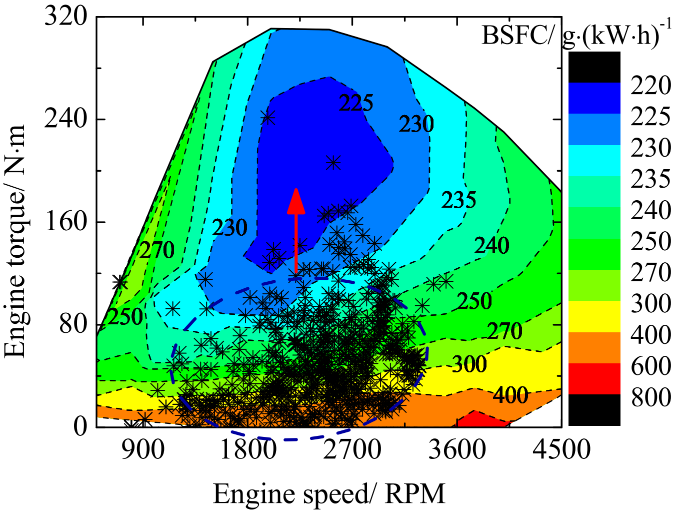

Figure 2 The locations of engine operation points on brake specific fuel consumption map

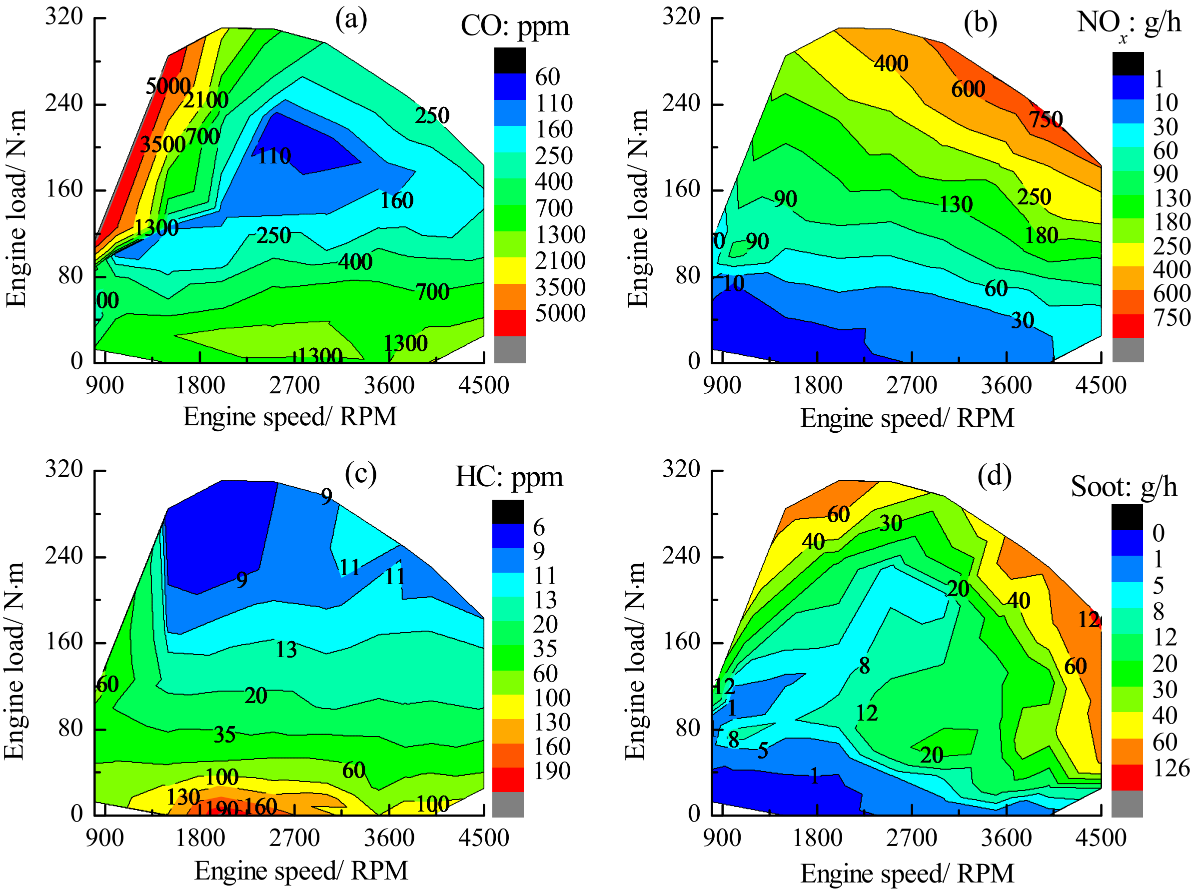

Figure 3 The emission maps of the diesel engine: (a) carbon monoxide; (b) nitrogen oxide; (c) hydrocarbon; (d) soot

Figure 4 shows the fuel consumption rate in WLTC. The fuel consumption rate was dominated by vehicle speed and acceleration. Huge fuel consumption rate was observed in extra-high vehicle speed zone, where huge aerodynamic drag caused the decrease of brake thermal efficiency. Ma et.

