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Speed-guided intelligent transportation system helps achieve low-carbon and green traffic: Evidence from real-world measurements

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A B S T R A C T

Intelligent transportation systems (ITS) have emerged as essential measures to manage traffic congestion and to reduce vehicular emission and energy consumption, while their effectiveness has not been directly quantified under real-world driving conditions. By conducting real-world driving and emission measurements with a portable emission measurement system, we found that the usage of the speed guided-ITS (SG-ITS) significantly reduces fuel consumption and pollutant emissions (i.e., carbon monoxide, nitrogen monoxide, nitrogen dioxide, and particle number) of both tested vehicles (a light-duty gasoline car and a heavy-duty diesel truck) through decreasing the frequency of starts and stops, the strength of acceleration, and the time proportions of acceleration and idle. These reductions obtained from real-world measurements are higher than those predicted by vehicle emission models such as Motor Vehicle Emission Simulator (MOVES) and Computer Programme to calculate Emissions from Road Transport (COPERT). Reductions in fuel consumption and pollutant emissions due to the usage of the SG-ITS are most efficient on urban roads (low traffic) among all the three road types, while the most time saving can be obtained on urban roads (high traffic). By combining a high-resolution vehicle emission inventory, we estimate that the implementation of the SG-ITS may significantly reduce the total vehicular exhaust emissions of nitrogen oxides, carbon monoxide, total hydrocarbons, and particulate matter in Beijing by 15.9%, 20.5%, 23.9%, and 22.5%, respectively. Our study directly evaluates the benefits of using SG-ITS based on real-world measurements, highlighting that implementation of the SG-ITS can be a practical policy option in terms of efficiently reducing energy consumption, mitigating urban air pollution, and alleviating urban traffic congestion.

1. Introduction

Motor vehicles remain the predominant anthropogenic source of atmospheric particulate matter (PM) and gaseous pollutants, affecting global climate, regional air quality, and public health (Maykut et al., 2003; Querol et al., 2007; West et al., 2016; Winkler et al., 2018; Zheng et al., 2017). To mitigate vehicle emission pollution and improve fuel economy, various efforts have been undertaken by both central and local governments all over the world. Currently, the predominant way is to directly reduce the pollutant emissions of individual vehicle by formulating rigid emission standard (European Commission, 2012), adopting new engine and vehicle technologies (Bergmann et al., 2009; Lähde et al., 2011), promoting fuel quality (Perumal and Ilangkumaran, 2018), and supplying renewable fuels (Jin et al., 2017). An alternative way is to improve traffic by modifying the transport

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infrastructure (e.g., widening existing roads and constructing new transit lines), implementing vehicle operating restrictions (e.g., odd-and-even license plate rule (Xie et al., 2017), congestion charges (Beevers and Carslaw, 2005), and low emissions zones (Holman et al., 2015)), and employing intelligent transportation systems (ITS) (Alrawi, 2017). In particular, compared with traditional methods which require large amount of long-term investments, the application of ITS is relatively low-cost and instant to reduce vehicular pollutant emissions and fuel consumption (Huang et al., 2018). Closely linked with a variety of elements (e.g., intelligent transportation infrastructure, vehicle connectivity, real-time information service, and big data technology), ITS are gradually employed to tackle the increasing traffic congestion and vehicle emission pollution (Fotouhi et al., 2014; Neilson et al., 2019; Sirohi et al., 2020; Souza et al., 2016; Zhang et al., 2018).

The control strategy and geometric configuration at the intersection, a critical element of the transportation network, can significantly affect the traffic conditions and the vehicle emissions (Alam and McNabola, 2014; Fernandes et al., 2016; Meneguzzer et al., 2017; Pandian et al., 2009; Samia et al., 2016). Various ITS technologies are thus developed to enhance the probability of vehicle passing through intersections during green-light periods and reduce the congestion at traffic intersections (Asadi and Vahidi, 2011; Mahler and Vahidi, 2014; Mandava et al., 2009; Schuricht et al., 2011; Sun and Liu, 2015; Tang et al., 2017;Yang et al., 2013; Yang et al., 2010). For example, Yang et al. (2010) investigated the active role of green wave speed guidance strategy via a microscopic traffic simulator named VISSIM, proving that the delays and stops can be both reduced by 29% for the vehicle on a suburban highway. Mandava et al., 2009 explored the essential role of arterial velocity planning model in reducing sharp acceleration/deceleration and break near intersections, indicating that 12–14% reductions in both energy consumption and pollutant emissions were obtained via simulations from an energy and emission model. Considering that the technologies utilized in these studies are to provide guiding speed to the drivers, the analogous ITS are categorized as speed-guided ITS (SG-ITS) herein. The analyses of the SG-ITS in previous studies were generally conducted by using models to simulate traffic activities (e.g., intelligent-driver model (Schuricht et al., 2011), VISSIM (Yang et al., 2010)) and/or vehicle fuel consumption and pollutant emissions (e.g., comprehensive modal energy and emissions model (CMEM) (Mandava et al., 2009), motor vehicle emission simulator (MOVES) (Tang et al., 2017)). However, considering the limitations of traffic flow models and emission models (e.g., the incapability of VISSIM to explore the complex traffic conditions near intersections (Tang et al., 2017) and the insensibility of MOVES on vehicle past short-term operating history (Liu and Barth, 2012)), models may not accurately reflect the traffic activity and the emission in the real world, leading to considerable uncertainty on the assessment of the effectiveness of the SG-ITS. Therefore, real-world measurements will be of immense necessity to make up for the shortcomings of model simulation and to obtain direct quantifications of the effectiveness of the SG-ITS.

In this study, we performed real-world vehicle emission measurements with a portable emission measurement system (PEMS) on two distinct routes and real-world vehicle driving measurements on a complicated route, consisting of urban roads with low traffic, urban roads with high traffic, and suburban roads, in Wuqing District, Tianjin, China. The effectiveness of the SG-ITS on driving behaviors, time-saving, fuel consumption, and pollutant emissions are directly investigated by driving the vehicle on the same route with and without the SG-ITS. An in-depth analysis of the real-world measurement data is conducted to elucidate how the changed driving behaviors affect fuel consumption and pollutant emissions. In addition, the influences of various vehicle types (i.e., light-duty gasoline passenger car and heavy-duty diesel truck) and road conditions (i.e., urban roads (low traffic), urban roads (high traffic), and suburban roads) on the effectiveness of the SG-ITS are further quantified. At last, the potential reduction of vehicular exhaust emissions in Beijing benefited from the implementation of the SG-ITS is also estimated based on the real-world measurement results, vehicle emission model simulations, and a high temporal-spatial vehicular emission inventory in a previous study (Jing et al., 2016).

2. Methods

2.1. Speed-guided ITS

The incentive in the SG-ITS is to improve traffic efficiency by reducing the frequency of vehicle stop at intersections. The technology in the SG-ITS is a digital road map similar to the kind employed by satellite navigation systems. Once the information on both the current location message of the vehicle and the timing of traffic lights is collected through a global positioning system (GPS) receiver and a traffic signal detector, respectively, proper travel speed to pass through the intersections will be worked out by background processors and provided to the drivers. Then, the vehicle equipped with a receiving plate to obtain speed information can travel at guided speeds and pass through the intersections during the green light periods. The diagram of the SG-ITS working principle is depicted in Fig. 1.

2.2. Test routes and vehicles

As one of the pilot National Smart Cities in China, Wuqing district in Tianjin City, equipped with the SG-ITS developed by Aiyicheng Technology (Tianjin) Co., Ltd, was selected to explore the effectiveness of the SG-ITS. Wuqing district is located in the middle of the two megacities (Beijing and Tianjin). The fleet composition in the Wuqing district can well represent those in Beijing and Tianjin. Besides, various road types and traffic conditions exit in the Wuqing district, which will be helpful to fully investigate the effectiveness of SG-ITS under real-world driving conditions. The test routes for the real-world measurements are demonstrated in Fig. S1. Two test routes (route 1 and route 2) for the light-duty gasoline passenger car (LDGC) and one suburban route (route 3) for the heavy-duty diesel truck (HDDT) were selected to perform real-world driving or emission measurements in December 2017. For the gasoline car, real-world emission tests were conducted on a short urban route (route 1, 12 km) where the traffic volume was usually less than 500 vehicles per hour (v/h) for one-way traffic and the vehicles driving on the route were mainly light-duty vehicles. To explore the influence of different road conditions (e.g., traffic volumes and road types) on the effectiveness of the SG-ITS, real-world driving behavior tests for the gasoline car were also conducted on another long route (route 2, 37 km), consisting of urban roads with low traffic volume (<500 v/h), urban roads with high traffic volume (>500 v/h), and suburban roads (<500 v/h). For the diesel truck, however, real-world emission measurements were carried out on a suburban route (route 3, 29 km) with low traffic volume (<500 v/h). The density of the signalized intersection, defined herein as the signalized intersection number per kilometers of road section length, is usually larger than 1 km^{-1} for the urban roads but less than 1 km^{-1} for the suburban roads. More details about the tested routes are provided in Table S1.

