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RESEARCH ARTICLE

Fuel economy and exhaust emissions of a diesel vehicle under real traffic conditions

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Abstract

Traffic and vehicle simulations are often developed individually. However, vehicle performance is heavily affected by traffic conditions. Cosimulations of traffic and vehicle under real-road situations can reflect the semi-real-world performance of vehicles, with traffic conditions being taken into considerations. This paper proposed an approach to combine the traffic and vehicle simulations that are realized by simulation of urban mobility (SUMO) and GT-Suite software, respectively. In this paper, the sensitivities of the road grade and vehicle speed to the fuel economy and exhaust emissions were investigated; vehicle fuel consumption and regular exhaust emissions on a real-road were analyzed; the effect of the traffic accident and congestions on fuel consumption and exhaust emissions were quantified. The results indicated that nitrogen oxides (NO_x) and soot emission were consistent with fuel consumption rate, which was dominated by vehicle acceleration whose effect was aggravated by road grade. The fuel penalties caused by accident were in the range of 0.015-0.023 kg depending on the severity of the accidents. The fuel consumption increased from 1.199 to 1.312 kg and 1.559 kg for 900 and 1800 vehicles/h traffic flow cases compared with 180 vehicles/h traffic flow.

KEYWORDS

accident, congestion, diesel vehicle, exhaust emissions, fuel economy, real-road simulation

1 | INTRODUCTION

Fossil fuel increasingly consumed by automobiles due to traffic growth significantly aggravates the dependency of a nation on the fossil fuel importation. Hooftman et al[1] reported that the road transportation sector is an important source of carbon dioxide (CO_2), nitrogen oxides (NO_x), and particulate matter (PM), which have brought about serious problems to human health and environment.[2] It was also reported by reported by Delgado and Gonzalez[3] that road transport accounts for 23.4% of total CO_2 emission in 2017 in the world. Advanced technologies have been developed to decrease the fuel consumption and exhaust emissions on vehicle level (eg, driver training,[4] driving instruction,[5] speed optimization,[6] route choice,[7] shape optimization of vehicle body,[8] hybrid vehicles[9]) and on internal combustion engine level (eg, optimization in-cylinder combustion,[10] turbocharger,[11,12] energy management,[13,14] catalyst thermal management,[15] bio-fuel,[16,17] exhaust and coolant energy recycle[18]). Gao et al[19] adopted electrically heated catalyst (EHC) to decrease vehicle cold-start emissions, such that the emission level meets the Euro 6 limitations. However, fuel penalty is in the range of 6.49%-9.35% for different scenarios. Liu et al[20] investigated the effect of the injection strategies of dual fuels on combustion characteristics and emissions and found that a retarded pilot fuel injection slightly decreased of in-cylinder pressure and delayed the combustion phase. They found that the gas injection timing advanced by 4° crank angle (CA) resulted in the lowest soot emission, but the highest NO_x emission.

Biodiesel, as a potential alternative of diesel,[21,22] is a promising route of mitigating greenhouse gas emission,[23] and it can effectively alleviate the dependency on the fossil fuel importation. Biodiesel contains more oxygen and less polycyclic aromatic hydrocarbons (PAHs) and sulfur,[24-26] which help improve the in-cylinder combustion and reduce PM formation.[27,28] As shown in reference,[29] biodiesel/polyoxymethylene dimethyl ethers blend fuel significantly improved the engine brake thermal efficiency and deceased PM emission.[30] The highest brake thermal efficiency reported by Oishi et al[31] is 27.79% from a dual-fuel mode of 80% biodiesel + 20% methane. It is also conducive to diesel particulate filter (DPF) regeneration[32] since the oxidation activity of biodiesel PM is much higher than the diesel counterpart.[33] Coskun et al[34] investigated the homogenous charge compression ignition (HCCI) combustion, which combined the merits of spark ignition and compression ignition engines and found higher brake thermal efficiency and lower exhaust emissions. However, the ignition of the HCCI combustion was hard to control, which led to the instability of engine operations.[34,35] To improve fuel economy on vehicle level, Mensing et al[36] optimized the vehicle speed trajectories to achieve eco-driving, and the potential improvement of fuel economy was discussed. They found that fuel economy could be improved by ~34% in theory for a free-flow urban driving, but the gain decreased by 16%~54% if safe driving conditions were considered. In the work,[37] 203 drivers were monitored on a real-road of Australia and five training courses that the averaged fuel consumption dropped by 4.6% compared with pre-training.

For the current regulations, more and more attentions have been paid to real-world driving, which can reflect the real performance of vehicles. The impact of regulatory on-road test on vehicle emissions based on a Euro 6-complaint diesel vehicle was assessed by Mendoza-Villafuerte[38] who reported that NO_x emission was underestimated (by up to 85%) under the current boundary conditions. Yu et al[39] improved the urban bus emissions and fuel consumption modeling by incorporating passenger load factor into real-world driving. Real-world fuel consumption and exhaust emissions were also tested by Yuan et al[40] under hot-stabilized conditions using different vehicles meeting different emission regulation. Similar work was done by Serrano et al[41] based on two identical vehicles; in this work, a new methodology using on-road tests was developed, and their approach presented excellent performance of vehicle testing.

Silva et al[42] developed a numerical model to estimate vehicle fuel consumption and regular exhaust emissions under urban driving conditions. The model was used to simulate 14 urban trips made by two Ford vehicles. Although it predicted CO_2 emission with relatively high precision, the model did not work well with the gear-shift control strategy, which is an important factor for vehicle performance.[9] Additionally, it could not simulate the vehicle performance under real-road situation with different traffic conditions (eg, congestion, traffic light, and accident) on vehicle performance. It was difficult to develop a mathematical model to estimate the fuel consumption and exhaust emissions with a high confidence level because of the variability and nonlinearity of vehicle fuel consumption and exhaust emissions. Zhou et al[43] reviewed the vehicle fuel consumption models and factors related to fuel economy. It was shown that the factors related to road conditions, driver behavior, and traffic characteristics presented the most significant effect on fuel consumption.

Bieker et al[44] took the city of Bologna as an example to conduct the traffic simulation using SUMO software under a real-world scenario. It considered different kinds of traffic conditions, such as traffic congestion, traffic light, traffic accident; meantime, the real-road network and road characteristic (elevation, rolling resistance factor) were took into account. Dynamic traffic congestion simulation was done by Wang et al,[45] and the formation of the traffic congestion was simulated using an upgraded medium traffic model. In the work, the traffic simulation platform was constructed from the viewpoint of quantitative traffic congestion. Traffic congestion as a common problem has affected many cities around the world; in Hu's research, an actual urban traffic simulation model (AUTM) was set up for simulating traffic congestion and predicting the effect of adding overpasses and roadblocks.[46] This method could be applied to a large-scale real-world scenario in different traffic congestion situations, and the predicted accuracy of the traffic congestion reached 89%. Vissim, SUMO, and Aimsun are powerful software to simulate the dynamic traffic conditions; however, they are difficult to accurately analyze the fuel consumption and exhaust emissions to assess the effect of traffic conditions on fuel economy and pollutants.

