Impact of drivers on real-driving fuel consumption and emissions performance

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Abstract

Eco-driving has attracted great attention as a cost-effective and immediate measure to reduce fuel consumption significantly. Understanding the impact of driver behaviour on real driving emissions (RDE) is of great importance for developing effective eco-driving devices and training programs. Therefore, this study was conducted to investigate the performance of different drivers using a portable emission measurement system. In total, 30 drivers, including 15 novice and 15 experienced drivers, were recruited to drive the same diesel vehicle on the same route, to minimise the effect of uncontrollable real-world factors on the performance evaluation. The results show that novice drivers are less skilled or more aggressive than experienced drivers in using the accelerator pedal, leading to higher vehicle and engine speeds. As a result, fuel consumption rates of novice drivers vary in a slightly greater range than those of experienced drivers, with a marginally higher (2%) mean fuel consumption. Regarding pollutant emissions, CO and THC emissions of all drivers are well below the standard limits, while NO_x and PM emissions of some drivers significantly exceed the limits. Compared with experienced drivers, novice drivers produce 17% and 29% higher mean NO_x and PM emissions, respectively. Overall, the experimental results reject the hypothesis that driver experience has significant impacts on fuel consumption performance. The real differences lie in the individual drivers, as the worst performing drivers have significantly higher fuel consumption rates than other drivers, for both novice and experienced drivers. The findings suggest that adopting eco-driving skills could deliver significant reductions in fuel consumption and emissions simultaneously for the worst performing drivers, regardless of driving experience.

Keywords**:** Real driving emissions; Driver behaviour; Gaseous and particulate emissions; Fuel consumption; Diesel vehicle; Portable emission measurement system

1. Introduction

To combat climate change, 191 out of 197 Parties to the United Nations Framework Convention on Climate Change (UNFCCC) have ratified the Paris Agreement as of May 2021, which aims to limit global warming to be < 2 ºC and preferably < 1.5 ºC compared to pre-industrial levels (United Nations, 2021). Many countries have set ambitious carbon reduction targets via the Nationally Determined Contributions (NDCs) (Dong *et al.*, 2018; Salvia *et al.*, 2021). Most countries (>90%) expressed their NDCs as absolute emission reduction from the level in a specified base year (e.g. 2005) or emission reduction below the 'business as usual' level by a specified target year (e.g. 2030), which ranged from 13% to 88% and from 11.5% to 53.5%, respectively (UNFCCC, 2021). Road transport is a significant sector of energy consumption, accounting for 23% of global energy related CO_2 emissions in 2018 (Huang *et al.*, 2019b; International Energy Agency, 2021). It is also a major contributor of urban air pollutants, causing significant health and economic damages globally (Anenberg *et al.*, 2019; 2017; Huang *et al.*, 2020). Therefore, reducing carbon and pollutant emissions from the road transport sector is an essential step to achieve the abatement target.

Various measures have been taken to reduce fuel consumption and emissions of on-road vehicles, such as stricter vehicle emission standards, cleaner combustion engines, hybrid/battery electric vehicles, and alternative fuels. However, an important but often overlooked factor is driver behaviour, which has great impacts on the fuel consumption and emissions performance of a vehicle. It was estimated that the factors that drivers have control over (except vehicle selection) could potentially improve on-road fuel economy by up to 45% per driver (Ng *et al.*, 2021; Sivak and Schoettle, 2012; Wang and Lin, 2020). Such great improvements could be achieved in a relatively simple and low-cost manner, i.e. a change of driver behaviour via eco-driving training classes and/or on-board driver assistance devices. Eco-driving refers to driving strategies that minimise vehicle fuel consumption. The broad definition of eco-driving includes strategic (vehicle selection and maintenance), tactical (route selection and vehicle load) and operational (driver behaviour) decisions, while traditional definition is usually limited to the post-purchase driver behaviours (Huang *et al.*, 2018a; Sivak and Schoettle, 2012). Eco-driving technology has attracted great attention as a cost-effective and immediate measure to improve fuel efficiency in recent years (Alam and McNabola, 2014; Huang *et al.*, 2018a; Sovacool and Griffiths, 2020; Zhang *et al.*, 2019). While a main challenge is that eco-driving studies usually reported large reductions of fuel consumption in driving simulations or short-term experiments, but much smaller reductions in field trials or long-term experiments (Huang *et al.*, 2018a).