al [44] investigated the fuel consumption under different driving styles, that the fuel consumption in the acceleration process accounted for 56.5% of the overall fuel consumption, and the value of deceleration process was less than 5.7%. The vehicle was recommended to avoid frequent acceleration and deceleration, and to operate at medium-high vehicle velocity conditions in eco-driving, whose effort could be achieved by predicting the traffic conditions [45], training the drivers [46] and choosing the routes [47]. Additionally, the fuel consumption was at a medium level around 1300 s, caused by small vehicle acceleration despite of high vehicle velocity. The cold start and warm up process were taken into consideration in WLTC, which lowered vehicle fuel economy. The warm status of the engine could be reflected by coolant and lubricating oil temperature. Reference [48] indicated that the fuel consumption decreased by ~8% and ~14% if the lubricating oil temperature increased by 4 °C and 10 °C, respectively, in the first 6 minutes from cold start. In addition, the fuel economy improvement could research ~7% during a 22°C cold start NEDC, as indicated by Will et. al [49]. The low fuel economy was mainly caused by poor in-cylinder combustion, much heat loss and high viscosity of lubricating oil. Reference [20] indicated that the energy loss caused by viscosity reached 25% if the engine operated under −20 °C atmosphere. For the daily short distance journey, the warm up process accounted for a huge percentage of the whole duration, where the fuel economy had a huge space for improvement.

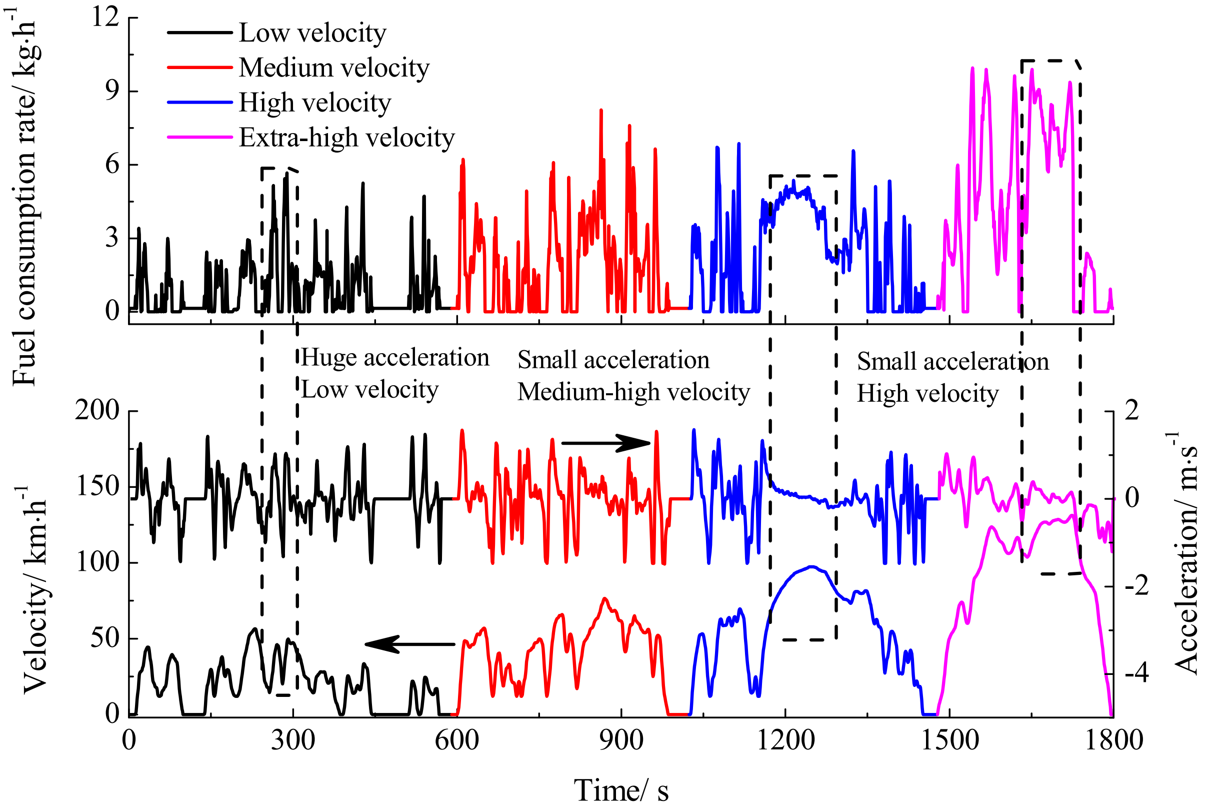

Figure 4 The fuel consumption rate in worldwide harmonized light vehicles test cycles