Due to the complexity and high cost of the real-world test, especially for those heavy-duty vehicles (such as 40 t trucks) that frequent tests in a long journey and fully loaded situations are unrealistic, the real-road simulation is necessary. Additionally, vehicle performance simulation with high precision on real roads considering the traffic conditions is still a gap. SUMO has an excellent ability of traffic simulation, and GT-Suite is powerful for vehicle performance simulation. In this paper, the merits of the SUMO and GT-Suite were taken to propose a new approach combining the traffic and vehicle simulations to investigate the real-road fuel consumption and exhaust emissions. This is the first time to combine the traffic and vehicle simulations to investigate the vehicle performance under the "real-road situation" to the authors' knowledge. In the simulation, the real-road conditions were used, such as the road elevation and rolling resistance factor; hence, the simulation results were much more closer to the real-road driving. This paper was organized as the following structure: (a) the introduction of the new approach of the real-road simulation, combining the traffic and vehicle simulations; (b) the sensitivities of the road grade and vehicle speed on fuel economy and regular exhaust emissions; (c) simulations of the fuel economy and regular exhaust emissions on real road; and (d) the effects of the accident and congestions on the penalty of fuel consumption and exhaust emissions under real-road conditions.

2 | REAL-ROAD SIMULATIONS OF VEHICLE FUEL ECONOMY AND EXHAUST EMISSIONS

The current vehicle simulations are mostly based on the driving cycles suggested in emission regulations, such as New European Driving Cycle (NEDC),[47] Federal Test Procedure (FTP),[15] and Worldwide harmonized Light vehicles Test Cycles (WLTC).[48] Solomon[49] researched the influence of road geometry on vehicle emissions and fuel consumption, with the conclusion that exhaust emissions and fuel consumption have a direct relation with the road grade, which indicated the importance of considering the real-road conditions. The simulations based on these driving cycles contained few information of the real-road network and the traffic conditions. Figure 1 shows the new method of vehicle simulation on a real-road network. The real-road driving simulation could be achieved by the combination of traffic and vehicle simulations. The traffic simulation is conducted by SUMO software[50]; meanwhile, the vehicle simulation is done using GT-Suite software. The process of the real-road vehicle simulation is as following: (a) obtain the 2D real-road network; (b) integrate the road elevation into the 2D real-road network; (c) extract the targeted route for further simulation; (d) load the real-road network and traffic information into SUMO software; and (e) input the traffic simulation results into GT-Suite software to finish the vehicle simulation. It should be noted that in the 3rd step, the crossways of other roads and the target one remained and there was traffic flow as well. 2D OpenStreetMap contained the information of the real-road network (eg, number of lanes, road geometries, and speed limitations), except for road elevations. The road elevations (from Nasa SRTM) were integrated into the real-road network using the method in osmosis-srtm-plugin instructions.[47-51] The traffic demands were imported using the commands of SUMO, where the traffic flow, vehicle types, and vehicle routes were generated automatically. TraCI4Matlab was used to integrate the SUMO traffic simulator and Matlab,[52] in which target vehicle could be monitored. Madireddy et al[53] also combined the microscopic traffic simulation model with the emission model; however, the emission model was set up based on the vehicle speed and acceleration, and this method was with a low precision.

3 | VALIDATION OF THE VEHICLE MODEL

Table 1 shows the specifications of the diesel vehicle, which meets the Euro 6 emission regulation. The engine is a four-cylinder, turbocharged, direct-injection engine. The maximum power output and torque are 103 kW and 325 N·m, which are corresponding to 4000 and 1500 rpm, respectively.

Figure 2 shows the tested brake-specific fuel consumption (BSFC) as the functions of engine speed and torque. The optimal BSFC zone is in the range of 1500-3100 rpm and 90-310 N m, where the BSFC is below 230 g/(kW h). Figure S1 shows the exhaust emission maps, which were obtained using engine test bench. BSFC map and exhaust emission maps are basic inputs of the vehicle model in order to investigate the fuel economy and exhaust emissions. Figure 3 is the validation of vehicle model under WLTC, which indicates a high precision of the vehicle model.

4 | RESULTS AND DISCUSSION

4.1 | Sensitivities of the road grade and vehicle velocity to the fuel economy and exhaust emissions

Due to the significant changes of the road elevations for the mountain motorways, the road grade being higher than 3% is in a large proportion. Vehicle speed and road grade are two of the most important factors which affect vehicle fuel economy and exhaust emissions. Figures 4-6 show the sensitivities of vehicle speed and road grade to the fuel economy and exhaust emission factors. The fuel consumption was much low if the road grade was negative, except for extrahigh and extralow vehicle speed zones. The fuel consumption was almost doubled when the road grade increased from 0% to 4% that was in the range of