Understanding the effect of driver behaviour on fuel consumption and emissions is of great importance for developing, informing and better targeting effective eco-driving programs. Ma *et al.* (2015) developed a vehicle-engine combined model for studying the effect of driving style on fuel consumption of buses. Their results showed that driving characteristics during acceleration were decisive for 56.5% of total fuel consumption, while deceleration was only responsible for less than 5.7% of total fuel consumption. Choi and Kim (2017) modelled the critical aggressive acceleration values of a liquefied petroleum gas (LPG) passenger car using on-board diagnostics (OBD) data. They found that an acceleration of 2.60 m/s^2 during starting and 1.47 m/s^2 during driving caused abrupt increases in fuel consumption. Gallus *et al.* (2017) measured the impact of driving styles on gaseous emissions of two diesel vehicles using a portable emission measurement system (PEMS). Their results showed that, compared with normal driving style, severe driving style (represented by stronger acceleration and later braking) resulted in 20%-40% higher CO_2 emissions and 50%-255% higher NO_x emissions, but insignificant differences in CO and HC emissions. Varella *et al.* (2019) reported that NO_x and CO_2 emissions were always larger under aggressive driving (represented by longer acceleration period until reaching speed limit) than normal driving, based on PEMS testing of three diesel and two petrol passenger cars. PEMS experiments on a diesel passenger car revealed a strong relationship between driving aggressiveness and NO_x emissions (Prakash and Bodisco, 2019). A recent PEMS study on six diesel trucks manufactured during 1995-2006 with little/no emission control also observed significantly higher gaseous and particulate emissions under aggressive driving (represented by higher relative positive acceleration) than normal driving (Dhital *et al.*, 2021). Gao *et al.* (2021) further demonstrated that the effect of driver behaviour on NO_x emissions of diesel passenger cars was depended on the after-treatment technologies. Yu *et al.* (2021) reported that both the driving operational intensity and the duration and frequency of individual manoeuvre influenced emission factors.

Existing studies on driver behaviour mostly examined the effect of vehicle dynamic parameters (e.g. acceleration and speed) or/and road conditions (e.g. road grade) on fuel consumption or/and specific emissions (e.g. CO_2 and NO_x). In addition, the different driver behaviours studied were usually simulated by the same driver(s) adopting different levels of aggressiveness. Few studies have investigated the drivers themselves as an independent factor. Therefore, this study was carried out to evaluate the performance of drivers with various levels of driving experience. It was hypothesised that drivers with different years of driving experience would perform differently in terms of driver behaviour, fuel consumption and pollutant emissions. In total, 30 drivers, including 15 novice and 15 experienced drivers, were recruited to drive the same diesel vehicle on the same route, which minimised the effect of uncontrollable real-world factors on the performance evaluation. The driver behaviour parameters were measured using an OBD logger, while the fuel consumption and gaseous and particulate emissions were measured using a state-of-the-art PEMS. The results are expected to reveal the performance differences among drivers and to provide valuable guidelines for developing effective eco-driving programs and devices.

2. Methods

2.1. Test drivers

A total of 30 drivers were recruited to undertake the real driving emissions (RDE) tests, including 15 novice and 15 experienced drivers (**Table 1**). All were male drivers due to the nature of the occupation, i.e. the goods transportation sector. The experienced drivers were professional drivers aged between 40-72 years, with at least 15 years of driving experience. In comparison, the novice drivers were aged between 21-40 years and had 3-5 years of driving experience. All drivers were asked to drive the same vehicle (section 2.2) on the same route (section 2.3) following their normal driving styles, with no training or driver assistance device provided. Each driver completed the RDE tests twice during the same periods in a day, i.e. one during 11.00-12.00 and the other during 14.00-15.00. Rush hours were avoided so that traffic density was low and drivers could freely adopt their normal driving styles.