Figure 5 shows the pipe out gaseous exhaust emissions tested in WLTC, which included the cold start and warm up process. It should be noted that part of the points were missed for CO emission due to the use of logarithmic coordinates, where CO mass flow rate was zero, resulting from the perfect catalyst performance and fuel cut-off. The peak values in the exhaust emission profiles were mainly caused by the acceleration process. Table 3 summarizes the accumulative exhaust emissions at different periods in WLTC, and comparisons were made with other published results. The emissions of Euro 5-complaint diesel vehicle were much higher than Euro 6-complaint vehicles, among which the authors' vehicle showed the best performance. It was evident that CO, HC and NO_x flow rates in the first 300 s were hundreds of times higher than normal conditions. The maximum values reached 4 mg/s, 12 mg/s and 20 mg/s for HC, NO_x and CO, whose accumulative emissions in the first 300 s accounted for 63.2%, 55.4% and 56.05% of the total emissions in WLTC, respectively. Such high exhaust emissions were mainly caused by poor in-cylinder combustion and low catalytic efficiency of diesel oxidation catalyst (DOC) and selective catalyst reduction (SCR). The results specifically indicated that more attentions should be focused on the cold start emissions from which much lower emissions standard could be reached. In a given driving cycle, with a total duration of ~1200 s, the exhaust temperature was below the catalyst light-off value for over 200 s [50]. Up to 80% of the accumulative CO and HC emissions were emitted during this period, which was less than 20% of the total duration of the cycle [51]. Reference [12] summarized the influence of the cold start and warm up on the exhaust emissions, and potential measures to decrease emissions in the period were reviewed. After the engine and catalyst were fully warmed up, the exhaust emissions decreased significantly that the accumulative pipe out emissions were 6.3 mg and 32.1 mg for HC and CO, respectively in the range of 1600 s~1800 s, where the NO_x emission was still with a high value of 165.5 mg, which resulted from the high in-cylinder combustion temperature. In order to further decrease the pipe out emissions to meet more stricter emission regulations, many technologies [12] were employed to decrease the cold start and warm up emissions. Lower HC and CO emissions were more accessible to meet lower emission limits, however, NO_x emission was still a challenge. The reference [52] also indicated that the warm up process also induced high NH_3 emission in WLTC, and increased potentials of the secondary particulate matter (PM) emission. As for the diesel PM, the mass reduction reached 90% after using diesel particulate filter (DPF), which showed a limited dependence on the engine operation conditions. However, PM number emission, being closely related to exhaust temperature [53], was much higher for the cold start than warmed conditions, which was mainly caused by HC condensation. The detailed analysis of PM number emission will be reported in further researches.

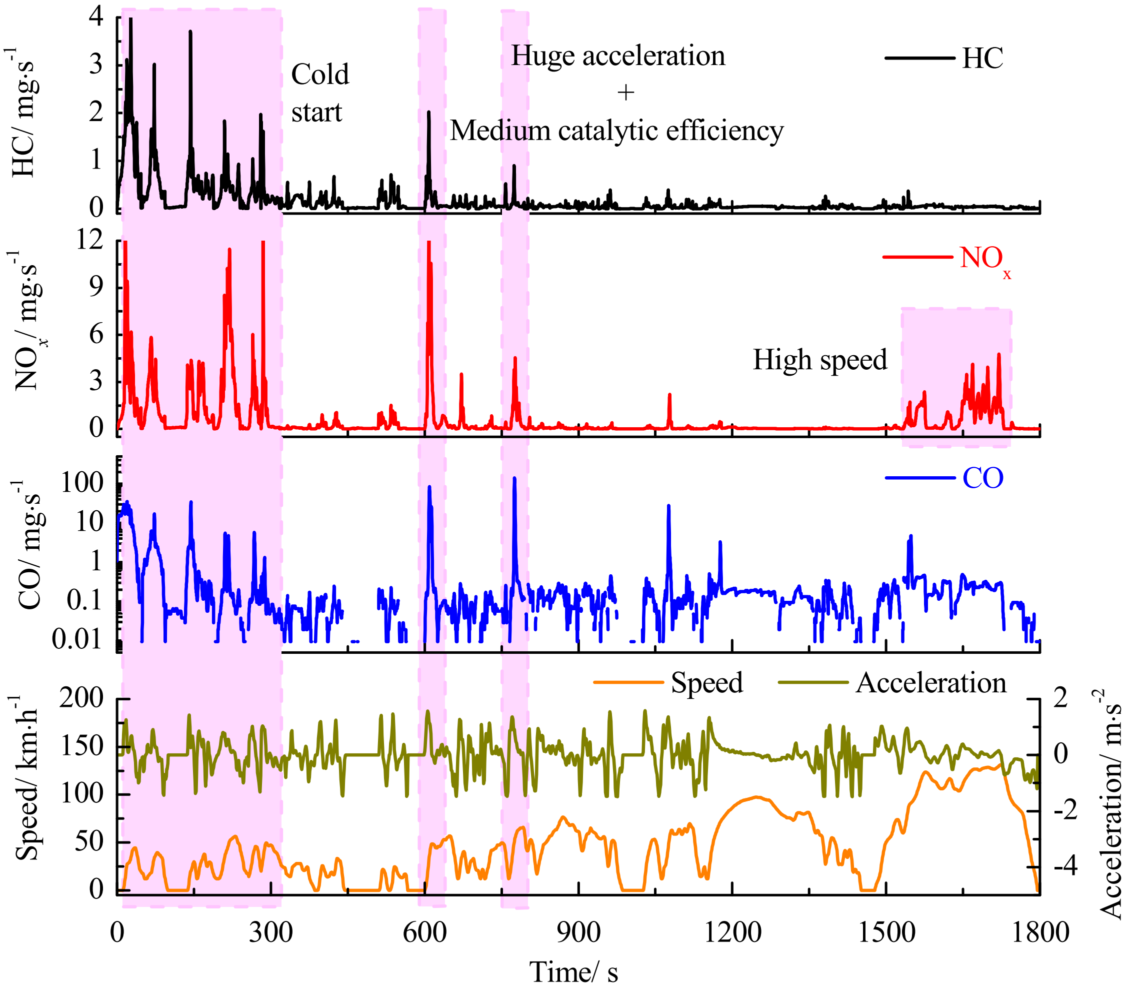

Figure 5 The diesel vehicle emissions in worldwide harmonized light vehicles test cycles