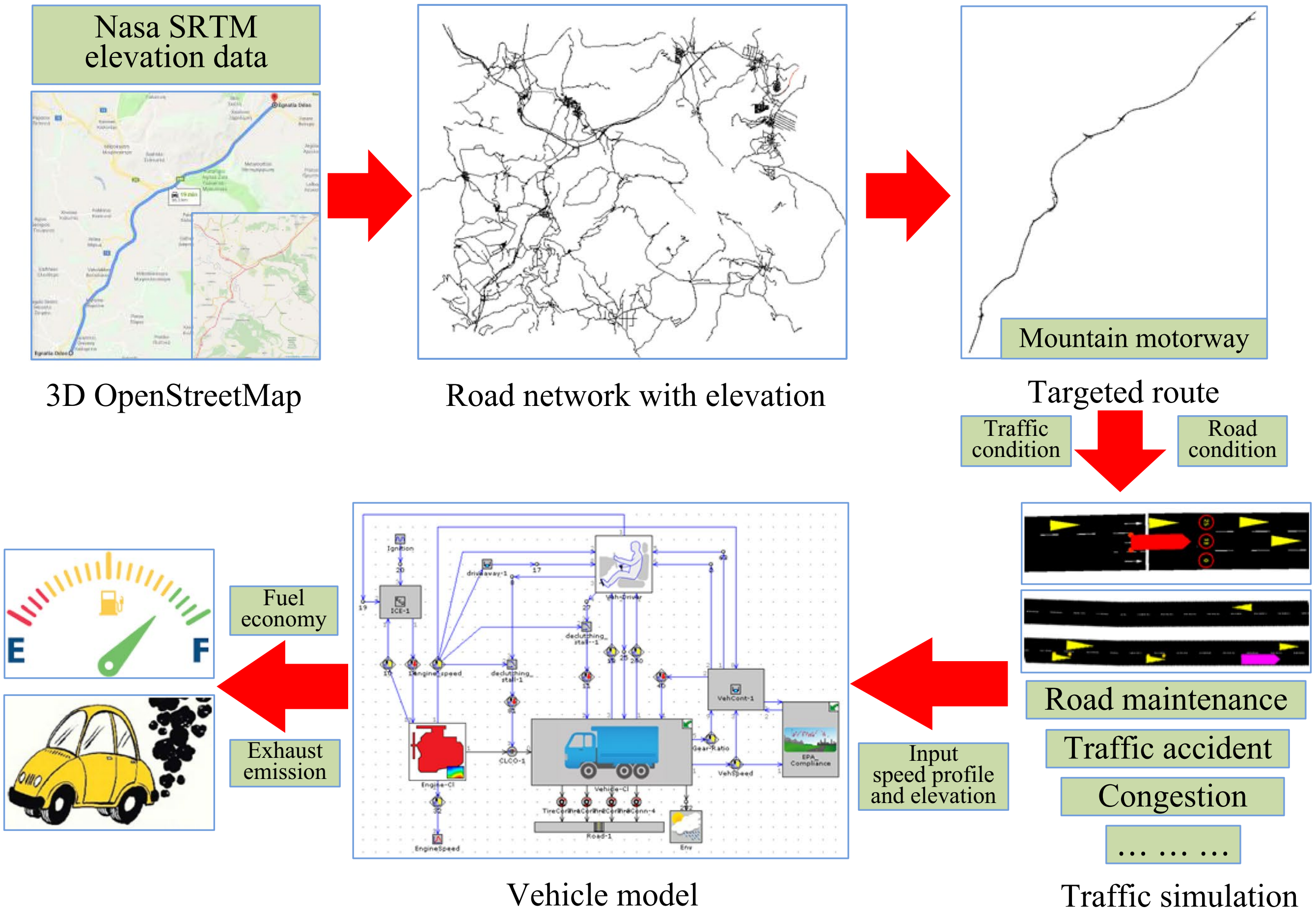

FIGURE 1 The method of vehicle simulation on a real-road network

the mountain road grade. NO_x and soot emissions are still challenges in meeting stricter emission regulations that it should combine the advanced vehicle technologies and driver training to pursue better performance. The tendency of NO_x emission factor was similar to the fuel consumption because high fuel consumption caused high in-cylinder combustion temperature and, further, more NO_x emission. NO_x and soot emissions were at a low level when the road grade was negative due to low in-cylinder combustion temperature, which was caused by low engine load. The highest soot emission zone was located in the ranges of 2%-4% road grade and 100-130 km/h vehicle speed, which was the same for carbon monoxide (CO) emission factor, since the formations of CO and soot were under the condition of oxygen shortage. It should be noted that CO and hydrocarbon (HC) emission factors were still high for low vehicle speed and negative road grade situations. In reference,[7] the fuel sensitivities of the road grade and averaged vehicle speed were also investigated. Costagliola et al[54] researched the impact of road grade on real-driving emissions from Euro 5-complaint diesel vehicles on urban, rural, and motorway roads with different grade (−4% to 5%). The road grade had a significant influence on fuel consumption and NO_x emission. CO_2 emission was almost linearly related to the variations of road slope. As indicated by Solomon,[49] the maximum energy saving and

TABLE 1 Specifications of the diesel vehicle

Specifications	Value
Vehicle mass	1505 kg
Vehicle frontal area	2.05 m^2
Maximum speed	170 km/h
Gear number	6
Fuel injection type	High pressure common rail
Fuel	Diesel
Engine type	In-line, four-cylinder, four stroke
Intake type	Turbocharged intercooler
Engine max power/kW	99 kW @ 4000 rpm
Engine max torque/N m	313 N m @ 1500 rpm
Stroke/mm	80.4
Bore/mm	79.1
Compression ratio	16.5
Emission regulation	Euro 6

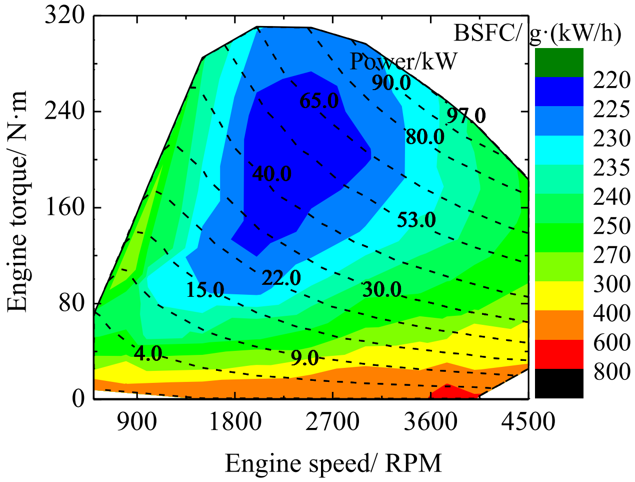

FIGURE 2 Brake-specific fuel consumption map

minimum exhaust emissions could be achieved when the vehicle speed was in the range of 50-70 km/h, which was lower than the author's results.

4.2 | Vehicle fuel consumption and exhaust emissions on real-road

Hooftman et al[1] indicated that Europe's emission regulations of passenger car were proved to fail when it came to NO_x by diesel engines, which made it necessary for the real-road investigation. Figure 7 shows the fuel consumption, NO_x, and soot emissions on real-road situations. The elevation of this road was in the range of 510-590 m. The maximum and minimum vehicle speeds were ~110 and ~75 km/h, respectively. There were many sections where the vehicle speed changed suddenly, which simulated the brake cases caused by traffic perturbations. Fuel consumption of the vehicle changed significantly, being from 0-21 kg/h, due to uphill, downhill, acceleration, and deceleration. Yu et al[39] indicated that the fuel consumption showed closely related to vehicle acceleration, which was similar to the authors' opinion. Most of the peak positions of NO_x and soot emissions were corresponding to the fuel consumption's, and these peaks were almost three times higher than regular values. The uphill aggravated the effect of acceleration on NO_x and soot emissions. Gallus's[55] results indicated that the penalty of fuel consumption and NO_x emission caused by a 5% road grade was in the range of 85%~115% based on two diesel vehicle road testing. In order to decrease the fuel consumption and exhaust emissions, an acceleration advisory tool was applied to a vehicle,[56] which was avoided to run under aggressive acceleration. It was achieved by the resistance in the acceleration pedal when drivers tried to accelerate rapidly. As can be seen from Figure 8, HC and CO emissions present less dependent on vehicle acceleration and road grade than NO_x and soot emissions. Because the tendency of CO and HC emission rates are not consistent with the elevation changes, meantime, the peak of CO and HC emission rates are not only in the acceleration process or on uphill roads.

4.3 | The effect of accident on fuel consumption

Large amounts of fuel are consumed if an accident happens on the road as vehicles start to stop and go. The fuel penalties caused by the accident differ significantly from vehicle to vehicle, which depends on how far the target vehicle is from the accident, and how seriously the vehicle speed is affected. However, the fuel penalty of the whole traffic is almost the same, as long as the severity of the accident is known (the accident-affected area, accident-affected time). In this section, the fuel penalty caused by the accident was analyzed from the point of individual vehicle and the group. The scenarios of the real-road accident are shown in Figure 9.

As soon as the accident happened, a sign of slowing down was set up 200 m before the accident place. Then, the other vehicles had to change the lanes and decelerated, and the accident-affected region was enlarged gradually. The vehicle speed was set as 10 km/h from the deceleration sign to the accident vehicle in order to avoid the secondary accident. The individual vehicle speed under the effect of real-road accident is shown in Figure 10. In the accident-affected area, the vehicle speed decelerated gradually to a rather low value and accelerated to a