2.2. Test vehicle

A Toyota HiAce diesel light goods vehicle (LGV) was used for RDE tests in this study. The vehicle was selected because diesel vehicles are the main sources of air pollutants in urban areas and consume significant amounts of fossil fuels due to their high mileage travelled, despite being only a small proportion of total vehicles (Anenberg *et al.*, 2017; Huang *et al.*, 2021). In particular, Toyota HiAce is the most popular model of diesel vehicles running on Hong Kong roads (Huang *et al.*, 2018b). **Table 2** gives the specifications of the test vehicle. The test vehicle was manufactured in 2014 and had an odometer reading of 53050 km at the beginning of test. It is powered by a 2982 cc turbocharged diesel engine and equipped with exhaust after-treatment systems of diesel oxidation catalyst (DOC), diesel particulate filter (DPF), and exhaust gas recirculation (EGR).

2.3. Test route

A test route representative of daily driving in Hong Kong has been designed (**Fig. 1a**). The test route is a round trip starting from the Jockey Club Heavy Vehicle Emissions Testing and Research Centre, with a total distance of 19 km including 5 km of urban driving, 6 km of rural driving and 8 km of highway driving. The whole trip takes about 25-30 minutes to complete. The urban roads usually have 1-2 lanes in one direction and have a speed limit of 50 km/h. They are characterized with high traffic volume, traffic lights, roundabouts and pedestrian crossings. The rural roads usually have 2-3 lanes in one direction, with a speed limit of 70 km/h, moderate traffic volume, traffic lights and roundabouts. Highways are wider (3-4 lanes per direction) and faster (speed limit of 80 km/h or above), with no traffic lights or pedestrian crossings.

2.4. Real driving emissions measurements

The RDE experiments were performed using a set of the state-of-the-art PEMS (**Fig. 1b**), including an AVL M.O.V.E Gas PEMS 493 for gaseous emissions measurements and an AVL M.O.V.E PM PEMS 494 for particulate matter (PM) measurements. Regarding gaseous emissions, CO (ppm) and CO_2 (%) were measured by a non-dispersive infra-red (NDIR) analyzer, NO and NO_2 (ppm) were measured by a non-dispersive ultra-violet (NDUV) analyzer, and total hydrocarbons (THC) (ppm) were measured by a heated flame ionization detector (FID). The PM PEMS combined a photo-acoustic measurement unit with a gravimetric filter module. The time-resolved PM emissions (µg) were calculated from the mass of the particle filter, the time-resolved soot signal and the exhaust mass flow. The particle filter was conditioned in an air-conditioned chamber for three hours before and after the test. Then the filter was weighed by a Sartorius air quality microbalance, which is designed for weighing 47 mm filters specified in the EPA regulation. It is based on gravimetric analysis and provides a resolution from 1 µg to 6 g. A 2.5-inch EFM-2 was used to measure the exhaust flow rate and gas temperature. A weather station was mounted on the vehicle roof to measure ambient temperature, relative humidity and atmospheric pressure during on-road tests. A Peiseler MT pulse transducer was used to measure the vehicle wheel speed. In addition, a Garmin global positioning system (GPS) was mounted on the vehicle roof to track the route, elevation and ground speed.

The PEMS was installed in the cabin of the test vehicle and the sampling line was connected to the tailpipe to measure gaseous and PM emissions. The sampling line was heated to 190 °C to avoid condensation of THC. A Honda EU 30IS generator and three lead acid batteries with a capacity of 150 Ah were mounted inside the test vehicle to supply power for the instruments. In the present study, all the data were recorded at a sampling rate of 10 Hz. Furthermore, engine control unit (ECU) data were obtained via the OBD system, including accelerator pedal position, vehicle speed, engine speed, engine coolant temperature and throttle position. To assure data accuracy, the Gas PEMS was zeroed using pure nitrogen gas before each test and was calibrated using EPA Bar 97 standard gases before and after the tests on each day. All tests were conducted under hot start conditions when the OBD coolant temperature reading was above 80 °C before the tests.