Table 3 Accumulative gaseous exhaust emissions in worldwide harmonized light vehicles test cycles

				Emission factors/ mg·km^{-1}			
	0 s ~300 s	300 s~1600 s	1600 s~1800 s	Authors' Euro 6	Ref. [54] Euro 5	Ref. [55] Euro 6	Ref. [7] Euro 6
HC/ mg	163.0	88.6	6.3	11.08	~125	~9	~50
NO_x/ mg	561.4	286.1	165.5	43.54	~63	~205	~92
CO/ mg	816.1	607.8	32.1	62.58	~405	~220	~90

3.2 Sensitivities of the fuel economy and exhaust emissions to eco-driving factors

This part of work was done by vehicle simulations under WLTC. Figure 6 shows the validations of the simulation model. The correlation (R^2) between 1800 test data and the simulation results was 0.846, which indicated the high precision of the vehicle model. Majorities of the vehicle operation points were located between the two dark lines, only a couple of points were out of the scope, which was caused by the fluctuations during testing or failing to capture the details in the driving cycle for the simulation model. Extra-high velocity points had the best correlations. The boundary conditions used to validate the vehicle model were shown in Table 4.

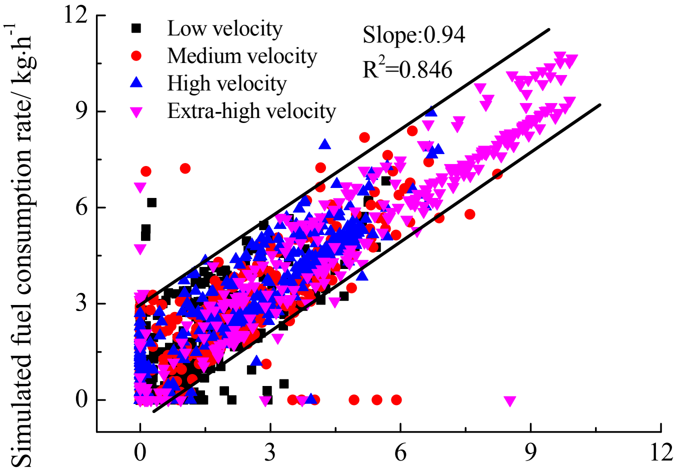

Figure 6 Simulation model validation using testing data

Table 4 The boundary conditions of the vehicle model used for the validation

Target factors	Value
Drag coefficient	0.31
Grade/ %	0
Mass/ kg	1500
Rolling resistance coefficient	0.012
Wind speed/ m·s^{-1}	0
Average vehicle speed/ m·s^{-1}	18.75
Coolant temperature/ °C	100
Gear shift perfection/ %	75

Table 5 shows the case definitions of different combinations of eco-driving factors. These values covered the commonly used ranges of daily vehicle driving. The gear shift perfection meant how much was the vehicle velocity timing, where the gear was shifted, similar to the optimal value. The single variable method was adopted that the other factors were kept the same as Table 4, except for the target ones. The boundary conditions of these cases were based on Table 4.

Table 5 The case definitions

Target factors	Factor levels			
	Level 1	Level 2	Level 3	Level 4
Drag coefficient	0.29	**0.31**	0.33	0.35
Road grade/ %	**0**	2	4	6
Mass/ kg	**1500**	2000	2500	3000
Rolling resistance coefficient	0.011	**0.012**	0.013	0.014
Wind velocity/ m·s^{-1}	**0**	3	6	9
Average vehicle velocity/ m·s^{-1}	**18.75**	39.40	56.55	91.88
Coolant temperature/ °C	40	60	80	**100**
Gear shift perfection/ %	25	50	**75**	100