The specifications of the tested vehicles are presented in Table 1. The fuel used here was obtained directly from the local market and was of quality in line with China 5. To minimize the impact of driver's driving habits on the test results, two local drivers were

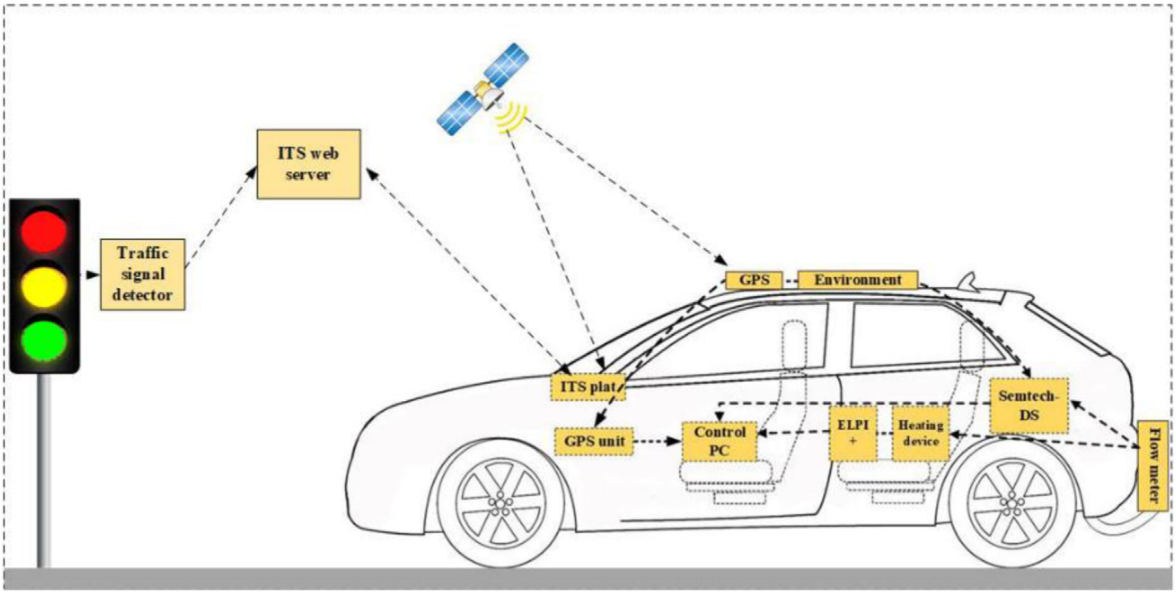

Fig. 1. Schematic diagram of the installation and working principle of PEMS and SG-ITS.

Table 1
Specifications of the tested vehicles.

Parameters	Specifications	
Vehicle brand	Volkswagen Golf	Dongfeng Captain
Vehicle model	LDGC	HDDT
Gross/curb weight (t)	1.76/1.28	14.6/4.40
Engine type	Turbocharged, direct injection	Intercooling Turbocharged
Fuel type	Gasoline	Diesel
Max. engine power (kw)	96	103
Max. engine torque (N.m)	225	502
Displacement (L)	1.4	3.7
After treatments	Three-way catalytic converter	–
Emission standard	Euro 5	Euro 3
Model year	2015	2013
Odometer (km)	19,654	34,847
Gear	Automatic 7	Manual 6

arranged to drive the tested vehicles alternately on route 1 and route 3. Once one driver finished two continuous trips, including one trip with the SG-ITS and another without the SG-ITS, another driver would be arranged to drive the vehicle for the next two continuous trips. Considering that the vehicle category on urban route 1 and suburban route 3 was relatively stable during the test period and the traffic volumes on both routes were low (<500 v/h), the traffic conditions during the test period can reasonably be considered the same and will hardly affect the results of the experiment. For the driving behavior tests on route 2, however, significant traffic variations between adjacent trips occurred due to the complicated traffic conditions. To eliminate the impact of traffic variations on test results, two gasoline cars, including the previous one and another of the same model, were employed to start at the same time and the same starting location for each trip. The rule between the two gasoline cars was that one drive with the SG-ITS and another drive without the SG-ITS. For the next trip, the vehicle under driving with the SG-ITS in the previous trip will be changed to driving without the SG-ITS, and another under driving without the SG-ITS in the previous trip will be changed to driving with the SG-ITS. The number of driving trips both with and without the SG-ITS was 12 on route 1, 9 on route 2, and 3 on route 3.

2.3. Measurement system

Emissions data from real-world emission tests on route 1 and route 3 were collected by a united PEMS, consisting of a Semtech-DS Gas PEMS for gaseous pollutants and a new electrical low-pressure impactor (ELPI+) for real-time particle number (PN) concentrations. The Semtech-DS, developed by Sensors Inc., uses a heated flame ionization detector (HFID) to measure the exhaust gas concentrations of total hydrocarbons (THC), a non-dispersive infrared sensor (NDIR) to detect CO and CO_2, and a non-dispersive ultraviolet sensor (NDUV) to obtain nitrogen monoxide (NO) and nitrogen dioxide (NO_2) concentration. Additionally, several other units fixed around the vehicle body were also included: an exhaust flow meter (EFM) equipped with a pitot-tube pressure device for the exhaust flow rate, a GPS for the vehicle speed and geographic location information (i.e., altitude, latitude, and longitude), and a weather probe for the ambient humidity and temperature. Constrained by the limited space in the gasoline car, together with the safety considerations, the THC of the gasoline car was not measured. The ELPI+, developed by Dekati Ltd., was utilized to classify particles over an aerodynamic diameter range of 6 nm–10 μm in a flow rate of 10 L/min. Particles in this study were directly measured by the ELPI + without a dilution system but equipped with a specialized external heating device (Dekati Ltd,). By heating the impactor, the heating device allows direct measurement of up to 180 °C aerosol samples from the exhaust pipe. Additionally, the heating device and the sampling tube near the exit of the exhaust flow meter of the PEMS were connected by a 1.5 m heated sampling line, the temperature of which was controlled and maintained stability around 180 °C by a secondary integrated digital control unit. For the driving behavior tests on route 2, however, only a GPS unit was equipped in each car due to the shortage of available instruments to conduct simultaneous real-world emission tests for the two gasoline cars. The diagram of the installation of PEMS is also shown in Fig. 1.

To ensure the accuracy of the PEMS, routine calibrations before and after tests of gaseous and particle pollutants were conducted by controlling for the zero and span drift of the gaseous analyzers, purging and verifying the zero flow of the EFM, and executing flush and zero calibrations for the electrometer in the ELPI+. All pollutant emissions were tracked at 1 Hz frequency. The whole PEMS, together with a co-driver, weighed approximately 240 kg (100 kg for instruments, 60 kg for batteries, and 80 kg for the co-driver), accounting for nearly 18% of the gasoline car's curb weight. For the emission tests of the diesel truck, a diesel generator (120 kg) was used to replace batteries to power the instruments. The whole PEMS and the co-driver resulted in nearly 7% of the curb weight of the diesel truck. Time synchronization of data acquired by different devices was performed before data analysis due to the different response times of different instruments. The emissions of all gaseous pollutants were obtained without the ambient humidity correction in this study (Weiss et al., 2011).

2.4. Model simulation

As the significant widespread vehicle emission models in the world, MOVES (EPA, 2017) and Computer Programme to calculate Emissions from Road Transport (COPERT) (EEA, 2016) were both used herein to obtain vehicle fuel consumption and pollutant emissions based on real-world vehicle driving cycles. COPERT (version 5 used here) can estimate vehicle emissions by multiplying real-world activity data by the speed-related emission factors contained in the model. To further reflect the variations of vehicle driving behaviors affected by the usage of SG-ITS, real-world driving data were separated into three modes: urban with speed <40 km/h, rural with speed 40–80 km/h, and highway with speed >80 km/h. Then, according to the average speeds and distance proportions for different modes, the fuel consumption and pollutant emissions during the tested trip with/without SG-ITS can be worked out through COPERT. However, unlike COPERT that predict emissions mainly based on average speed (Ntziachristos et al., 2009), MOVES (version 2014b used here) can estimate vehicle emissions through the operating mode distribution approach. This approach allows one to classify the amount of travel time into various operation modes, namely vehicle specific power (VSP) bins, containing braking, idling, coasting and cruising/accelerating in different speed ranges and different ranges of VSP. Once the time proportions of different VSP-bins can be obtained, the fuel consumption and pollutant emissions of the tested trip with/without SG-ITS can then be worked out by MOVES through combining the VSP related fuel and pollutant emission rates contained in the model. Eventually, the effectiveness of the SG-ITS under different traffic conditions can be acquired via simulations from both models based on driving cycles with and without the SG-ITS.

3. Results and discussion

3.1. Driving behavior influenced by SG-ITS

Marked differences in the behaviors for driving with and without the SG-ITS were observed on all three routes, particularly near the intersections (Fig. 2). Driving with the SG-ITS on the road sections between adjacent intersections generally exhibited lower speed than driving without the SG-ITS, leading to larger proportions of speeds near 50 km/h and smaller proportions of speeds near 70 km/h for driving with the SG-ITS compared to driving without the SG-ITS (Fig. 3a1-a5 and Fig. S2a). Also, the usage of the SG-ITS led to 73.3%, 71.9%, and 65.0% fewer stops for driving on route 1, route 2, and route 3, respectively (Table S2). The time proportions of four driving modes (i.e., acceleration, deceleration, cruise, and idle mode), defined in Table S3, were also calculated to describe the differences in driving behaviors. Associated with the reduced stops, the proportions of low speeds below 10 km/h (Fig. 3a1-a5 and Fig. S2a) and the proportion of idle mode (Fig. 3c1-c5 and Fig. S2c) were found to be markedly reduced due to the usage of the SG-ITS. The proportion of idle mode was reduced by 96.8%, 59.5%, and 92.0% for driving on route 1 (Fig. 3c1), route 2 (Fig. S2c), and route 3 (Fig. 3c5), respectively. Due to the fewer stops and the smaller proportions of idle mode and low speeds below 10 km/h, the usage of the SG-ITS led to 8.0%, 7.9%, and 3.2% higher average speeds for driving on route 1, route 2, and route 3, respectively (Table S2).