2.5. Data treatment

The distance specific emission factors (EFs) were calculated from the PEMS data using the method defined in Appendix 4 of the Euro 6 RDE standard (European Commission, 2017). In engine emissions testing, some emissions are measured on a dry basis to achieve a high accuracy, as humidity could interfere with the spectrum (Giechaskiel *et al.*, 2019). However, wet-based emission concentrations are representative of real-world conditions. Therefore, firstly, the dry-based emission concentrations (c_{dry} , ppm or %) measured in AVL PEMS were converted to wet-based concentrations (c_{wet}, ppm or %) using equation (1). In this study, NO_x, CO and CO_2 emissions were measured on a dry basis due to the use of chillers, but THC emissions were measured on a wet basis due to the use of heated lines and combustion gas.

$$c_{wet} = c_{dry} \times k_w \quad (1)$$

where k_w is the dry-wet correction factor which is calculated by equations (2-5):

$$k_w = \left(\frac{1}{1+\alpha \times 0.005 \times (c_{CO_2} + c_{CO})} - k_{w1}\right) \times 1.008 \quad (2)$$

$$k_{w1} = \frac{1.608 \times H_a}{1000 + 1.608 \times H_a} \quad (3)$$

$$H_a = 622 \times \frac{\emptyset \times P_{sat}}{P_{amb} - \emptyset \times P_{sat}} \quad (4)$$

$$P_{sat} = 0.61078 \times \exp\left(\frac{17.27 \times T_{amb}}{T_{amb} + 237.3}\right) \quad (5)$$

where α is the H/C molar ratio (assuming $CH_{1.85}$ for diesel fuel), H_a is the ambient air humidity (g water / kg dry air), $\emptyset$ is the relative humidity, P_{sat} is the saturation vapour pressure (kPa) of water at ambient temperature T_{amb} (°C), and c_{CO_2} and c_{CO} are the CO_2 and CO concentrations (%), respectively. Secondly, the exhaust mass flow rate (q_m, kg/s) was calculated by equation (6):

$$q_m = \frac{q_v}{1000\times3600} \times \rho_e \times \frac{273}{101.3} \times \frac{P_e}{T_e} \quad (6)$$

where q_v is the measured volume flow rate of the exhaust (L/h), ρ_e is the standard exhaust density ($\rho_e = 1.2943$ kg/m^3 for diesel fuel at 101.3 kPa and 273 K), P_e is the measured exhaust pressure (kPa), and T_e is the measured exhaust temperature (K). Thirdly, the instantaneous mass emission rate (m_p, kg/s) was determined by equation (7):

$$m_p = u_p \times c_{p,wet} \times q_m \quad (7)$$

where u_p is the ratio of pollutant density and overall exhaust density. For diesel fuel, the u_p values are 1.586, 0.966, 1.517 and 0.553 for NO_x, CO, CO_2 and CH_4, respectively. Finally, the distance specific EFs (g/km) of each trip were calculated by summing the instantaneous emission mass (g) and then dividing by the driving distance (km) using equation (8), in which *dt* is the time interval and *v* is the vehicle speed. The fuel consumption rates (FC, L/100 km) were calculated using equation (9) by the principle of carbon balance. It should be noted that DPF regenerations occurred during the RDE tests, which could greatly affect the emission performance, especially the PM and NO_x emissions (Ko *et al.*, 2019; Meng *et al.*, 2020; Smith *et al.*, 2019). Therefore, tests with DPF regenerations were excluded in this study to eliminate their impacts on the driver performance evaluation.

$$EF_p = \frac{\sum m_p \cdot dt}{\sum v \cdot dt} \quad (8)$$

$$\mathrm{FC} = 0.0379EF_{CO_2} + 0.0595EF_{CO} + 0.1202EF_{THC} \quad (9)$$

3. Results and discussion

3.1. Driver behaviour

Driver behaviour was assessed using the data obtained from the OBD system, including accelerator pedal position, vehicle speed, engine speed, coolant temperature and throttle position. Among these parameters, the accelerator pedal position is of primary importance. This is because from the perspective of a driver, the main operations under control that affect engine load are the accelerator and brake pedal positions, which collectively control the vehicle speed and represent the aggressiveness of a driver. In particular, the accelerator pedal position determines the fuel supply rate, while fuel consumption is minimum during braking as many modern engines cut fuel supply during hard braking (Ma *et al.*, 2015; Wang *et al.*, 2021). The other OBD parameters (e.g. engine speed, throttle position and coolant temperature) are a result of the accelerator pedal position, on which a driver has no direct control.