Figure 7 shows the sensitivities of the targeted factors on the vehicle fuel economy. The gear shift perfection, drag coefficient, rolling resistance coefficient and wind velocity had a smaller effect on the fuel economy, meantime, the fuel economy almost linearly decreased with these values. Zaabar and Chatti [56] pointed that the effect of road roughness (related to rolling resistance coefficient) on fuel consumption increased by ~1.75 for the van, ~1.70 for articulated truck, ~1.60 for medium car, ~1.35 for sport utility vehicle, and ~1.15 for the light vehicle. The value was similar with the authors' results (light vehicle). It still made a contribution to improve the vehicle fuel economy by decreasing the tire rolling resistance despite of relative small effect. It should be noted that the effect of the wind velocity would sharply increased if the wind velocity was above a threshold, which was similar to the vehicle velocity. The fuel consumption factor was almost doubled when the road grade increased from 0% to 6%, although the engine operation points moved to higher load regions (higher brake thermal efficiency), where BSFC was at a low level, as the indication of the arrow in Figure 2. The reference [57] indicated that the vehicle fuel economy under the flat route was better than that of the hilly routes by 15% to 20% in the real world driving. It was demonstrated by the comparisons of the fuel consumption under two different routes, but the same start point and destination. The average road grade was ~4% for the uphill sections. The fuel consumption factor was high when the velocity was low, and it changed little when the velocity reached 60 km/h, which was in the region of the optimal fuel economy. As for the coolant temperature, the fuel consumption factor decreased by ~25% when the temperature increased from 40 °C to 100 °C, which was in the range of the daily driving. Much fuel penalty was caused by the cold start and warm up process in the daily short distance journey. The poor fuel economy under low coolant temperature conditions was mainly caused by poor in-cylinder combustion, plenty of heat loss through coolant, and much friction loss, which resulted of a low brake thermal efficiency. Reference [58] indicated that the reduction of the brake thermal efficiency caused by the cold start was ~30%. Coolant and lubricating oil heating, heat storage materials, electric pumps of coolant and lubricating oil were used to improve the in-cylinder combustion, and decrease the friction loss by dropping the lubricating oil viscosity [24]. The gear shift perfection, vehicle velocity, road grade and rolling resistance coefficient (route-choice) were human-controllable factors, from which the fuel economy could reach the optimal value. As for the driver behaviors, the fuel consumption factor increased up to 40% for aggressive behavior compared with normal driving in reference [59]; additionally, the driver behavior caused 45% fuel reduction in reference [60]. Road-surface characteristic, e.g. rolling resistance coefficient, affected the vehicle fuel consumption factor by up to 7% [61], which was much smaller than the road grade.

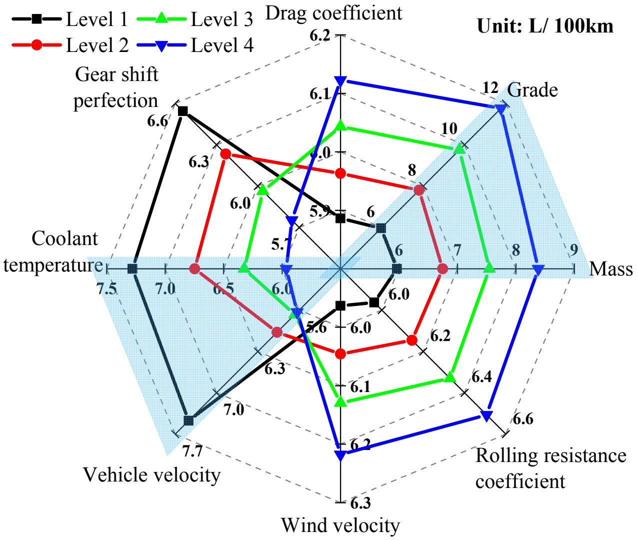

Figure 7 The sensitivities of the targeted factors to fuel economy

As indicated Section 3.1, the cold start and warm up process presented a significant effect on the gaseous exhaust emissions, which was mainly caused by the inefficiency of diesel after-treatments. The catalytic efficiency of after-treatments would keep at a high level and the variability was small, as long as the catalyst temperature reached the light-off value. Under that conditions, the pipe out emissions were mainly dependant on the emission formations in cylinders. Figures 8~10 show the gaseous emission factors, HC, CO and NO_x, respectively. The effects of the target factors on CO and HC emissions were opposite to the fuel economy generally. The related factors, leading the engine operation conditions to shift to higher engine load regions, would cause lower CO and HC emission factors generally. The CO emission factor decreased by ~80% when the average vehicle velocity increased from 18.75 km/h to 91.88 km/h. The radar net shapes of the emission factors were similar for HC and CO. With the value increasing of these factors, except for coolant temperature, the engine load increased, resulting of higher in-cylinder temperature. As for the effect of the coolant temperature, only the viscosity was considered rather than the in-cylinder combustion and heat loss. So the effect of the coolant temperature was opposite to other factors. If the in-cylinder combustion condition was taken into consideration, the situation would change.

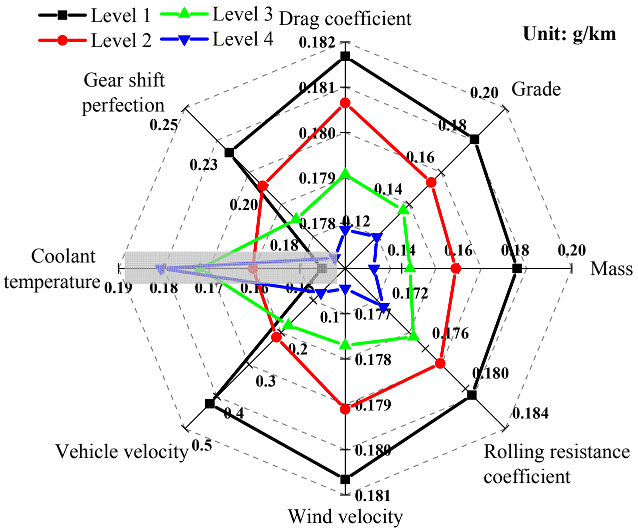

Figure 8 The sensitivities of the eco-driving factors to hydrocarbon emission factor