As shown in Fig. 3b1-b5 and Fig. S2b, the usage of the SG-ITS resulted in larger proportions of low acceleration and deceleration, but smaller proportions of high acceleration and deceleration. This finding is consistent with that compared with driving without the SG-ITS, the driving with the SG-ITS exhibited 89.2%, 74.7%, and 25.6% larger proportions of cruise mode for route 1 (Fig. 3c1), route 2 (Fig. S2c), and route 3 (Fig. 3c5), respectively. Associated with the larger proportions of cruise mode, the proportions of acceleration mode were reduced by 14.3%, 18.6%, and 19.4% for driving on route 1 (Fig. 3c1), route 2 (Fig. S2c), and route 3 (Fig. 3c5), respectively. Also, with the usage of the SG-ITS, 30.4%, 26.4%, and 17.3% lower values of trip-average relative positive acceleration (RPA), a speed-related average of the vehicle acceleration (Yang et al., 2020) and generally used to characterize the load of vehicle trips, were observed for driving on route 1, route 2, and route 3, respectively (Table S2). In particular, the average speed-bin RPA with the SG-ITS was lower than that without the SG-ITS when the speed was lower than 80 km/h, but slightly higher when the speed surpassed 80 km/h (Fig. 3d1-d5 and Fig. S2d), further proving that the usage of the SG-ITS can significantly reduce the frequency and strength of acceleration at low- and medium-speeds.

The different driving characteristics between with and without the SG-ITS can be interpreted by the different driving behaviors. Drivers without the SG-ITS generally arrive at the intersections during the non-green light periods and have to stop the vehicles, while drivers with the SG-ITS are usually able to catch up with green lights and pass through the intersections without stop. Such difference leads to fewer stops and smaller proportions of idle and low speed for driving with the SG-ITS compared to driving without the SG-ITS. Thus, the usage of the SG-ITS can generally help increase the average speed and reduce the travel time. Furthermore, drivers without the SG-ITS have to restart and accelerate the vehicles more frequently since the higher probability of stopping at the intersections. In particular, drivers without the SG-ITS get used to accelerating to high speeds during road sections between adjacent intersections. Drivers with the SG-ITS, on the other hand, will

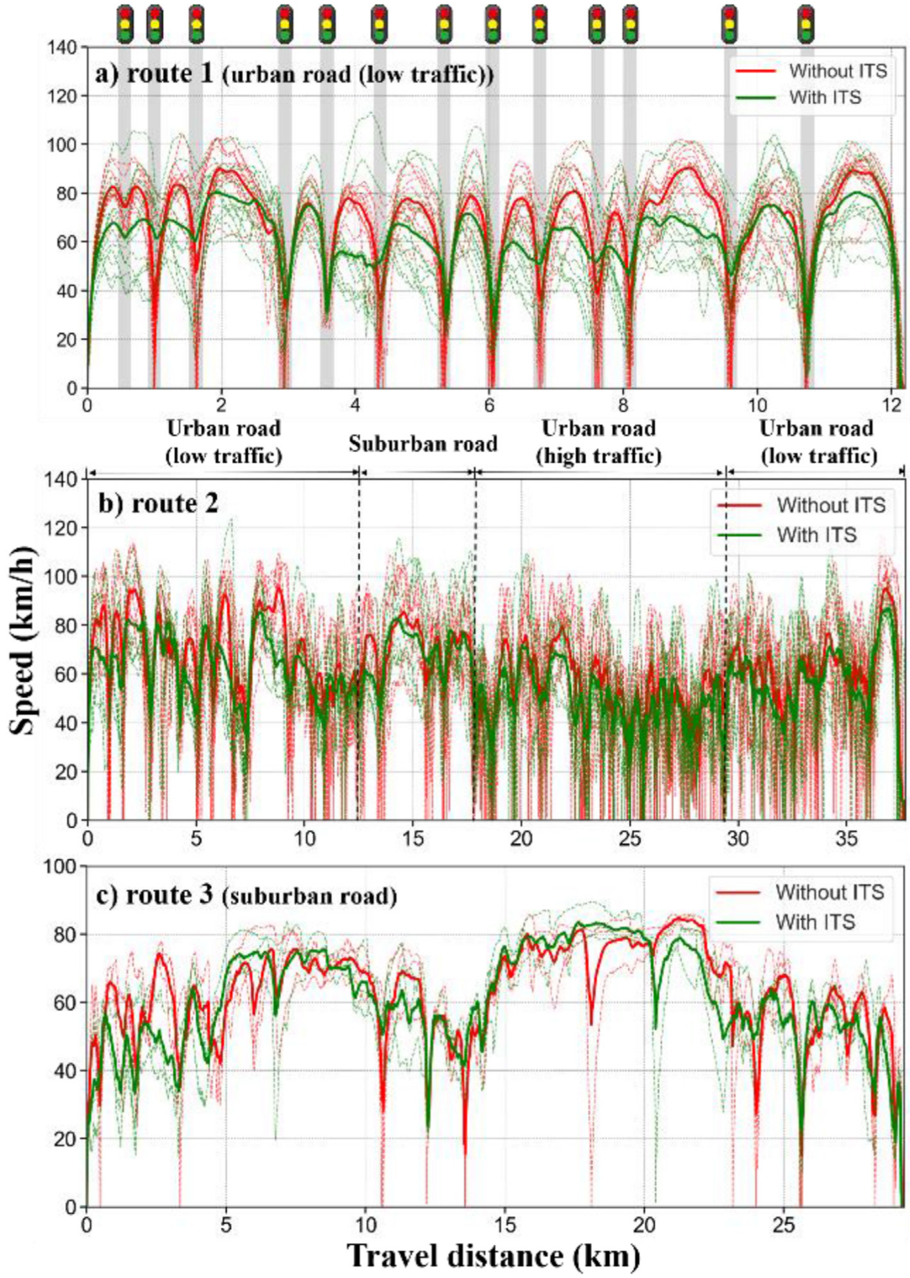

Fig. 2. Travel distance (km)-speed (km/h) curves for the gasoline car tests on route 1 (a) and route 2 (b), and the diesel truck tests on route 3 (c) with or without SG-ITS. The solid lines represent the average speed curves of tests, and the dashed lines represent the speed curve of each test. The grey shadows represent the locations of intersections on the trip.

be suggested to keep at a proper and constant speed enough to catch up with the traffic green lights. Therefore, lower RPA, smaller proportions of acceleration mode, and larger proportions of cruise mode can be achieved by the usage of the SG-ITS. In addition, during a road section between two adjacent intersections, the SG-ITS will sometimes suggest two speed options, a high speed (>80 km/h) to catch up with the current green light and a low speed to pass through the intersection during the next green light. If the driver chooses to catch up with the current green light to pass, hard acceleration leading to higher RPA at high speeds is sometimes inevitable.

The effect of the SG-ITS on driving behaviors varies with road types. The usage of the SG-ITS for the gasoline car led to more significant reductions in idle mode proportion (Fig. 3c1-c4) and stops (Table S2) on the suburban roads compared to urban roads with low and high traffic volumes. This can be interpreted by the low density of intersection and low traffic volumes on the suburban roads, which allows the drivers to have sufficient operating time and space to follow the guiding speed and avoid stops. However, the trip-average RPA on urban roads (low traffic) was more significantly reduced than that on the suburban roads (Table S2), mainly because the driving behaviors on the suburban roads even without the SG-ITS can be smooth enough (Table S2). On the other hand, compared with the suburban roads, a lower reduction in the trip-average RPA was achieved on urban roads (high traffic), probably due to its complex traffic conditions.