Table 3 summarises the overall statistics of the OBD data of novice and experienced drivers, which are the average values of each driver group (i.e. 15 novice and 15 experienced drivers). The instantaneous acceleration values were calculated from the vehicle speedevd using a time interval of one second. The minimum (min), mean, maximum (max) and standard deviation (SD) values of accelerations for each individual driver were calculated from the instantaneous accelerations. The overall acceleration statistics were calculated by averaging the acceleration values of 15 drivers. As shown in **Table 3**, the mean, maximum and variation (indicated by SD) of accelerator pedal position of novice drivers are 3%, 13% and 13% higher than those of experienced drivers, respectively. This indicates that novice drivers are more aggressive in the use of the accelerator pedal. As a result, novice drivers generate higher vehicle and engine speeds than experienced drivers, as shown by 5%, 14% and 10% higher mean, maximum and variation for vehicle speed and 5%, 9% and 10% higher for engine speed, respectively. The acceleration of the novice drivers also varies in a larger range (-4.49 to 3.91 m/s^2) than that of the experienced drivers (-3.80 to 3.56 m/s^2). In spite of the above differences, coolant temperatures and throttle positions are quite similar between the novice and experienced drivers.

Fig. 2 further shows the distribution of the travel time spent on different accelerator pedal positions. It should be noted that the minimum accelerator pedal position is 16% once the engine is started, so the first bin of 16%-17% includes both idling and deceleration conditions. Therefore, all drivers spend the most time on the first pedal position bin, with 46.1% for novice drivers and 43.9% for experienced drivers. **Fig. 2** confirms that novice drivers are less skilled or more aggressive in the use of the accelerator pedal. This is demonstrated by the distribution of accelerator pedal position that novice drivers spend more time on the low (i.e. 16%-17%, idling/deceleration) and high (i.e. >30%) pedal positions, but less time on moderate (i.e. 17%-30%) pedal positions when compared to the experienced drivers. In particular, one novice drivers would even press the accelerator pedal to over 70%. Since a key rule of eco-driving is gentle use of accelerator pedal, the results in **Fig. 2** imply that novice drivers would have higher fuel consumption and hence have bigger potentials of fuel saving when implementing eco-driving skills, which will be further discussed in section 3.2.

Fig. 3 demonstrates the distribution of travel time spent on different driving modes for novice and experienced drivers. The driving modes are classified based on vehicle speed (v) and acceleration (a), including deceleration (a < -0.1 m/s^2), idling (-0.1 m/s^2 ≤ a ≤ 0.1 m/s^2, v ≤ 3 km/h), cruising (-0.1 m/s^2 ≤ a ≤ 0.1 m/s^2, v > 3 km/h) and acceleration (a > 0.1 m/s^2). The acceleration bin is further classified into mild and hard accelerations using a threshold of 1.47 m/s^2, which is the critical aggressive acceleration value that causes abrupt rises in fuel consumption during driving (Choi and Kim, 2017). As shown in **Fig. 3**, novice drivers spend less time on cruising mode but longer time on all other driving modes than experience drivers. This indicates that novice drivers are less skilled in maintaining a steady speed and manoeuvre more frequently in acceleration and deceleration in the traffic flow. In particular, the novice drivers (3.6%) use hard acceleration more frequently than the experienced drivers (3.0%), which would cause higher fuel consumption. Eco-driving usually encourages early anticipation of traffic and road conditions to reduce the frequent use of acceleration and deceleration pedals, which helps avoid unnecessary accelerating, braking, speeding and idling. Based on these eco-driving criteria, experienced drivers perform better than novice drivers. Therefore, eco-driving training programs and on-board driver assistance devices should be more effective in improving the performance of novice drivers. Overall, the difference is relatively small between the novice and experienced drivers, as the error bars largely overlap under different driving conditions. Despite the small differences, the results in **Fig. 3** are well correlated with the fuel consumption performance shown in **Fig. 4**.