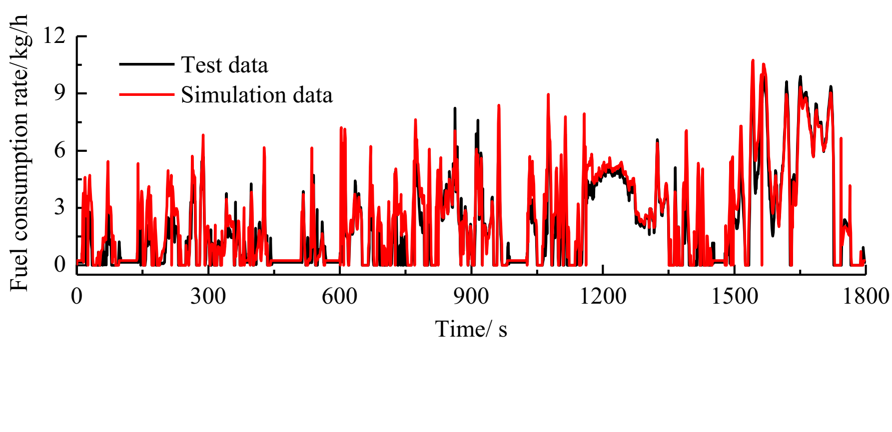

FIGURE 3 Vehicle model validation

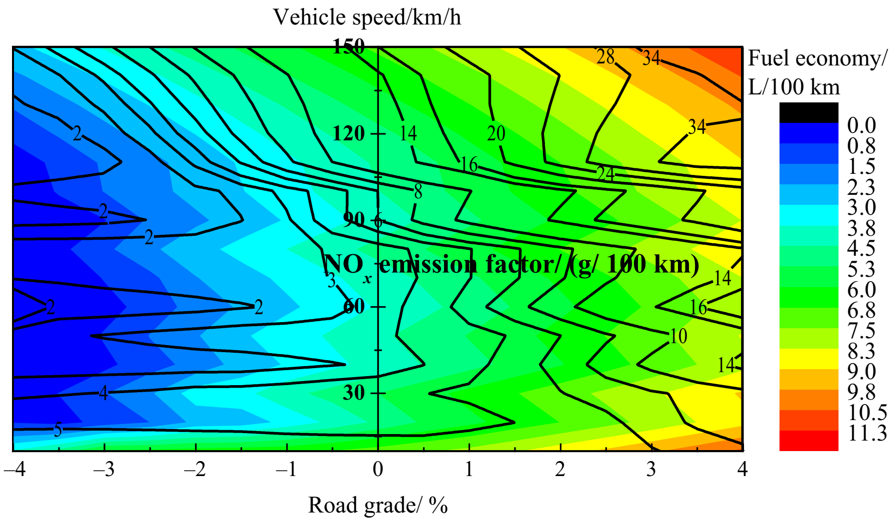

FIGURE 4 Fuel economy and NO_x emission factors vs road grade and vehicle velocity

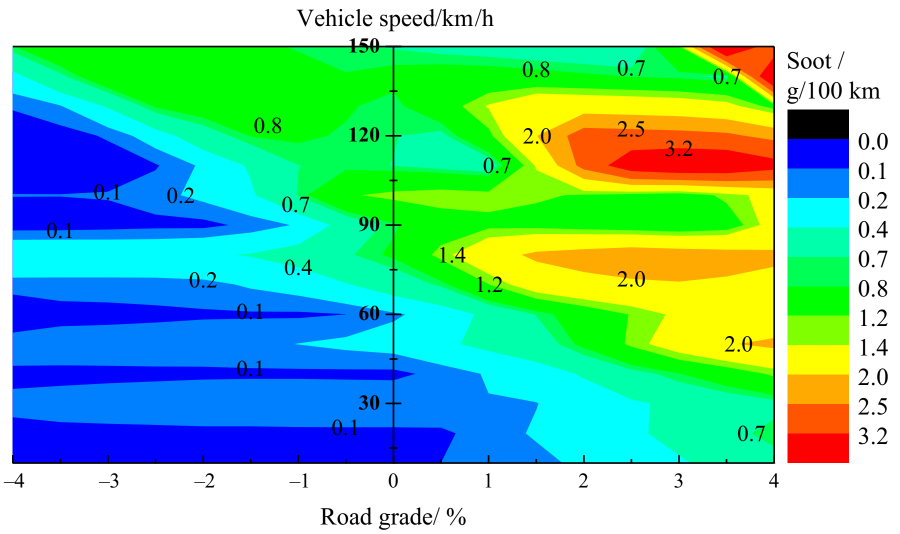

FIGURE 5 Soot emission factors vs road grade and vehicle velocity

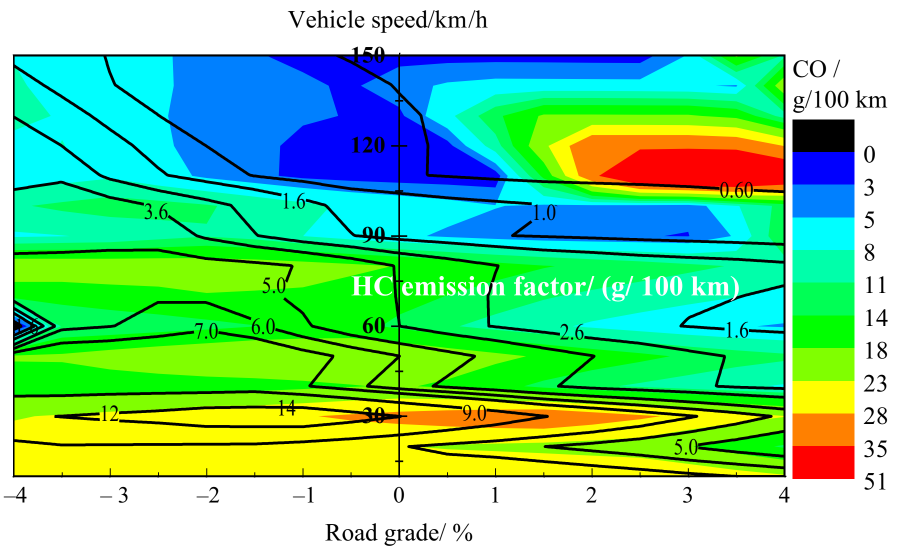

FIGURE 6 CO and HC emission factors vs road grade and vehicle velocity

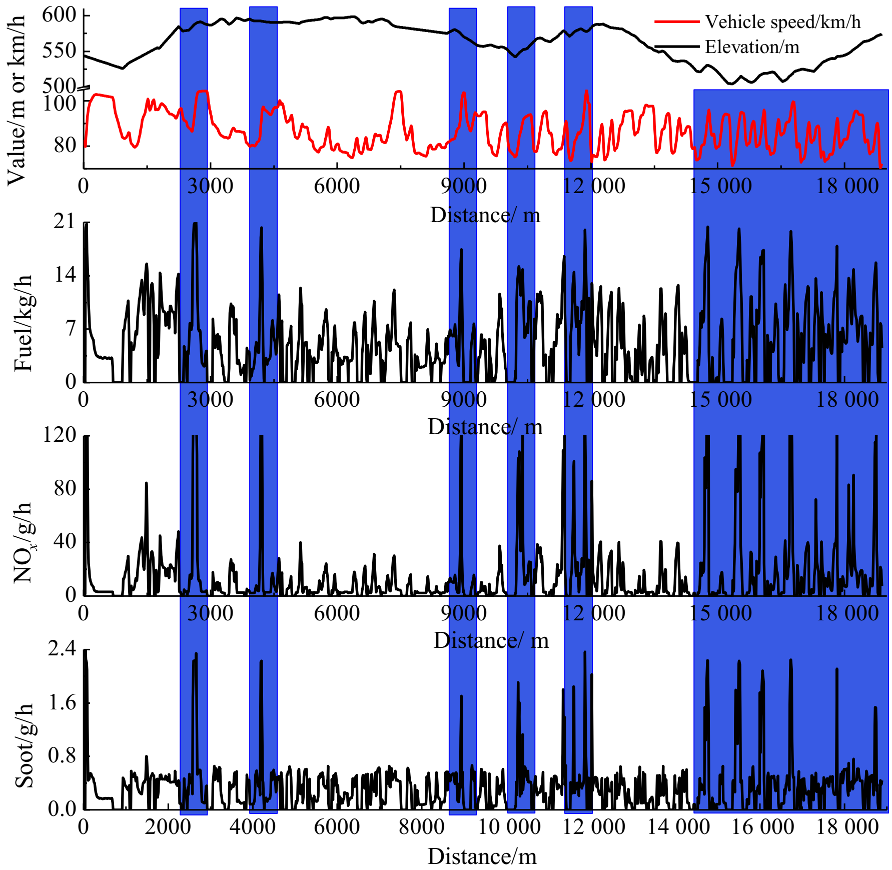

FIGURE 7 Vehicle fuel consumption, NO_x, and soot emissions on a mountain motorway