Under the same road type, the effects of the SG-ITS on driving behaviors also vary with road traffic volumes. The usage of the SG-

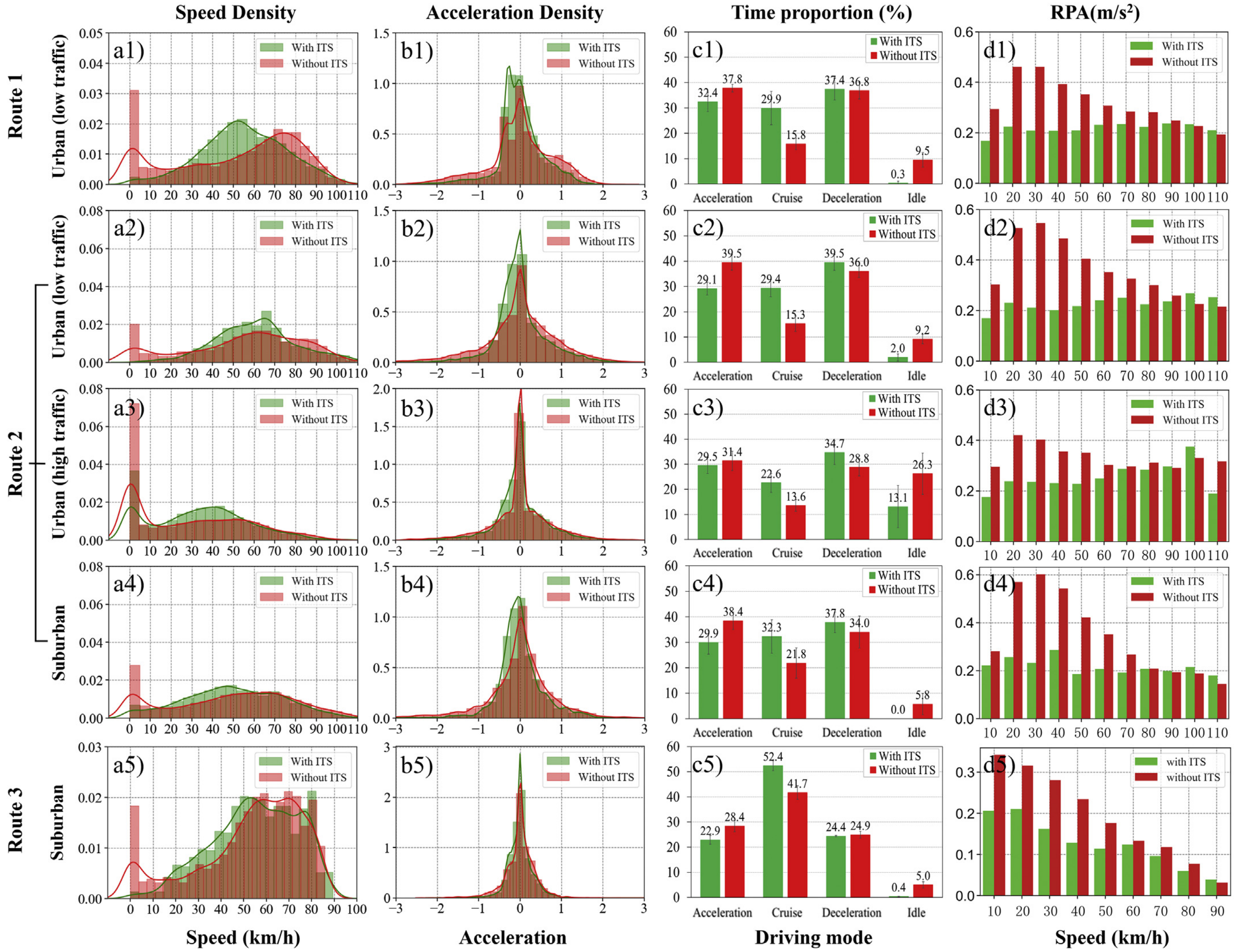

Fig. 3. Comparison of the speed (a1-a5) and acceleration (b1-b5) density distribution, trip-average time proportions of driving modes (c1-c5), and trip-average RPA of different bins of speed (d1-d5) with and without SG-ITS on route 1, route 2, and route 3. Route 2 is further classified as urban roads with low traffic, urban roads with high traffic, and suburban roads according to the traffic volume and density of the signalized intersection.

ITS led to higher reductions in RPA, stops, and proportions of acceleration and idle mode on urban roads (low traffic) compared to urban roads (high traffic) (Table S2 and Fig. 3c1-c4), because it is challenging to drive the vehicle at the guiding speed suggested by the SG-ITS under high traffic volume conditions due to the limited operating space. However, more considerable promotion in the average driving speed (in other words, more time saving) on urban roads (high traffic) (12.9%) was achieved compared to urban roads (low traffic) (2.6%) (Table S2). This phenomenon may be explained by that once the vehicle can not successfully pass the intersection, more waiting time is generally required under the congested traffic conditions frequently caused by high volumes. Substantially, the time savings for each car under the congested traffic conditions will, in return, improve the efficiency of road network traffic, alleviate traffic congestion, and reduce vehicle emissions.

In terms of the impacts of vehicle type on the effectiveness of the SG-ITS, the usage of the SG-ITS led to more significant reductions in stops, RPA, and proportions of acceleration and idle mode for the gasoline car compared to the diesel truck both on the suburban roads (Table S2 and Fig. 3c4-c5). Also, the promotion in the average driving speed was more significant for the gasoline car compared to the diesel truck (Table S2). Moreover, a larger proportion of cruise mode and a smaller RPA were observed for the diesel truck compared to the gasoline car under driving both with and without the SG-ITS, indicating that the driving behavior of the diesel truck is smoother than that of the gasoline car. These phenomena suggest that the large inertia of the truck, mainly due to its heavy weight, inhibits its rapid speed change, and therefore constrains the ability of the driver to follow the guiding speed perfectly.

3.2. Fuel consumption and pollutant emission reduction

A carbon balance method based on the real-time carbonaceous gaseous emission rates was employed to calculate the instantaneous fuel consumption rates (Wu et al., 2015). Considering that the emission rates of THC are usually two orders of magnitude lower than that of CO_2 (Kousoulidou et al., 2013), the lack of THC emissions herein would have little impact on the calculation of fuel consumption for the gasoline car. The fuel consumption rates can be calculated as Eq. (1):

$$ER_{Fuel} = \frac{\frac{M_C}{M_{CO_2}} \times ER_{CO_2} + \frac{M_C}{M_{CO}} \times ER_{CO} + W_{HC} \times ER_{HC}}{W_C} \quad (1)$$

where ER_{Fuel}, ER_{CO_2}, ER_{co}, and ER_{HC} (g/s) represent the instantaneous rates of fuel, emission rates of CO_2, CO, and THC, respectively; M_{CO}, M_{CO_2}, and M_C (g) represent the molecular or atomic mass of carbon monoxide, carbon dioxide, and carbon, respectively; and W_C (gasoline: 0.866, diesel: 0.863) and W_{HC} (gasoline: 0.866, diesel: 0.863) represent the carbon balance in the fuel and average carbon mass balance of THC in the exhaust gas, respectively.

The trip-average emission factors (EFs) of the gasoline car and the diesel truck measured by PEMS are displayed in Table 2. Most of the observed CO and NO_x EFs of the gasoline car agreed with the Euro 5 emission limits (CO: 1 g/km, NO_x: 0.06 g/km), except the NO_x EFs under driving without the SG-ITS with an excess of 18.7%. However, the real-world NO_x EFs of the gasoline car under driving without the SG-ITS was still far below the real driving emission limit (0.126 g/km), which is defined as multiplying the conformity factor (2.1 for NO_x) to the emission limits. Besides, the pollutant EFs for the tested diesel truck in our study were in good agreement with the previous studies as shown in Table S4 (Huo et al., 2012; Wu et al., 2012; Yao et al., 2015; Zhang et al., 2016). From the real-world emission results, we find that the SG-ITS plays a significant role in decreasing fuel consumption and pollutant emissions for both tested vehicles. The usage of the SG-ITS resulted in 18.9% lower fuel consumption, and 28.6%, 31.3%, 32.6%, and 24.9% lower CO, NO, NO_2, and PN emissions, respectively, for the gasoline car. Lower fuel consumption (8.1%) and emissions of CO (9.9%), NO (7.5%), NO_2 (6.3%), PN (8.9%), and THC (9.6%) of the diesel truck were also caused by the usage of the SG-ITS (Table 2).

Distinct trip-average fuel consumption and pollutant emissions in different speed bins for both tested vehicles were found in the measurements. Lower speed-bin fuel consumption and pollutant EFs under low- and medium-speeds (<80 km/h) were caused by the usage of the SG-ITS for both tested vehicle (Fig. 4 a1-a5 and b1-b6). In particular, more significant reductions in the low- and medium-speed bins were found for the gasoline car compared to the diesel truck, probably due to the lower value and less significant decrease in RPA for the diesel truck. Moreover, for speeds below 80 km/h, the differences between driving with and without the SG-ITS in speed-bin EFs generally decreased as the speed increased. Such trends were closely linked with the variation of speed-bin RPA (Fig. 3d1 and d5), suggesting that the lower frequency and strength of acceleration caused by the usage of the SG-ITS at low- and medium-speeds has a crucial impact on reducing fuel consumption and pollutant emissions. This is likely because the acceleration of vehicles temporarily increased the engine speed but decreased the air/fuel ratio, leading to incomplete mixing of air and fuel, lower combustion efficiency, and thereby more fuel consumption and pollutant emissions (Suarez-Bertoa and Astorga, 2018; Überall et al., 2015; Wang et al., 2016). Additionally, lower fuel consumption and pollutant emissions were also related to the smaller proportions of severe deceleration (Fig. 3b1-d5) caused by the usage of the SG-ITS, primarily because more extra work by the engine is needed to make up the energy lost during braking. Besides, the effects of the SG-ITS on average speed-bin EFs reflect that the usage of speed-dependent emission models would result in substantial uncertainty in estimating vehicle emissions in the real world (O'Driscoll et al., 2016).