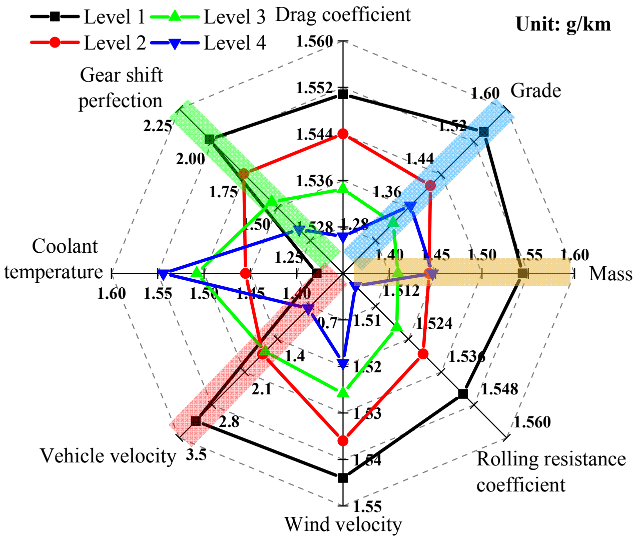

Figure 9 The sensitivities of the eco-driving to carbon monoxide emission factor

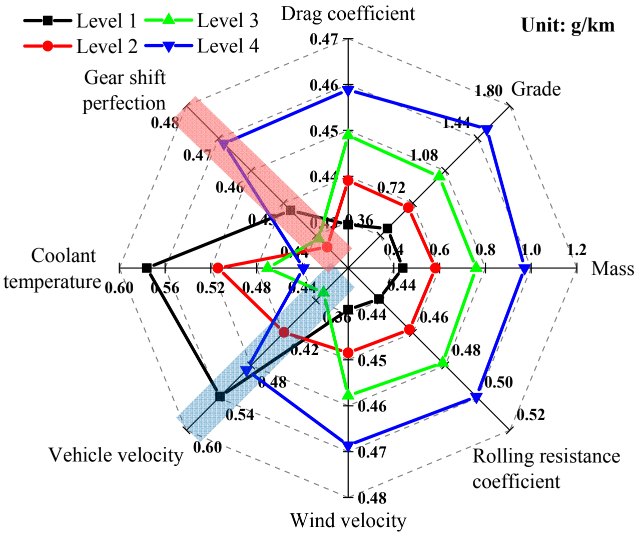

Figure 10 The sensitivities of the eco-driving to nitrogen oxide emission factor

The NO_x emission was still a challenge for conventional vehicles to meet stricter emission regulations despite many technologies were adopted. The overall tendency of the NO_x emission sensitivities to eco-driving factors were similar to the fuel consumption factor, more fuel injection meant higher in-cylinder combustion temperature, with the results of more NO_x formation. NO_x emission factor was extremely sensitive to vehicle velocity, road grade, and vehicle mass, whose huger values meant higher engine power output necessity. Figure 11 shows the sensitivities of the targeted factors on soot emission factor. In this figure, only the dry soot was considered; in fact, the particle mass emission showed closely related to the exhaust temperature and HC emission, which could condense and adsorb on particle surfaces. Drag coefficient and wind velocity could be neglected since the effect was less than 3% in the given range. DPF presented a perfect performance on the particle mass control. Recently, the focus had been paid on the particle number, which was clearly clarified in Euro 6 emission regulation.