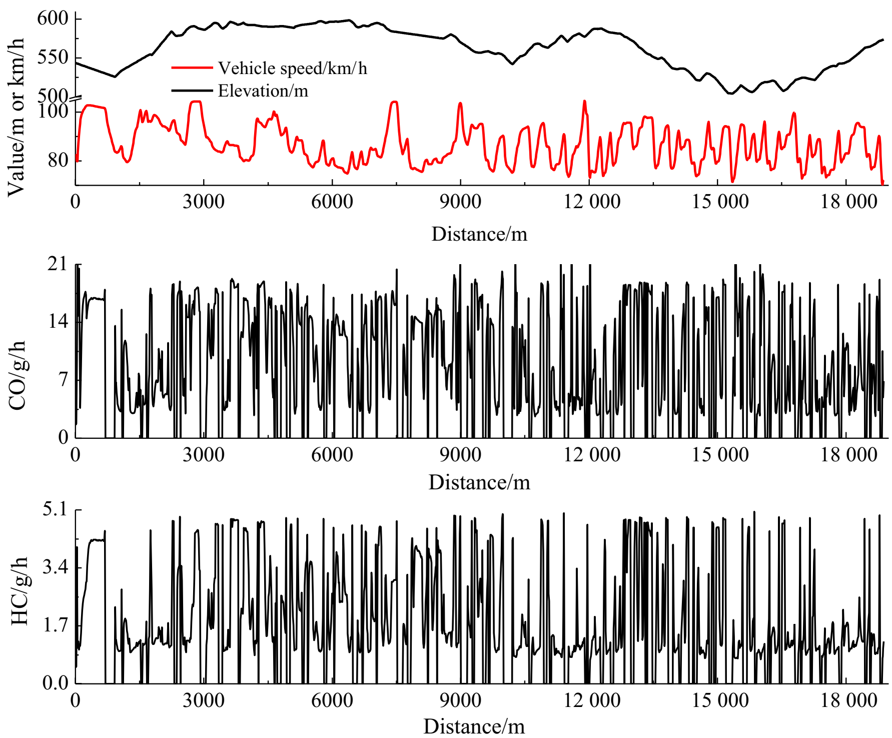

FIGURE 8 CO and HC emissions on a mountain motorway

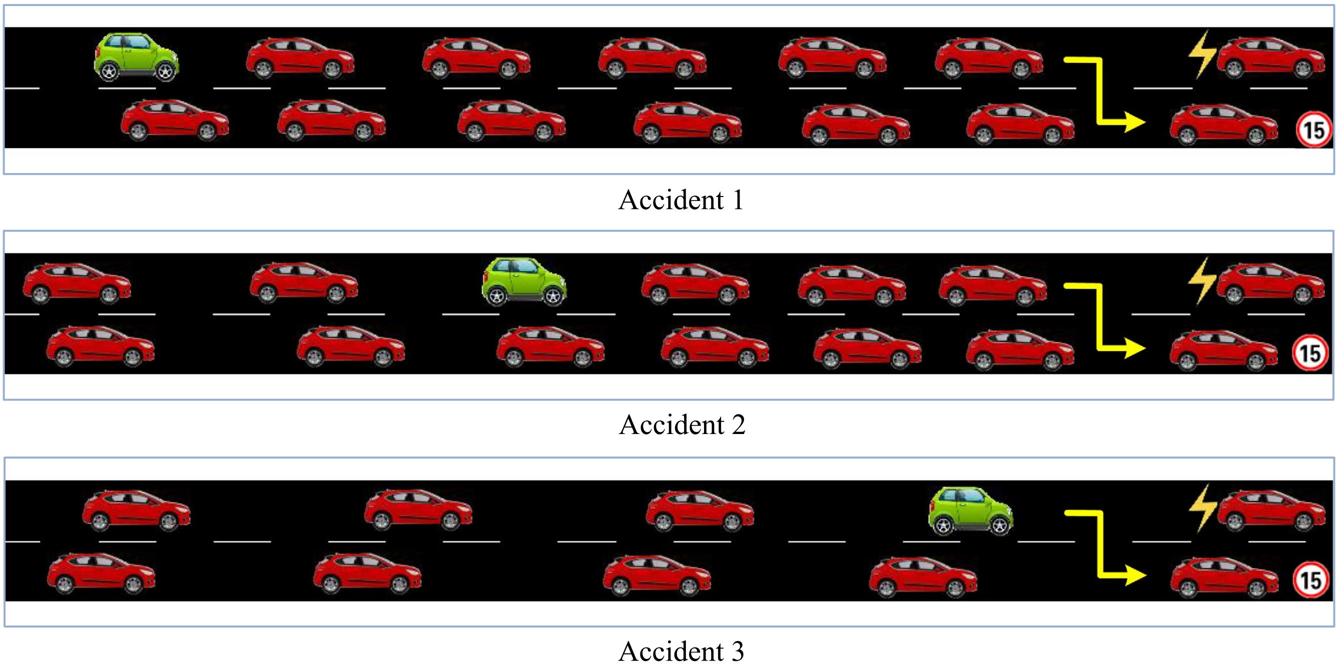

FIGURE 9 The scenarios of accident happened at different relative positions

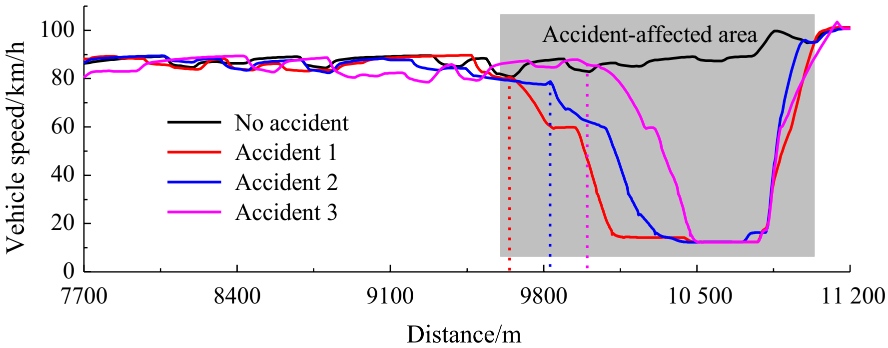

FIGURE 10 Vehicle speed profiles on real-road under different accident scenarios: accident car at 10 700 m

TABLE 2 The fuel consumption of individual vehicle under different accident scenarios (9500-12 000 m)

Accident	Fuel consumption/kg	NO_x/mg	HC/mg	CO/mg	Soot/mg
NO	0.140	0.288	0.052	0.238	0.0114
1	0.163	0.405	0.099	0.375	0.0120
2	0.160	0.406	0.079	0.321	0.0121
3	0.155	0.404	0.074	0.302	0.0121

high speed after passing the accident vehicle. Take the vehicle speed profiles as the input parameters of vehicle model, the fuel penalty caused by the accident could be estimated.