3.2. Fuel consumption and pollutant emissions

Fig. 4 compares the fuel consumption performance between the novice and experienced drivers. As shown in **Fig. 4**, the fuel consumption rates of novice drivers span a slightly bigger range (10.00-11.97 L/100 km) than those of experienced drivers (10.04-11.86 L/100 km). This is expected as the OBD data in **Table 3** has revealed that the novice drivers use accelerator pedal in a larger range than the experienced drivers. This implies that novice drivers have more potential for saving fuel with eco-driving style: 13% for the worst novice driver *vs* 12% for the worst experienced drivers, if they are improved to the median performance level. In addition to the larger range, the median and mean fuel consumption rates of novice drivers are also slightly (0.2% and 2%, respectively) higher than those of experienced drivers.

Although the two groups of drivers have very different ages and driving experiences, the results in **Figs 3** and **4** demonstrate that experienced and novice drivers have very similar driver behaviours and fuel consumption rates in terms of means and ranges when driving the same vehicle on the same route. The real differences are among the individual drivers: i.e. the worst performing drivers have much higher fuel consumption rates than other drivers, for both groups of drivers. This explains why previous eco-driving experiments observed high heterogeneity among drivers (Barla *et al.*, 2017) and implies that eco-driving technology will only be effective for some drivers.

Fig. 5 compares the pollutant emissions performance of the novice and experienced drivers. Generally, CO (**Fig. 5a**) and THC (**Fig. 5b**) emission factors are relatively low for both driver groups, with the median and mean values very close to zero. Even their maximum values are well below the corresponding standard limits (i.e. 0.74 g/km for CO and 0.07 g/km for THC of Euro 5 1760-3500 kg diesel LGVs). During the RDE testing, the instantaneous CO and THC readings are mostly below the detection limits of the gas analysers, which can be attributed to the lean combustion mode (usually referred as non-premixed or diffusion flames) in diesel engines. Such low readings are more prone to be affected by measurement uncertainties. Thus, a comparison of these parameters between novice and experienced drivers would not be reliable. An early emissions survey using chassis dynamometer testing showed similarly low CO and HC emission factors of in-use diesel LGVs (Huang *et al.*, 2019a). This proves the small discrepancy between laboratory and real driving emissions for diesel CO and HC, even under the influence of driver behaviours. Therefore, this study will focus on NO_x and PM emissions which are the main pollutants from diesel vehicles and as well as the major concerns of urban air pollution.

As shown in **Fig. 5c**, NO_x emission factors of all the drivers significantly exceed the standard limit (i.e. 0.28 g/km), by 532% for the worst novice driver and 606% for the worst experienced driver. This is expected as many studies have reported that real-driving diesel NO_x emissions are significantly higher than both the standard limits and laboratory test values (Degraeuwe and Weiss, 2017; Fu *et al.*, 2013; Kousoulidou *et al.*, 2013; Weiss *et al.*, 2011). This study further demonstrates that driver behaviour is a significant factor contributing to the discrepancy between standard limit and real-driving emissions. For experienced drivers, the real-driving NO_x emission factors vary in a large range from 0.32 to 1.98 g/km, with a median of 0.75 g/km and a mean of 0.83 g/km (corresponds to 1.2-7.1, 2.7 and 3.0 times the standard limit, respectively). Comparing with experienced drivers, the NO_x emission factors of novice drivers vary in a smaller range (0.56-1.77 g/km) while the median and mean values are 18% and 17% higher, respectively. Regarding PM (**Fig. 5d**), the distributions of emission factors are highly skewed for both driver groups. The majority of drivers have PM emissions close to zero while a few drivers have high emissions, with up to 24.8 and 22.8 times the standard limit (i.e. 0.0045 g/km) for novice and experienced drivers, respectively. In comparison, the median and mean PM emission factors of novice drivers are 35% and 29% higher than that of experienced drivers, respectively.