For the gasoline car, acceleration mode shared 32.4–37.8% of the driving time but contributed to 49.6–58.6% of the total fuel consumption, and 43.6–48.2%, 55.4–57.3%, 72.7–79.8%, and 81.6–84.6% of the total NO_2, NO, CO, and PN emissions, respectively (Table S5). However, likely due to the lower strength of acceleration, acceleration mode for the diesel truck accounted for comparable driving time (22.9–28.4%) but much less fuel consumption (27.4–33.3%) and pollutant emissions (25.1–30.0%, 25.2–30.3%, 34.1–41.2%, 30.3–36.5%, and 21.4–28.6% of the NO_2, NO, CO, PN, and THC, respectively) (Table S5). Clearly, more substantial contributions of acceleration mode to CO and PN emissions compared to NO_2 and NO emissions were found for both tested vehicles, and the differences were more evident for the gasoline car.

As shown in Fig. 4c1-c5 and d1-d6, for low speeds below 20 km/h for the diesel truck and below 30 km/h for the gasoline car, the

Table 2
Vehicle exhaust pollutant EFs and fuel consumption obtained from PEMS measurements and predicted by vehicle emission models.

Vehicle (route)	Model/PEMS		SG-ITS/DR	Fuel (L/100 km)	NO_2 (mg/km)	NO (mg/km)	CO (g/km)	THC (mg/km)	PN (E+12 [a]/km)
LDGC (route 1)	MOVES 2014b		with ITS[a]	7.46 ± 0.38	2.29 ± 0.66	12.3 ± 3.4	0.40 ± 0.01	2.16 ± 0.66	N/A
			without ITS[b]	8.59 ± 0.35	3.31 ± 0.54	17.7 ± 2.8	0.53 ± 0.01	3.22 ± 0.55	N/A
			DR (%)	13.3	30.8	30.5	24.5	32.9	N/A
	COPERT 5v2.2		with ITS	6.21 ± 0.07	0.12 ± 0.04	21.0 ± 1.4	0.27 ± 0.01	N/A	N/A
			without ITS	6.45 ± 0.08	0.12 ± 0.02	21.0 ± 1.0	0.28 ± 0.01	N/A	N/A
			DR (%)	3.7	0	0	3.5	N/A	N/A
	PEMS		with ITS	9.9 ± 1.1	3.81 ± 1.89	45.1 ± 23.2	0.20 ± 0.08	N/A	2.15 ± 1.07
			without ITS	12.2 ± 2.2	5.65 ± 1.61	65.6 ± 12.7	0.28 ± 0.12	N/A	2.86 ± 0.82
			DR (%)	18.9	32.6	31.3	28.6	N/A	24.9
HDDT (route 3)	MOVES 2014b		with ITS	18.8 ± 1.2	237.2 ± 14.9	354.0 ± 22.3	0.23 ± 0.01	98.5 ± 5.32	N/A
			without ITS	19.5 ± 1.0	244.2 ± 15.5	364.5 ± 23.1	0.24 ± 0.01	98.8 ± 7.46	N/A
			DR (%)	3.6	2.9	2.9	3.9	0.3	N/A
	COPERT 5v2.2		with ITS	21.5 ± 0.5	704.4 ± 18.6	4327.3 ± 114.2	1.24 ± 0.05	N/A	N/A
			without ITS	21.8 ± 0.7	715.4 ± 26.9	4394.8 ± 165.2	1.28 ± 0.06	N/A	N/A
			DR (%)	1.7	1.5	1.5	3.2	N/A	N/A
	PEMS		with ITS	12.8 ± 0.2	404.6 ± 58.3	7582.3 ± 152.8	1.64 ± 0.17	124.3 ± 24.6	29.3 ± 11.7
			without ITS	13.9 ± 0.2	432.1 ± 81.6	8196.1 ± 145.1	1.82 ± 0.38	136.6 ± 21.6	32.4 ± 14.5
			DR (%)	8.1	6.3	7.5	9.9	8.9	9.6
LDGC (route 2)	MOVES 2014b	Whole	DR (%)	11.2	24.1	24.1	18.9	23.5	N/A
		Suburban	DR (%)	9.7	11.6	11.2	5.4	6.1	N/A
		Urban[c]	DR (%)	10.8	22.1	21.8	18.5	21.9	N/A
		Urban[d]	DR (%)	11.7	27.5	25.9	22.9	26.7	N/A

[a] Driving with guiding speed suggested by SG-ITS.
[b] Driving without guiding speed suggested by SG-ITS.
[c] Road section with high traffic volume.
[d] Road section with low traffic volume.

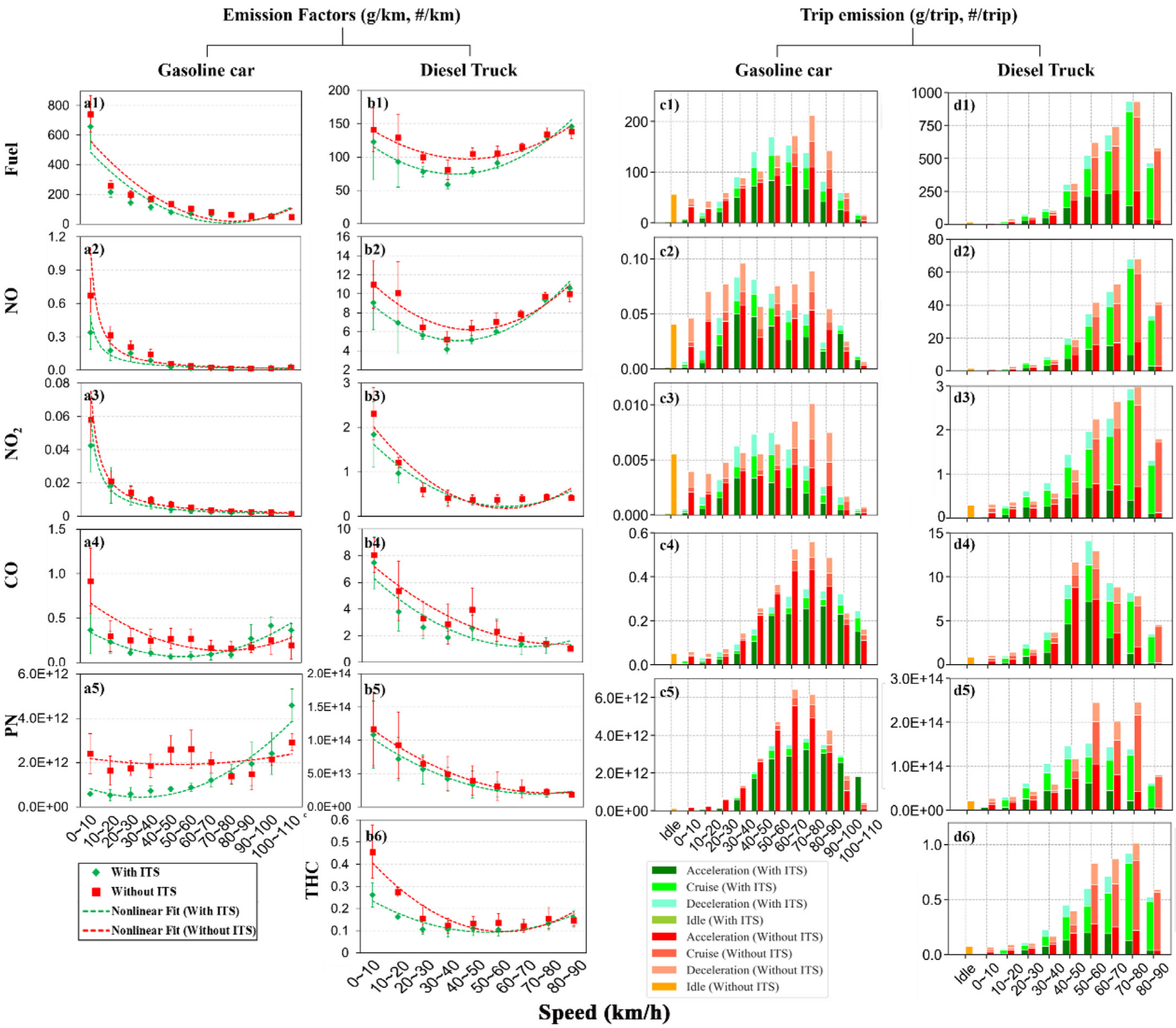

Fig. 4. Comparison of the average speed-bin emission parameters with and without the SG-ITS: emission factors for the gasoline car (a1-a5); emission factors for the diesel truck (b1-b6); total trip emissions for the gasoline car (c1-c5); total trip emissions for the diesel truck (d1-d5). Features of fuel consumption and emissions of NO, NO_2, CO, PN, and THC are displayed here.

usage of the SG-ITS led to lower fuel consumption and pollutant emissions due to the smaller contributions of acceleration mode in these speed bins. In particular, more significant reductions in low speeds of the gasoline car were observed for the fuel consumption and NO_x emissions compared to CO and PN emissions. For medium speeds around 70 km/h, due to the lower contributions of acceleration modes, lower fuel consumption and pollutant emissions were caused by the usage of SG-ITS for both tested vehicles. The fuel consumption and pollutant emissions at these speeds were more significantly reduced by the usage of the SG-ITS for the gasoline car compared to the diesel truck. For speeds around 40 km/h, due to the higher contributions of cruise and deceleration modes, higher speed-bin values were observed under driving with the SG-ITS for fuel consumption and pollutant emissions of both tested vehicles except the CO and PN of the gasoline car. In addition, the trip-average CO and PN emissions under driving with the SG-ITS for speeds around 80 km/h were evidently higher than those for speeds around 40 km/h, likely due to higher EFs of CO and PN at high speeds for the gasoline car.