The fuel penalty was in the range of 0.015-0.023 kg for the given scenarios, as shown in Table 2. It should be noted that NO_x emission changed slightly even though the traveling time increased; however, HC, CO, and soot emissions increased significantly. Based on the data, the relation of individual vehicle fuel penalty and the distance between the target vehicle and accident vehicle can be obtained, as Equation 1,

$$f_i = f(x_i) \tag{1}$$

where x_i is the distance between the accident vehicle and the affected vehicle i (the distance started from the affected point, which differed for individual vehicle). Further, the total fuel penalty could be calculated if the traffic flow and accident evolution could be gotten, as Equation 2.

$$F = \sum_{1}^{n} f_i \tag{2}$$

F, the total fuel penalty caused by the accident; f_i, the fuel penalty of individual vehicle i. Due to much fuel consumption and exhaust emission, penalty will be caused by

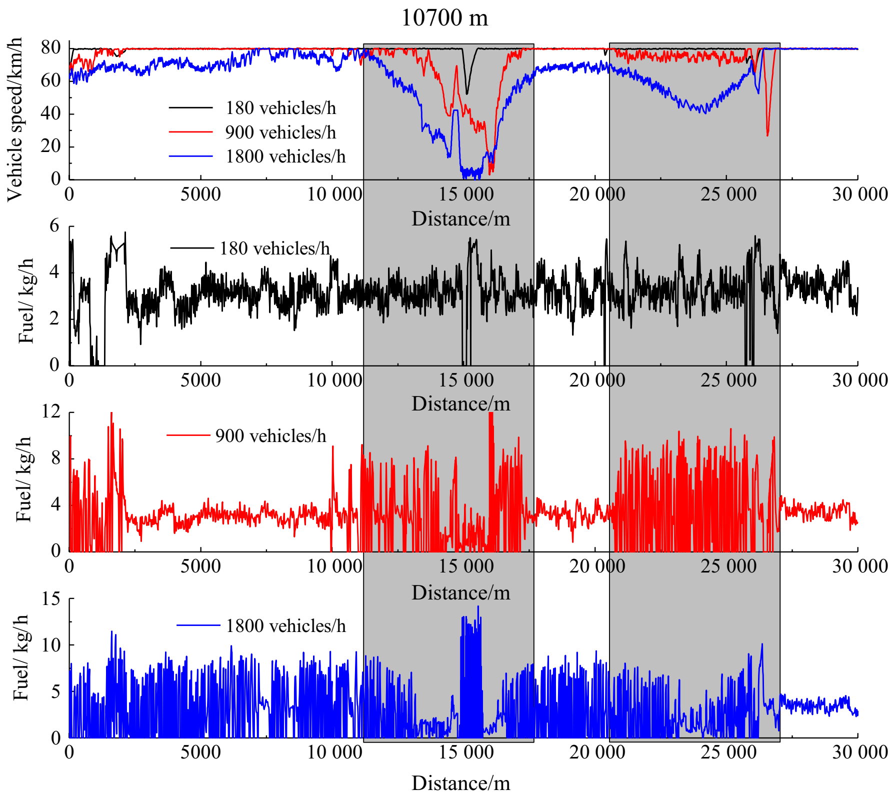

FIGURE 11 Fuel consumption rate under different congestion situations

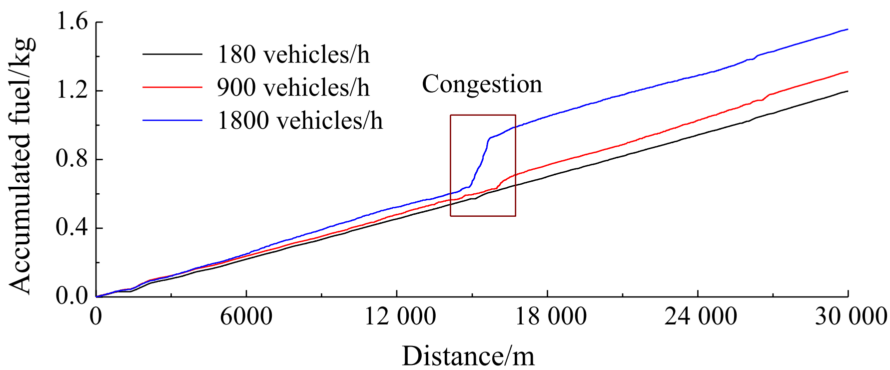

FIGURE 12 Accumulative fuel consumption under different congestion situations

traffic accident, and accident charging of wreckers can be considered to be a warn to further enhance the driving safety.

4.4 | The effect of congestion on fuel consumption

The effect of vehicle speed caused by congestion (heavy traffic flow) is different from that of accident situations, where the vehicle would recover from low speed situation once the target vehicle passed the accident; however, it had several low speed regions for regular congestions, as shown in Figure 11. The accumulated fuel consumption as the series of distance is shown in Figure 12. In the simulation, three different traffic flows were set to simulate traffic congestions. The simulation was also based on the real-road network. As indicated in the reported work[57] that the commonly used traffic simulation model (average speed models) exclude the effect of traffic congestions on fuel consumption and exhaust emissions. The vehicle was almost under the free-flow condition for 180 vehicles/h traffic flow situation that the vehicle was almost kept at a constant speed, which greatly decreased the times of acceleration and deceleration. It significantly improved the fuel economy because the acceleration dominated the fuel consumption rate, as discussed above. The fluctuations of the vehicle speed increased greatly for 900 and 1800 vehicles/h traffic flow, and vehicle speed fluctuations seriously worsen the fuel economy. Greenwood et al[58] estimated the penalty of vehicle fuel consumption and emissions caused by traffic congestion using the acceleration noise. This approach provided a better predictive ability than those of traditional speed-flow methods, whose errors reached 200% for passenger cars,

TABLE 3 Fuel consumption and exhaust emissions under different traffic flow (30 km distance in total)

Traffic flow/vehicles/h	Fuel consumption/kg	NO_x/g	HC/g	CO/g	Soot/g
180	1.199	1.225	1.107	5.170	0.117
900	1.312	2.050	0.957	4.312	0.115
1800	1.559	3.319	1.118	4.639	0.121

even higher for trucks. The fuel consumption in the authors' work increased to 1.312 and 1.559 kg (Table 3); meanwhile, NO_x emission increased by 67.3% and 170.1% for 900 and 1800 vehicles/h traffic flow, respectively. However, HC, CO, and soot emissions were the least for 900 vehicles/h traffic flow in the three cases. As for HC and CO, the emission factors decreased to a rather low level due to the use of advanced after-treatment technologies; however, NO_x emission is still an issue. The congestion made it even worse to achieve the ultralow emission vehicles. Figliozzi[59] analyzed CO_2 emission for different levels of congestions that congestion and speed limits had a significant impact on vehicle CO_2 emission, which was caused by longer travel time. Bharadwaj et al[60] investigated the impact of congestion on fuel consumption for road transport in Mumbai that ~51% of traveling time caused by congestion would led to ~53% more fuel consumption. In order to decrease the traffic congestion, the congestion price was recommend, and a mathematical approach for dynamic congestion price was proposed.[61]