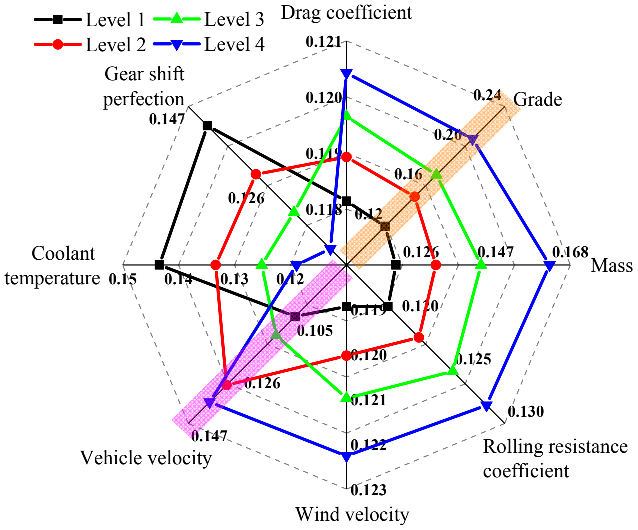

Figure 11 The sensitivities of the eco-driving to soot emission factor

3.3 The choice of vehicle operation for eco-driving

Most of the reported papers about the eco-driving were only focused on improving the fuel economy or decreasing emission factors, however, balances between the fuel economy and exhaust emissions were necessary. In this part, the choice of the optimal vehicle operation regions for eco-driving was analyzed from the points of fuel economy and exhaust emissions. Figures 12 and 13 show the fuel economy and gaseous emissions verse vehicle velocity. The optimal fuel economy zone was in the range of 40 km/h~110 km/h. The overall tendency of the fuel economy verse vehicle velocity was the same as the literature [40]. Higher gears were recommended to improve the fuel economy under the conditions of sufficient torque output and comfort. HC and CO emission factors decreased with vehicle velocity, however, it increased generally for NO_x. The overall emission factor tendency was similar to the reference [59]. The optimal velocity region for exhaust emissions, under the compromise of the NO_x emission with HC and CO emission factors, was 70 km/h~110 km/h, which was covered by the optimal fuel economy region. This made the foundations for the driver instructions to achieve the eco-driving. The decrease of the exhaust emissions was significant after applying the eco-driving rules [62].

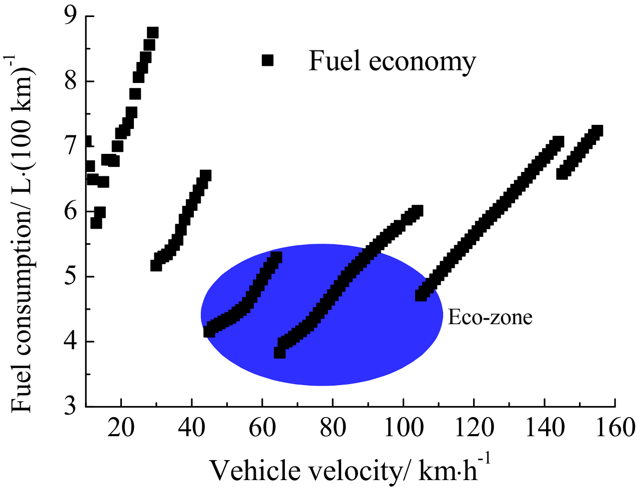

Figure 12 Fuel economy *vs.* vehicle velocity

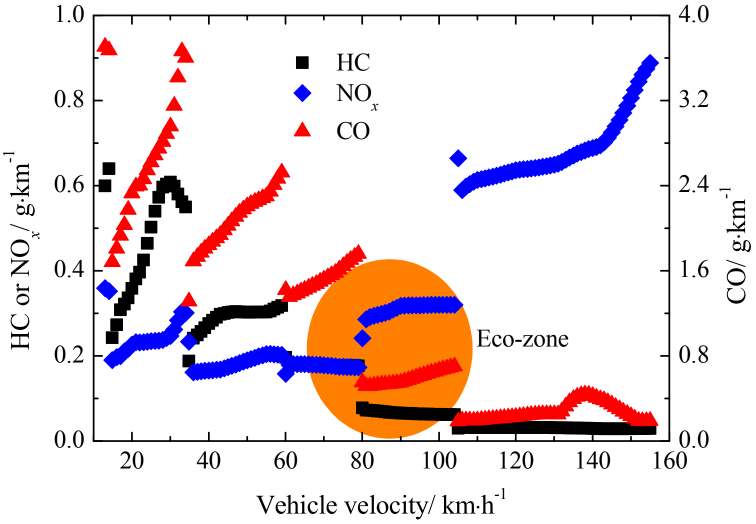

Figure 13 Gaseous emission factors *vs.* vehicle speed

As indicated in Section 3.2, vehicle velocity and road grade presented the most significant effect on fuel economy and exhaust emissions. Also, the vehicle velocity and routes were human-controllable factors in eco-driving. Figures 14 and 15 show the fuel economy and emission factor maps as the function of the vehicle velocity and road grade. The vehicle velocity was an average value, which was obtained under different period combinations of low, medium, high and extra-high velocity zones in WLTC. The points A, B, C, D and E were referred to different routes chosen by the drivers. Fuel consumption factor almost linearly increased with the road grade. The fuel economy could be improved by avoiding running on the roads with huge grades, which may prolong the journey distance inevitably. In order to ensure arriving the destination punctually, the vehicle velocity should be increased to compensate the prolonged distance, as the direction from point A to point B in Figure 14. For eco-driving, it must be satisfied with the equations 1 and 2,

$$s_A \cdot f_A \geqslant s_B \cdot f_B \qquad (1)$$

$$s_A \cdot v_B \geqslant s_b \cdot v_A \qquad (2)$$

where, s_A and s_B were the distances of the journey when choosing route A and route B, respectively; v_A and v_B were the average velocity in route A and route B, respectively; f_A and f_B were the fuel consumption factors when choosing route A and route B, respectively. However, some compromise between the fuel economy and the journey duration could be made in some cases, where the limitation of the equation 2 would be faded. The NO_x emission was still a issue for meeting stricter emission regulations that higher vehicle velocity with a lower road grade would be helpful. As for the CO and HC emissions, the eco-driving direction was consistent with the fuel economy. In the future work, multiple external factors would be taken into consideration to provide the instructions for eco-driving. Also, the optimal route choice would be made based on the predictions of fuel consumption and exhaust emissions, which would be benefit from the research.