3.3. *Simulation of emission reductions with vehicle emission models*

Table 2 presents the fuel consumption and pollutant EFs obtained from PEMS measurements and predicted by vehicle emission models for driving with and without the SG-ITS. The decrease ratio (DR: %) in Table 2 was employed to describe the reduction effect of the usage of the SG-ITS on fuel consumption and pollutant emissions. In addition, detailed information about the fuel consumption and pollutant EFs for the gasoline car under different road types of route 2 predicted by the MOVES is provided in Table S6. Despite the uncertainty due to the limited representation of the tested vehicles for the whole kinds of these vehicles and the shortage of test verification for the emission model, the difference of fuel consumption and pollutant EFs between model simulation and PEMS measurement is unimportant in this study because the purpose herein is to investigate the DR rather than to obtain accurate emission values. As demonstrated in Table 2, small or negligible DRs under driving with the SG-ITS can be obtained for fuel consumption and pollutant EFs predicted by the COPERT model, as the COPERT model is mainly based on average speed and insensitive to the changes in the actual operating modes of vehicles. On the other hand, the DRs obtained from the MOVES are more comparable to those obtained from PEMS measurements. This is mainly because the VSP approach adopted by the MOVES can well represent the actual operating modes of vehicles and estimate the emissions caused by stop-and-go traffic conditions (Nesamani et al., 2017). Despite that the DRs obtained from MOVES simulations remain lower than those from PEMS measurements, which is probably caused by uncertainties of the models such as the incapability of the MOVES to reflect the effect of vehicle past short-term operating activity on current emissions (Liu and Barth, 2012), the MOVES is still helpful in elucidating the impacts of the SG-ITS on reducing vehicle emissions and fuel consumption when the real-word operating mode distributions can be obtained.

Lower reductions in fuel consumption and pollutant emissions of the gasoline car were observed on the suburban roads compared to the urban roads (Table 2), which is probably related to the smoother driving behaviors and thereby lower RPA (Table S2) on the suburban roads. Compared with urban roads (high traffic), more significant reductions caused by the usage of the SG-ITS were acquired on the urban roads (low traffic), probably due to its higher reductions in stops and RPA. In addition, attributed to both the lower value and lower reductions of RPA for the diesel truck, lower DRs were observed for the diesel truck compared to the gasoline car on the same type of roads (suburban roads).

In this study, the exhaust volatile organic compounds (VOCs) mainly produced via incomplete combustion inside the engine (Costagliola et al., 2014) were not measured. However, from MOVES simulation, we derive the decreased emissions of VOCs for both tested vehicles (Tables S6 and S7), likely due to the improvement of engine combustion efficiency due to the lower frequency and strength of acceleration. Given that VOCs and NO_x are the most important precursors for secondary PM and O_3, the SG-ITS exhibits an enormous potential in mitigating haze and ozone pollution in urban areas.

3.4. Prediction of emission reduction based on emission inventory

To further demonstrate the potential benefits of utilizing the SG-ITS in megacities, we made a rough estimation of the feasible vehicular emission reduction with the usage of the SG-ITS in Beijing using a high temporal-spatial resolution vehicle emission inventory. This inventory in Beijing has been previously established by Jing. et al. (Jing et al., 2016) via a bottom-up approach, which requires local vehicle emission factors and real-time traffic data. Compared with traditional macro-scale vehicle emission inventory, this inventory could better predict vehicle emission levels in distributions of time and space. With this inventory, the daily average light-duty vehicle (i.e., light-duty gasoline/diesel vehicle, light-duty truck, and taxi) emissions of NO_x, CO, THC, and PM in Beijing for the year of 2016 were estimated to be 31.05, 307.09, 17.49, and 0.88 Mg/day for the urban freeways, respectively, and 53.04, 526.51, 29.95, and 1.50 Mg/day for the urban roads, respectively (Jing et al., 2016). The total daily average medium- and heavy-duty vehicle emissions of NO_x, CO, THC, and PM were 75.55, 121.94, 3.99, and 3.28 Mg/day for the urban freeways, respectively, and 129.07, 209.06, 6.84, and 5.59 Mg/day for the urban roads, respectively. In addition, the emissions emitted during the daytime and nighttime are 70% and 30% of the emissions on the whole day for the urban roads, respectively.

Based on the real-world DR on urban roads (low traffic) for the gasoline car and that on the suburban roads for the diesel truck, the DRs obtained from MOVES for different road types of route 2 are used to estimate the real-world DRs on different road types for both tested vehicles. Meanwhile, the ratios of DRs between different road types for the gasoline car are assumed to the same as those for the diesel truck. In addition, since the PM emission for both tested vehicles and the THC emission for the gasoline car were not measured in the real world, the real-world DRs of PM and THC are obtained by multiplying their respective DR obtained from MOVES by the minimum value in ratios of DR between the real-world and MOVES for other pollutants. The real-world DRs of PM and THC for the gasoline car on urban roads (low traffic) are estimated to be 26.2% and 33.7%, respectively, while the real-world DR of PM for the diesel truck on the suburban roads is expected to be 7.6%. Here, we assume that the emission DRs on the urban freeways in Beijing are the same with that on the suburban roads in our measurements due to the similar signalized intersection density and average driving speed. Also, considering that the traffic activity on the urban roads in Beijing is higher during daytime but lower during nighttime, the emission DRs on urban roads (high traffic) and urban roads (low traffic) in our measurements are employed to the urban roads in Beijing during daytime and nighttime, respectively. The real-world decreased emissions (ΔE) for different pollutants can be calculated by Eq. (2):

$$\Delta E_i = \Sigma_j \Sigma_v (E_{i,j,v} \times DR_{i,v} \times \frac{DR'_{i,j}}{DR'_i}) \quad (2)$$

where, i is pollutant type, i = NO_x, CO, THC, and PM; j is road type, j = urban freeways, urban roads (daytime), and urban roads (nighttime); v is vehicle type, v = light-duty vehicle, medium- and heavy-duty vehicle; $DR_{i,v}$ is the real-world decrease ratio on pollutant of type i for the vehicle type v on special type road (urban freeways for the medium- and heavy-duty vehicle, and urban roads (nighttime) for the light-duty vehicle); $DR'_{i,j}$ is decrease ratio obtained from MOVES on route 2 on pollutant of type i for the road of type j; DR'_i is decrease ratio obtained from MOVES on route 2 on pollutant of type i for the special type road (urban freeways for the medium- and heavy-duty vehicle, and urban roads (nighttime) for the light-duty vehicle); $E_{i,j,v}$ is emissions of the pollutant of type i for vehicle type v on the road type j.

Based on the real-world emission measurements, the vehicle emission model simulations, and the vehicle emission inventory results obtained from Jing et al. (2016), the total vehicle emissions of NO_x, CO, THC, and PM in Beijing with the implementation of the SG-ITS are estimated as 242.82, 925.87, 44.34, and 8.71 Mg/day, respectively, which are 15.9%, 20.5%, 23.9%, and 22.5% lower than their related values without the usage of the SG-ITS, respectively.

4. Conclusions and implications

In this study, we conducted real-world emission measurements and vehicle emission model simulations to investigate the performance of the SG-ITS on reducing fuel consumption and pollutant emissions. The conclusions are summarized as follows:

(1) The usage of the SG-ITS significantly changes the driving behaviors by reducing the frequency of stops and starts, the time proportions of acceleration and idle, and the strength of

acceleration. In particular, the usage of the SG-ITS can result in the largest reductions on urban roads (low traffic), largest time saving on urban roads (high traffic), and largest reductions in idle time proportion and stops on the suburban roads. In addition, more significant reductions are achieved on the gasoline car compared with the diesel truck.

(2) The differences in driving behaviors caused by the usage of SG-ITS result in more significant reduction effectiveness on real-world fuel consumption and pollutant emissions for the gasoline car (18.9% and 24.9–32.6% for fuel consumption and pollutant emissions, respectively) than the diesel truck (8.1% and 6.3–9.9% for fuel consumption and pollutant emissions, respectively). In addition, the largest reductions in fuel consumption and pollutant emissions are acquired on urban roads (low traffic), followed by on urban roads (high traffic) and on suburban roads.

(3) The usage of the SG-ITS can decrease the average speed-bin RPA for speeds less than 80 km/h, resulting in lower average speed-bin fuel consumption and pollutant EFs. Also, the differences in speed-bin EFs caused the SG-ITS generally decrease as the speed increase for these speeds. Moreover, the reductions in fuel consumption and pollutant emissions due to the usage of the SG-ITS are typically accounted for by the decreased contributions at speeds both below 20–30 km/h and around 70 km/h for both tested vehicles. However, the reductions in CO and PN emissions of the gasoline car are mainly due to the decreased contributions at speeds around 70 km/h.

(4) Based on the real-world emission measurements, the MOVES simulations, and a previous high-temporary vehicular emission inventory, large reductions of the total vehicle emissions in Beijing (ranging from 15.9% to 23.9% for different pollutants) can be obtained using with the implementation of SG-ITS.