5 | CONCLUSIONS

The real-world test of vehicle performance is time-consuming and expensive, even unrealistic, and the test is enslaved to the real traffic conditions that many factors are uncontrollable for investigators. The real-road simulation can reflect the vehicle performance with relative high precision to some extent. In this paper, a novel approach was proposed to jointly conduct the traffic and vehicle simulations on real-road network in order to investigate the effect of traffic conditions on vehicle performance, further to investigate the penalty of fuel consumption and regular exhaust emissions caused by traffic accident and congestion. The main conclusions are as the following:

1. The approach of the combination simulations of traffic and vehicle system contains the following: (a) 3D OpenStreetMap extraction (including road elevation); (b) traffic condition loading and simulation; and (c) vehicle simulations based on the traffic simulation results.
2. The tendency of the fuel consumption and NO_x emissions as the function of road grade and vehicle speed was similar; high soot emission region was located at high vehicle speed and road grade that the maximum soot emission factor reached 3.2 g/100 km.
3. In the real-road simulation, vehicle acceleration dominated the fuel consumption, which was aggravated by road grade. The tendency of the NO_x and soot emission rates was consistent with that of fuel consumption rate whose peaks were mainly happened in the acceleration process.
4. The fuel penalties caused by accidents were in the range of 0.015-0.023 kg under the given scenarios for individual vehicle. The fuel consumption increased from 1.199 to 1.312 kg and 1.559 kg for 900 and 1800 vehicles/h traffic flow, compared with 180 vehicles/h traffic flow situation; also, NO_x emission increased by 67.3% and 170.1%, respectively.

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REFERENCES

1. Hooftman N, Messagie M, Van Mierlo J, Coosemans T. A review of the European passenger car regulations–Real driving emissions vs local air quality. *Renew Sust Energ Rev*. 2018;86:1-21.
2. Gao J, Ma C, Xing S, Sun L, Liu J. Polycyclic aromatic hydrocarbon emissions of non-road diesel engine treated with non-thermal plasma technology. *Korean J Chem Eng*. 2016;33:3425-3433.
3. Delgado O, Gonzalez F. CO_2 emissions and fuel consumption standards for heavy-duty vehicles in the European Union. 2018.
4. Rutty M, Matthews L, Andrey J, Matto TD. Eco-driver training within the City of Calgary's municipal fleet: Monitoring the impact. *Transp Res D Transp Environ*. 2013;24:44-51.
5. Vaezipour A, Rakotonirainy A, Haworth N. Reviewing in-vehicle systems to improve fuel efficiency and road safety. *Procedia Manuf*. 2015;3:3192-3199.
6. Qian J, Eglese R. Fuel emissions optimization in vehicle routing problems with time-varying speeds. *Eur J Oper Res*. 2016;248:840-848.
7. Gao J, Chen H, Li Y, et al. Fuel consumption and exhaust emissions of diesel vehicles in worldwide harmonized light vehicles

test cycles and their sensitivities to eco-driving factors. *Energy Convers Manage*. 2019;196:605-613.
8. Mohamed-Kassim Z, Filippone A. Fuel savings on a heavy vehicle via aerodynamic drag reduction. *Transp Res D Transp Environ*. 2010;15:275-284.
9. Benajes J, García A, Monsalve-Serrano J, Martínez-Boggio S. Optimization of the parallel and mild hybrid vehicle platforms operating under conventional and advanced combustion modes. *Energy Convers Manage*. 2019;190:73-90.
10. Benajes J, Novella R, Pastor JM, Hernández-López A, Kokjohn SL. Computational optimization of the combustion system of a heavy duty direct injection diesel engine operating with dimethyl-ether. *Fuel*. 2018;218:127-139.
11. Galindo J, Tiseira A, Navarro R, Tarí D, Meano CM. Effect of the inlet geometry on performance, surge margin and noise emission of an automotive turbocharger compressor. *Appl Therm Eng*. 2017;110:875-882.
12. E J, Zhao X, Qiu L, et al. Experimental investigation on performance and economy characteristics of a diesel engine with variable nozzle turbocharger and its application in urban bus. *Energy Convers Manage*. 2019;193:149-161.
13. Gao J, Chen H, Tian G, Ma C, Zhu F. An analysis of energy flow in a turbocharged diesel engine of a heavy truck and potentials of improving fuel economy and reducing exhaust emissions. *Energy Convers Manage*. 2019;184:456-465.
14. Villani M, Tribioli L. Comparison of different layouts for the integration of an organic Rankine cycle unit in electrified powertrains of heavy duty Diesel trucks. *Energy Convers Manage*. 2019;187:248-261.
15. Gao J, Tian G, Sorniotti A, Karci AE, Di Palo R. Review of thermal management of catalytic converters to decrease engine emissions during cold start and warm up. *Appl Therm Eng*. 2019;147:177-187.
16. Polikarpov E, Albrecht KO, Page JP, et al. Critical fuel property evaluation for potential gasoline and diesel biofuel blendstocks with low sample volume availability. *Fuel*. 2019;238:26-33.
17. Lin R, Deng C, Ding L, Bose A, Murphy JD. Improving gaseous biofuel production from seaweed *Saccharina latissima*: The effect of hydrothermal pretreatment on energy efficiency. *Energy Convers Manage*. 2019;196:1385-1394.
18. Huang H, Zhu J, Deng W, Ouyang T, Yan BO, Yang XU. Influence of exhaust heat distribution on the performance of dual-loop organic Rankine Cycles (DORC) for engine waste heat recovery. *Energy*. 2018;151:54-65.
19. Gao J, Tian G, Sorniotti A. On the emission reduction through the application of an electrically heated catalyst to a diesel vehicle. *Energy Sci Eng*. 2019;7:2383-2397.
20. Liu H, Li J, Wang J, et al. Effects of injection strategies on low-speed marine engines using the dual fuel of high-pressure direct-injection natural gas and diesel. *Energy Sci Eng*. 2019;7:1994-2010.
21. Devarajan Y, Mahalingam A, Munuswamy DB, Arunkumar T. Combustion, performance, and emission study of a research diesel engine fueled with palm oil biodiesel and its additive. *Energy Fuels*. 2018;32:8447-8452.
22. Manaf ISA, Embong NH, Khazaai SNM, et al. A review for key challenges of the development of biodiesel industry. *Energy Convers Manage*. 2019;185:508-517.
23. Moore RH, Thornhill KL, Weinzierl B, et al. Biofuel blending reduces particle emissions from aircraft engines at cruise conditions. *Nature*. 2017;543:411.
24. Emetere ME, Jack-Quincy S, Adejumo A, et al. Empirical analysis of biodiesel effect on the automobile properties of diesel engine: a case study of olive and soya biomass. *Energy Sci Eng*. 2018;6:693-705.
25. Oishi Y, Situmorang RS, Sembiring RA, Kawai H, Ambarita H. Performance, rate of heat release, and combustion stability of dual-fuel mode in a small diesel engine. *Energy Sci Eng*. 2019.
26. Devarajan Y, Munuswamy DB, Mahalingam A, Nagappan B. Performance, combustion, and emission analysis of neat palm oil biodiesel and higher alcohol blends in a diesel engine. *Energy Fuels*. 2017;31:13796-13801.
27. Manojkumar C, Thomas JJ, Sabu V, et al. Reduced chemical kinetic mechanism for a waste cooking oil biodiesel/n-pentanol mixture for internal combustion engine simulation. *Energy Fuels*. 2018;32:12884-12895.
28. Kasumba J, Fukagawa NK, Holmén BA. Fuel composition effects on carbonyls and quinones in particulate matter from a light-duty diesel engine running biodiesel blends from two feedstocks. *Energy Fuels*. 2019;33:1133-1145.
29. Liu H, Ma X, Li B, Chen L, Wang Z, Wang J. Combustion and emission characteristics of a direct injection diesel engine fueled with biodiesel and PODE/biodiesel fuel blends. *Fuel*. 2017;209:62-68.
30. Soriano JA, García-Contreras R, Leiva-Candia D, Soto F. Influence on performance and emissions of an automotive diesel engine fueled with biodiesel and paraffinic fuels: GTL and biojet fuel farnesane. *Energy Fuels*. 2018;32:5125-5133.
31. Oishi Y, Situmorang RS, Sembiring RA, Kawai H, Ambarita H. Performance, rate of heat release, and combustion stability of dual-fuel mode in a small diesel engine. *Energy Sci Eng*. 2019;7(4):1333-1351.
32. Gao J, Ma C, Xing S, Sun L, Huang L. A review of fundamental factors affecting diesel PM oxidation behaviors. *Sci China Technol Sci*. 2018;61:330-345.
33. Gao J, Ma C, Xing S, Sun L, Huang L. Nanostructure analysis of particulate matter emitted from a diesel engine equipped with a NTP reactor. *Fuel*. 2017;192:35-44.
34. Coskun G, Demir U, Soyhan HS, Turkcan A, Ozsezen AN, Canakci M. An experimental and modeling study to investigate effects of different injection parameters on a direct injection HCCI combustion fueled with ethanol–gasoline fuel blends. *Fuel*. 2018;215:879-891.
35. Coskun G, Delil Y, Demir U. Analysis of an HCCI engine combustion using toluene reference fuel for different equivalence ratios–Comparison of experimental results with CFD and SRM simulations. *Fuel*. 2019;247:217-227.
36. Mensing F, Bideaux E, Trigui R, Tattegrain H. Trajectory optimization for eco-driving taking into account traffic constraints. *Transp Res D Transp Environ*. 2013;18:55-61.
37. Jeffreys I, Graves G, Roth M. Evaluation of eco-driving training for vehicle fuel use and emission reduction: a case study in Australia. *Transp Res D Transp Environ*. 2018;60:85-91.
38. Mendoza-Villafuerte P, Suarez-Bertoa R, Giechaskiel B, et al. NO_x, NH_3, N_2O and PN real driving emissions from a Euro VI heavy-duty vehicle. Impact of regulatory on-road test conditions on emissions. *Sci Total Environ*. 2017;609:546-555.