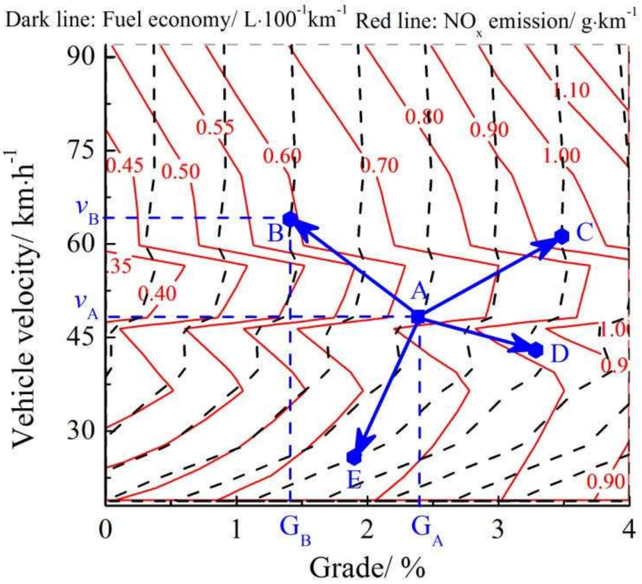

Figure 14 Fuel economy and nitrogen oxide emission *vs.* vehicle speed and road grade

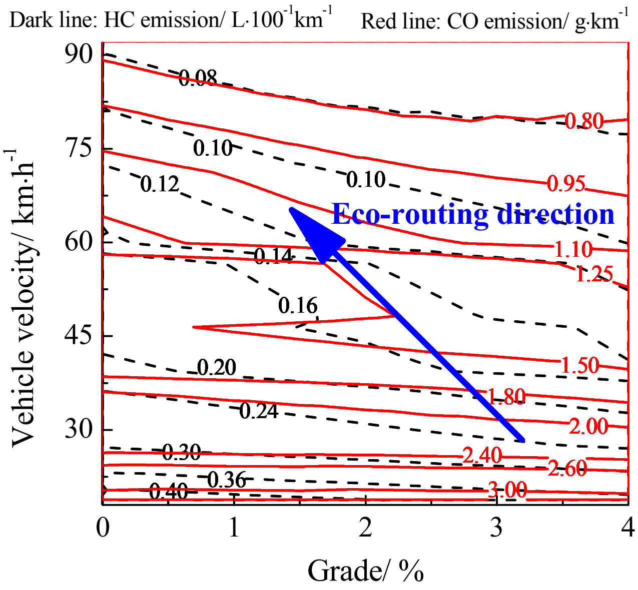

Figure 15 Carbon monoxide and hydrocarbon emissions *vs.* vehicle speed and road grade

It should be noted that the suggestions for eco-driving are also suitable for heavy-duty vehicles, such as 40 t delivery trucks, which regularly operate on the international mountain motorways with variable road grades (e.g. from Turin to Istanbul). In addition, the effect of the eco-driving on fuel consumptions of heavy-duty trucks should be huger than light-duty vehicles, because the heavy-duty trucks are usually fully loaded, which increases the sensitivities of the fuel consumption and exhaust emissions to the eco-driving factors. For the autonomous vehicles, it also makes the foundations of decreasing fuel consumption and exhaust emissions that the Electronic Control Unit (ECU) automatically controls the engine operation points to work around the optimal zones based on the provided suggestions in this paper.

4. Conclusions

Diesel vehicles are widely used due to their excellent fuel economy and durability, while the exhaust emissions are still a challenge to meet stricter emission regulations although the emission concentrations have reached a low level. In this paper, gaseous regular emissions and fuel consumption rates of a diesel vehicle were tested under WLTC, and their sensitivities to the eco-driving factors were investigated. The main conclusions were as the following:

(1) The engine operation points under WLTC were mainly located at the regions of medium engine speed and low engine load, which were out of the optimal BSFC zones. Vehicle acceleration and speed dominated the fuel consumption rates under WLTC.

(2) Exhaust emissions in the first 300 s dominated the accumulative emissions of the whole WLTC, they were 63.2%, 55.4% and 56.05% of the total emissions for HC, NO_x and CO, respectively. HC and CO emissions were at a rather low level after the engine was fully warmed up. In the last 200 s of WLTC, NO_x emission was much high, results from the high in-cylinder temperature despite of high catalyst efficiency.

(3) The road grade, coolant temperature, vehicle mass and velocity presented the most sensitive to vehicle fuel economy, whose radar net shapes of their sensitivity was similar to NO_x and soot emission factors. The optimal velocity zones of the fuel economy and exhaust emissions were in the range of 70 km/h~110 km/h. For the eco-driving, a higher velocity and lower road grade were recommended, and a balance between the fuel economy and driving duration was necessary in some case.

Based on this research, the route-choice for eco-driving will be conducted by the predictions of the fuel consumption at different routes, combined with traffic and geographic information system (GIS). Meantime, the eco-driving guidance for drivers will be performed by Smartphone app, which will provide driving suggestions based on traffic and GIS information.

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consumption under real-world conditions while still meeting relevant Euro VI emission standards. AUTOPILOT brings IoT (Internet of Things) into the automotive world (via real-world use cases) to transform connected vehicles into highly and fully automated vehicle.

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