Fig. 6 plots the NO_x and PM emission factors against the fuel consumption rates for novice and experienced drivers. Generally, both NO_x and PM emission factors are positively correlated with fuel consumption rates, except for PM emission factors of two drivers (one novice driver and one experienced driver). This can be explained by their engine operation conditions. For the novice driver (i.e. Driver 21), the exhaust temperature (>350 °C) was significantly above the normal level (250 °C) during the first 100 s and the majority of PM emissions were generated during this time. However, the exhaust CO_2 concentration and PM filter colour were normal, thus this test was considered a normal test (i.e. no DPF regeneration event). The high exhaust temperature indicates that abnormal combustion has occurred and resulted in high PM emissions. For the experienced driver (i.e. Driver 3), the previous test had a DPF regeneration event at the end of the test, which could have led to higher PM emission factor of Driver 3. The results in **Fig. 6** demonstrate that high pollutant emissions are usually associated with high fuel consumption rates. This implies that eco-driving could simultaneously improve the fuel consumption and emissions performance of the worst performing drivers.

The above experimental results reject the hypothesis that driver experience has significant impacts on the fuel consumption performance of a vehicle. Instead, the individual driver's behaviour matters most. Therefore, **Fig. 7** is plotted to explore the correlation between fuel consumption rate and accelerator pedal use of all individual drivers. The mean accelerator pedal position obtained from the OBD system represents the aggressiveness of a driver. **Fig. 7** shows that drivers with more aggressive use of accelerator pedal generally have higher fuel consumption rates than other drivers. This suggests that gentle use of accelerator pedal will be an effective eco-driving practice for both experienced and novice drivers.

4. Conclusions

This study aimed to investigate the impact of driving experience on fuel consumption and pollutant emissions under real driving conditions. Two groups of drivers (i.e. novice *vs* experienced drivers) were used to test the hypothesis. Outcomes were expected to inform and better target eco-driving programs. Driver behaviour was evaluated using OBD data, while driver performance of fuel consumption and gaseous and particulate emissions was evaluated using PEMS data. In total, 30 drivers were recruited for the RDE tests, and drove the same vehicle (i.e. a diesel LGV) on the same route during the same periods of a day, to minimise the effect of environmental and vehicle configuration factors on the performance evaluation. The main findings are summarised as follows:

(1) Novice drivers are less skilled or more aggressive than experienced drivers in the use of accelerator pedal, which are demonstrated by their longer time spent on low and high pedal positions but less time on moderate pedal position. As a result, novice drivers also show higher vehicle speed, acceleration and engine speed than those experienced drivers. In addition, novice drivers spend more time on driving modes of idling, mild acceleration and hard acceleration, but less time on cruising mode. Based on eco-driving criteria, experienced drivers perform better than novice drivers.

(2) There is a wider range of fuel consumption rates from driving by novice drivers than by experienced drivers, implying that novice drivers have greater potential for fuel saving by implementing eco-driving technology. The mean fuel consumption rate of novice drivers was slightly (2%) higher than that of experienced drivers.

(3) CO and THC emissions of all drivers are well below the standard limits, while NO_x and PM emissions of some drivers significantly exceed the limits. Compared with experienced drivers, novice drivers have 17% and 29% higher mean NO_x and PM emissions, respectively. In addition, the distributions of NO_x and PM emissions are highly skewed, and high NO_x and PM

emissions are usually associated with high fuel consumption rates. Thus, adopting eco-driving style for those worst performing drivers could significantly reduce their pollutant emissions and fuel consumption simultaneously.

(4) Overall, the experimental results reject the hypothesis that driver experience has significant impacts on fuel consumption performance. There are relatively small differences in the driver behaviour, fuel consumption and pollutant emissions between experienced and novice drivers in terms of means and ranges, in spite of the large differences in driver ages and experiences. The real differences are among the individual drivers, as the worst performing drivers have much higher fuel consumption rates than other drivers, for both groups of drivers. The findings suggest that eco-driving style will only be effective for certain drivers, regardless of their driving experience. Gentle use of accelerator pedal will be an effective eco-driving practice for all drivers.

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Yuhan Huang: Funding acquisition, Formal analysis, Writing - original draft, Writing - review & editing. **Elvin C.Y. Ng:** Funding acquisition, Experiments, Writing - review & editing. **John L. Zhou:** Supervision, Writing - review & editing. **Nic C. Surawski:** Writing - review & editing. **Xingcai Lu:** Writing - review & editing. **Bo Du:** Writing - review & editing. **Hugh Forehead:** Writing - review & editing. **Pascal Perez:** Writing - review & editing. **Edward F.C. Chan:** Funding acquisition, Writing - review & editing.

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