39. Yu Q, Li T, Li H. Improving urban bus emission and fuel consumption modeling by incorporating passenger load factor for real world driving. *Appl Energy*. 2016;161:101-111.
40. Yuan W, Frey HC, Wei T, et al. Comparison of real-world vehicle fuel use and tailpipe emissions for gasoline-ethanol fuel blends. *Fuel*. 2019;249:352-364.
41. Serrano L, Carreira V, Câmara R, da Silva MG. On-road performance comparison of two identical cars consuming petrodiesel and biodiesel. *Fuel Process Technol*. 2012;103:125-133.
42. Silva CM, Farias TL, Frey HC, Rouphail NM. Evaluation of numerical models for simulation of real-world hot-stabilized fuel consumption and emissions of gasoline light-duty vehicles. *Transp Res D Transp Environ*. 2006;11:377-385.
43. Zhou M, Jin H, Wang W. A review of vehicle fuel consumption models to evaluate eco-driving and eco-routing. *Transp Res D Transp Environ*. 2016;49:203-218.
44. Bieker L, Krajzewicz D, Morra A, et al. Traffic simulation for all: a real world traffic scenario from the city of Bologna In: Behrisch M, Weber M, eds. *Modeling Mobility with Open Data*. Cham: Springer; 2015;47-60.
45. Wang L, Lin S, Yang J, et al. Dynamic traffic congestion simulation and dissipation control based on traffic flow theory model and neural network data calibration algorithm. *Complexity*. 2017;5067145:1-11.
46. Hu W, Wang H, Qiu Z, Yan L, Nie C, Du BO. An urban traffic simulation model for traffic congestion predicting and avoiding. *Neural Comput Appl*. 2018;30:1769-1781.
47. Zhu G, Liu J, Fu J, Xu Z, Guo Q, Zhao HE. Experimental study on combustion and emission characteristics of turbocharged gasoline direct injection (GDI) engine under cold start new European driving cycle (NEDC). *Fuel*. 2018;215:272-284.
48. Gschwend D, Soltic P, Wokaun A, Vogel F. Review and performance evaluation of fifty alternative liquid fuels for spark-ignition engines. *Energy Fuels*. 2019;33:2186-2196.
49. Solomon S. Impact of road geometry and surface types on fuel consumption and greenhouse gas emissions. *AAU*. 2018.
50. Daniel Krajzewicz JE, Behrisch M, Bieker L. Recent development and applications of SUMO – simulation of urban mobility. *Int J Adv Syst Meas*. 2012;5:128-138.
51. Osmosis. 2019. https://wiki.openstreetmap.org/wiki/Osmosis.
52. Acosta AF, Espinosa JE, Espinosa J. TraCI4Matlab: enabling the integration of the SUMO road traffic simulator and Matlab® through a software re-engineering process. In: Behrisch M, Weber M, eds. *Modeling Mobility with Open Data. Lecture Notes in Mobility*. Cham: Springer; 2015;155-170.
53. Madireddy M, De Coensel B, Can A, et al. Assessment of the impact of speed limit reduction and traffic signal coordination on vehicle emissions using an integrated approach. *Transp Res D Transp Environ*. 2011;16:504-508.
54. Costagliola MA, Costabile M, Prati MV. Impact of road grade on real driving emissions from two Euro 5 diesel vehicles. *Appl Energy*. 2018;231:586-593.
55. Gallus J, Kirchner U, Vogt R, Benter T. Impact of driving style and road grade on gaseous exhaust emissions of passenger vehicles measured by a Portable Emission Measurement System (PEMS). *Transp Res D Transp Environ*. 2017;52:215-226.
56. Larsson H, Ericsson E. The effects of an acceleration advisory tool in vehicles for reduced fuel consumption and emissions. *Transp Res D Transp Environ*. 2009;14:141-146.
57. Smit R, Brown A, Chan Y. Do air pollution emissions and fuel consumption models for roadways include the effects of congestion in the roadway traffic flow? *Environ Model Softw*. 2008;23:1262-1270.
58. Greenwood I, Dunn R, Raine R. Estimating the effects of traffic congestion on fuel consumption and vehicle emissions based on acceleration noise. *J Transp Eng*. 2007;133:96-104.
59. Figliozzi MA. The impacts of congestion on time-definitive urban freight distribution networks CO_2 emission levels: results from a case study in Portland, Oregon. *Transp Res Part C Emerg Technol*. 2011;19:766-778.
60. Bharadwaj S, Ballare S, Chandel MK. Impact of congestion on greenhouse gas emissions for road transport in Mumbai metropolitan region. *Transp Res Procedia*. 2017;25:3538-3551.
61. Kachroo P, Gupta S, Agarwal S, Ozbay K. Optimal control for congestion pricing: theory, simulation, and evaluation. *IEEE Trans Intell Transp Syst*. 2016;18:1234-1240.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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