Nowadays, various efforts concerning traffic control and technical improvement have been undertaken to increase the fuel economy and mitigate exhaust pollution. As the first real-world measurement to study the effectiveness of the SG-ITS, this study provides a direct evaluation of the impact of the SG-ITS in different road conditions for different vehicle types. Our results indicate that implementation of the SG-ITS in urban areas is a practical policy option in terms of energy savings, vehicle emission reductions, and traffic congestion management in both short and long terms. For example, the usage of the SG-ITS can achieve 18.9% fuel saving on urban roads, which is apparently higher than the reductions in fuel consumption caused by the advanced vehicle (2–8%) and engine (4–10%) technologies (Zhou et al., 2016). The predicted reductions in vehicle PM (22.5%) and NO_x (15.9%) emissions with the implementation of the SG-ITS in Beijing city are also higher than the reductions (12.0%) in both vehicle exhaust PM and NO_x emissions caused by the implementation of congestion charging policy in urban areas (Beevers and Carslaw, 2005). In addition, 12.9% of time saving on urban roads (high traffic) can be obtained by the usage of the SG-ITS, which will improve the traffic capacity and mitigate emissions from all on-road vehicles. Moreover, in addition to the effectiveness of the SG-ITS on reducing fuel consumption and exhaust emissions, the eco-driving behaviors caused by the usage of the SG-ITS will also be helpful to reduce non-exhaust (e.g., tire and brake wear) emissions (Hagino et al., 2015; Mathissen et al., 2011), suggesting the significant role of the SG-ITS in the future even with the increasing proportion of electric vehicles.

Declaration of competing interest

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

CRediT authorship contribution statement

Zhiwen Yang: Writing - original draft, Visualization, Formal analysis, Conceptualization, Methodology, Investigation, Data curation. **Jianfei Peng:** Writing - review & editing, Supervision, Methodology. **Lin Wu:** Resources, Conceptualization, Funding acquisition. **Chao Ma:** Investigation, Methodology. **Chao Zou:** Investigation, Methodology. **Ning Wei:** Investigation, Methodology. **Yanjie Zhang:** Investigation, Methodology. **Yao Liu:** Validation. **Michel Andre:** Supervision. **Dong Li:** Resources. **Hongjun Mao:** Supervision, Resources, Validation, Funding acquisition.

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Appendix A. Supplementary data

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References

Alam, M.S., McNabola, A., 2014. A critical review and assessment of Eco-Driving policy & technology: benefits & limitations. Transport Pol. 35, 42–49. https://doi.org/10.1016/j.tranpol.2014.05.016.

Alrawi, F., 2017. The importance of intelligent transport systems in the preservation of the environment and reduction of harmful gases. Transport. Res. Procedia. 24, 197–203. https://doi.org/10.1016/j.trpro.2017.05.108.

Asadi, B., Vahidi, A., 2011. Predictive cruise control: utilizing upcoming traffic signal information for improving fuel economy and reducing trip time. IEEE Trans. Contr. Syst. Technol. 19 (3), 707–714. https://doi.org/10.1109/TCST.2010.2047860.

Beevers, S.D., Carslaw, D.C., 2005. The impact of congestion charging on vehicle emissions in London. Atmos. Environ. 39 (1), 1–5. https://doi.org/10.1016/j.atmosenv.2004.10.001.

Bergmann, M., Kirchner, U., Vogt, R., Benter, T., 2009. On-road and laboratory investigation of low-level PM emissions of a modern diesel particulate filter equipped diesel passenger car. Atmos. Environ. 43 (11), 1908–1916. https://doi.org/10.1016/j.atmosenv.2008.12.039.

Costagliola, M.A., Murena, F., Prati, M.V., 2014. Exhaust emissions of volatile organic compounds of powered two-wheelers: effect of cold start and vehicle speed. Contribution to greenhouse effect and tropospheric ozone formation. Sci. Total Environ. 468–469c, 1043–1049. https://doi.org/10.1016/j.scitotenv.2013.09.025.

Dekati Ltd. High temperature ELPI®+. https://www.dekati.com/products/high-temperature-elpi/.

EEA, 2016. EMEP/EEA air pollutant emission inventory guidebook 2016, EEA-R-2016-21. https://www.eea.europa.eu/publications/emep-eea-guidebook-2016.

U.S. Environmental Protection Agency (EPA), 2017. MOVES onroad technical reports. https://www.epa.gov/moves/moves-onroad-technical-reports.

European Commission, 2012. Amending regulation (EC) No 7152007 of the European Parliament and of the Council and Commission regulation (EC) No 6922008 as regards emissions from light passenger and commercial vehicles (Euro 6). Off J Eur Union 142, 16–24, 2012.

Fernandes, P., Pereira, S.R., Bandeira, J.M., Vasconcelos, L., Silva, A.B., Coelho, M.C., 2016. Driving around turbo-roundabouts vs. conventional roundabouts: are there advantages regarding pollutant emissions? Int. J. Sustain. Transport. 10 (9), 847–860. https://doi.org/10.1080/15568318.2016.1168497.

Fotouhi, A., Yusof, R., Rahmani, R., Mekhilef, S., Shateri, N., 2014. A review on the applications of driving data and traffic information for vehicles' energy conservation. Renew. Sustain. Energy Rev. 37, 822–833. https://doi.org/10.1016/j.rser.2014.05.077.

Hagino, H., Oyama, M., Sasaki, S., 2015. Airborne brake wear particle emission due to braking and accelerating. Wear 334–335, 44–48. https://doi.org/10.1016/j.wear.2015.04.012.

Holman, C., Harrison, R.M., Querol, X., 2015. Review of the efficacy of low emission zones to improve urban air quality in European cities. Atmos. Environ. 111, 161–169. https://doi.org/10.1016/j.atmosenv.2015.04.009.

Huang, Y., Ng, E.C.Y., Zhou, J.L., Surawski, N.C., Chan, E.F.C., Hong, G., 2018. Eco-driving technology for sustainable road transport: a review. Renew. Sustain. Energy Rev. 93, 596–609. https://doi.org/10.1016/j.rser.2018.05.030.

Huo, H., Yao, Z., Zhang, Y., Shen, X., Zhang, Q., He, K., 2012. On-board measurements of emissions from diesel trucks in five cities in China. Atmos. Environ. 54, 159–167. https://doi.org/10.1016/j.atmosenv.2012.01.068.

Jin, D., Choi, K., Myung, C.-L., Lim, Y., Lee, J., Park, S., 2017. The impact of various ethanol-gasoline blends on particulates and unregulated gaseous emissions characteristics from a spark ignition direct injection (SIDI) passenger vehicle. Fuel 209, 702–712. https://doi.org/10.1016/j.fuel.2017.08.063.

Jing, B., Wu, L., Mao, H., Gong, S., He, J., Zou, C., Song, G., Li, X., Wu, Z., 2016. Development of a vehicle emission inventory with high temporal–spatial resolution based on NRT traffic data and its impact on air pollution in Beijing – Part 1: development and evaluation of vehicle emission inventory. Atmos. Chem. Phys. 16 (5), 3161–3170. https://doi.org/10.5194/acp-16-3161-2016.

Kousoulidou, M., Fontaras, G., Ntziachristos, L., Bonnel, P., Samaras, Z., Dilara, P., 2013. Use of portable emissions measurement system (PEMS) for the development and validation of passenger car emission factors. Atmos. Environ. 64, 329–338. https://doi.org/10.1016/j.atmosenv.2012.09.062.

Lähde, T., Rönkkö, T., Happonen, M., Söderström, C., Virtanen, A., Solla, A., Kytö, M., Rothe, D., Keskinen, J., 2011. Effect of fuel injection pressure on a heavy-duty diesel engine nonvolatile particle emission. Environ. Sci. Technol. 45 (6), 2504–2509. https://doi.org/10.1021/es103431p.

Liu, H., Barth, M., 2012. Identifying the effect of vehicle operating history on vehicle running emissions. Atmos. Environ. 59, 22–29. https://doi.org/10.1016/j.atmosenv.2012.05.045.

Mahler, G., Vahidi, A., 2014. An optimal velocity-planning scheme for vehicle energy efficiency through probabilistic prediction of traffic-signal timing. IEEE Trans. Intell. Transport. Syst. 15 (6), 2516–2523. https://doi.org/10.1109/TITS.2014.2319306.

Mandava, S., Boriboonsomsin, K., Barth, M., 2009. Arterial velocity planning based on traffic signal information under light traffic conditions. 12th Int. IEEE. Conf. Intell. Transport. Sys. 1–6. https://doi.org/10.1109/ITSC.2009.5309519.

Mathissen, M., Scheer, V., Vogt, R., Benter, T., 2011. Investigation on the potential generation of ultrafine particles from the tire–road interface. Atmos. Environ. 45 (34), 6172–6179. https://doi.org/10.1016/j.atmosenv.2011.08.032.

Maykut, N.N., Lewtas, J., E, K., Larson, T.V., 2003. Source apportionment of PM2.5 at an urban IMPROVE site in seattle, Washington. Environ. Sci. Technol. 37 (22), 5135–5142. https://doi.org/10.1021/es030370y.

Meneguzzer, C., Gastaldi, M., Rossi, R., Gecchele, G., Prati, M.V., 2017. Comparison of exhaust emissions at intersections under traffic signal versus roundabout control using an instrumented vehicle. Transport. Res. Procedia. 25, 1597–1609. https://doi.org/10.1016/j.trpro.2017.05.204.

Neilson, A., Indratmo, Daniel, B., Tjandra, S., 2019. Systematic review of the literature on big data in the transportation domain: concepts and applications. Big Data Res 17, 35–44. https://doi.org/10.1016/j.bdr.2019.03.001.

Nesamani, K.S., Saphores, J.-D., McNally, M.G., Jayakrishnan, R., 2017. Estimating impacts of emission specific characteristics on vehicle operation for quantifying air pollutant emissions and energy use. J. Traffic Transport. Eng. 4 (3), 215–229. https://doi.org/10.1016/j.jtte.2017.05.007.

Ntziachristos, L., Gkatzoflias, D., Kouridis, C., Samaras, Z., 2009. COPERT: A European Road Transport Emission Inventory Model. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 491–504.

O'Driscoll, R., Apsimon, H.M., Oxley, T., Molden, N., Stettler, M.E.J., Thiyagarajah, A., 2016. A portable emissions measurement system (PEMS) study of NOx and primary NO2 emissions from Euro 6 diesel passenger cars and comparison with COPERT emission factors. Atmos. Environ. 145, 81–91. https://doi.org/10.1016/j.atmosenv.2016.09.021.

Pandian, S., Gokhale, S., Ghoshal, A.K., 2009. Evaluating effects of traffic and vehicle characteristics on vehicular emissions near traffic intersections. Transport. Res. Transport Environ. 14 (3), 180–196. https://doi.org/10.1016/j.trd.2008.12.001.

Perumal, V., Ilangkumaran, M., 2018. Water emulsified hybrid pongamia biodiesel as a modified fuel for the experimental analysis of performance, combustion and emission characteristics of a direct injection diesel engine. Renew. Energy 121, 623–631. https://doi.org/10.1016/j.renene.2018.01.060.

Querol, X., Viana, M., Alastuey, A., Amato, F., Moreno, T., Castillo, S., Pey, J., Rosa, J.D.L., Campa, A.S.D.L., Artíñano, B., 2007. Source origin of trace elements in PM from regional background, urban and industrial sites of Spain. Atmos. Environ. 41 (34), 7219–7231. https://doi.org/10.1016/j.atmosenv.2007.05.022.

Samia, Boubaker, Ferid, Rehimi, Adel, Kalboussi, 2016. Impact of intersection type and a vehicular fleet's hybridization level on energy consumption and emissions. J. Traffic Transport. Eng. 3 (3), 253–261. https://doi.org/10.1016/j.jtte.2016.05.003.

Schuricht, P., Michler, O., Baker, B., 2011. Efficiency-increasing driver assistance at signalized intersections using predictive traffic state estimation. 14th Int. IEEE. Conf. Intell. Transport. Sys. 347–352. https://doi.org/10.1109/ITSC.2011.6083111.

Sirohi, D., Kumar, N., Rana, P.S., 2020. Convolutional neural networks for 5G-enabled Intelligent Transportation System : a systematic review. Comput. Commun. 153, 459–498. https://doi.org/10.1016/j.comcom.2020.01.058.

Souza, A.M.D., Yokoyama, R.S., Maia, G., Loureiro, A., Villas, L., 2016. Real-time path planning to prevent traffic jam through an intelligent transportation system. 2016 IEEE Symposium on Computers and Communication (ISCC) 726–731. https://doi.org/10.1109/ISCC.2016.7543822.

Suarez-Bertoa, R., Astorga, C., 2018. Impact of cold temperature on Euro 6 passenger car emissions☆. Environ. Pollut. 234, 318–329. https://doi.org/10.1016/j.envpol.2017.10.096.

Sun, J., Liu, H.X., 2015. Stochastic eco-routing in a signalized traffic network. Transport. Res. C Emerg. Technol. 59, 32–47. https://doi.org/10.1016/j.trc.2015.06.002.

Tang, T.-Q., Zhang, J., Liu, K., 2017. A speed guidance model accounting for the driver's bounded rationality at a signalized intersection. Phys. Stat. Mech. Appl. 473, 45–52. https://doi.org/10.1016/j.physa.2017.01.025.

Überall, A., Otte, R., Eilts, P., Krahl, J., 2015. A literature research about particle emissions from engines with direct gasoline injection and the potential to reduce these emissions. Fuel 147, 203–207. https://doi.org/10.1016/j.fuel.2015.01.012.

Wang, Y., Zheng, R., Qin, Y., Peng, J., Li, M., Lei, J., Wu, Y., Hu, M., Shuai, S., 2016. The impact of fuel compositions on the particulate emissions of direct injection gasoline engine. Fuel 166, 543–552. https://doi.org/10.1016/j.fuel.2015.11.019.

Weiss, M., Bonnel, P., Hummel, R., Provenza, A., Manfredi, U., 2011b. On-road emissions of light-duty vehicles in europe. Environ. Sci. Technol. 45 (19), 8575–8581. https://doi.org/10.1021/es2008424.

West, J.J., Cohen, A., Dentener, F., Brunekreef, B., Zhu, T., Armstrong, B., Bell, M.L., Brauer, M., Carmichael, G.R., Costa, D.L., 2016. What we breathe impacts our health: improving understanding of the link between air pollution and health. Environ. Sci. Technol. 50 (10), 4895–4904. https://doi.org/10.1021/acs.est.5b03827.

Winkler, S.L., Anderson, J.E., Garza, L., Ruona, W.C., Vogt, R., Wallington, T.J., 2018. Vehicle criteria pollutant (PM, NOx, CO, HCs) emissions: how low should we go? npj Clim. Atmos. Sci. 1 (1), 26. https://doi.org/10.1038/s41612-018-0037-5.

Wu, Y., Zhang, S., Li, M.L., Ge, Y.S., Shu, J.W., Zhou, Y., Xu, Y.Y., Hu, J.N., Liu, H., Fu, L., 2012. The challenge to NOx emission control for heavy-duty diesel vehicles in China. Atmos. Chem. Phys. 12 (19), 9365–9379. https://doi.org/10.5194/acpd-12-18565-2012.

Wu, X., Zhang, S., Wu, Y., Li, Z., Zhou, Y., Fu, L., Hao, J., 2015. Real-world emissions and fuel consumption of diesel buses and trucks in Macao: from on-road measurement to policy implications. Atmos. Environ. 120, 393–403. https://doi.org/10.1016/j.atmosenv.2015.09.015.

Xie, X., Tou, X., Zhang, L., 2017. Effect analysis of air pollution control in Beijing based on an odd-and-even license plate model. J. Clean. Prod. 142, 936–945. https://doi.org/10.1016/j.jclepro.2016.09.117.

Yang, Y., Chen, S., Jian, S., 2010. Modeling and evaluation of speed guidance strategy in VII system. 13th Int. IEEE. Conf. Intell. Transport. Sys. 1045–1050. https://doi.org/10.1109/ITSC.2010.5625271.

Yang, Z.W., Liu, Y., Wu, L., Martinet, S., Zhang, Y., Andre, M., Mao, H.J., 2020. Real-world gaseous emission characteristics of Euro 6b light-duty gasoline- and diesel-fueled vehicles. Transp. Res. D: Transp. Environ. 78 https://doi.org/10.1016/j.trd.2019.102215.

Yang, B., Wang, Y., Hu, J., Deng, Y., 2013. A traffic efficiency promotion algorithm for urban arterial roads based on speed guidance. 2013 International Conference on Connected Vehicles and Expo (ICCVE). https://doi.org/10.1109/ICCVE.2013.6799918.

Yao, Z., Wu, B., Wu, Y., Cao, X., Jiang, X., 2015. Comparison of NOx emissions from China III and China IV in-use diesel trucks based on on-road measurements. Atmos. Environ. 123, 1–8. https://doi.org/10.1016/j.atmosenv.2015.10.056.

Zhang, Q., Wu, L., Yang, Z., Zou, C., Liu, X., Zhang, K., Mao, H., 2016. Characteristics of gaseous and particulate pollutants exhaust from logistics transportation vehicle on real-world conditions. Transport. Res. Transport Environ. 43, 40–48. https://doi.org/10.1016/j.trd.2015.09.005.

Zhang, S., Niu, T., Wu, Y., Zhang, K.M., Wallington, T.J., Xie, Q., Wu, X., Xu, H., 2018. Fine-grained vehicle emission management using intelligent transportation system data. Environ. Pollut. 241, 1027–1037. https://doi.org/10.1016/j.envpol.2018.06.016.

Zheng, X., Wu, Y., Zhang, S., Hu, J., Zhang, K.M., Li, Z., He, L., Hao, J., 2017. Characterizing particulate polycyclic aromatic hydrocarbon emissions from diesel vehicles using a portable emissions measurement system. Sci. Rep. 7 (1), 10058. https://doi.org/10.1038/s41598-017-09822-w.

Zhou, M., Jin, H., Wang, W., 2016. A review of vehicle fuel consumption models to evaluate eco-driving and eco-routing. Transp. Res. D: Transp. Environ. 49, 203–218. https://doi.org/10.1016/j.trd.2016.09.008.