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## Article

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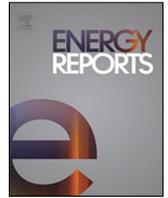
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## Research paper

# On-road NO<sub>x</sub> emissions of a modern commercial light-duty diesel vehicle using a blend of tyre oil and diesel



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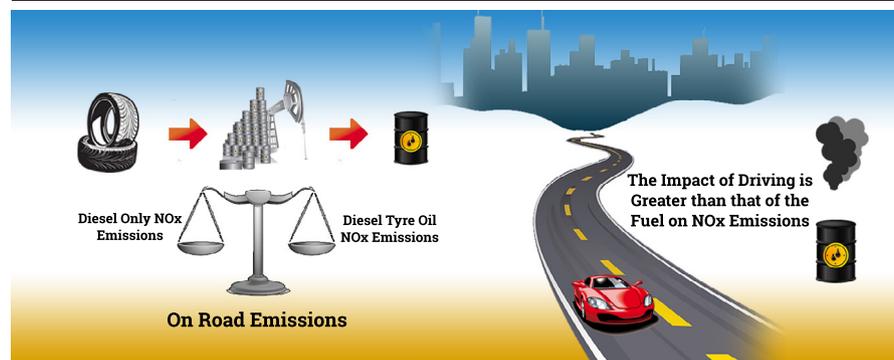
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## HIGHLIGHTS

- A blend of diesel/tyre oil was tested on-road.
- No significance difference in NO<sub>x</sub> emissions were observed.
- Variation and driving dynamics were more influential than the fuel type on emissions.
- On-road NO<sub>x</sub> emissions significantly exceeded that of the regulations.
- There is significant variability in on-road emissions, repeatability is unlikely.

## GRAPHICAL ABSTRACT



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## ABSTRACT

As a potential means of offsetting diesel fuel usage and reducing the environmental impact of used tyres, this study investigates the NO<sub>x</sub> emissions of a modern commercial passenger vehicle run on a blend of diesel and tyre pyrolysis oil (TPO). The test vehicle was driven on a route representative of the driving expected by a courier. Vehicle drivability with the TPO/diesel blend, compared to neat diesel, was not reported to be perceived differently by the automotive industry experienced driver. Additionally, the NO<sub>x</sub> emissions were comparable between the neat diesel trip and those run on the blend of TPO/diesel. Interestingly, the results showed that short transients had a substantive impact on aggregate NO<sub>x</sub> emissions—making conclusive on-road comparisons between fuels difficult. Despite this, the data collected for this study indicate that there is no substantive NO<sub>x</sub> emissions degradation when running the TPO/diesel blend.

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## 1. Introduction

Real world emission measurements can provide valuable information regarding actual road vehicles emissions in contrast to engine or chassis dynamometer tests (Franco et al., 2013). However, the results of these techniques are less repeatable when compared to laboratory studies, mainly due the presence of added

factors, such as: driver behaviour, environmental or traffic conditions, or extremely transient operation (Cicero-Fernández et al., 1997). Nevertheless, as some of these factors are challenging to reproduce in laboratory measurements, on-road studies can play a substantial role reducing the shortcomings of emission models. For instance, a portable emission measurement system (PEMS) was used to evaluate the effect of ambient temperature during on-road vehicle testing, where a series of trips were made over a year with a wide range of temperature from −25 to +20 °C (Hawirko and Checkel, 2003). The authors found that

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emission factors were highly correlated to ambient temperature and further used this information to characterise emission behaviour during cold-start operation.

In a typical Tier-II Indian city, using a light passenger car it was found that on-road emissions for CO, HC, NO<sub>x</sub>, CO<sub>2</sub> were respectively 63%, 155%, 64% and 31% higher compared to the emission results acquired using the worldwide harmonised light vehicles test cycle (WLTC) (Pathak et al., 2016). Similarly, on-road vehicle emissions, in Mol, Belgium, have been compared to the laboratory drive-cycle NEDC (new European driving cycle) (Pelkmans and Debal, 2006). In this study, on-road CO and NO<sub>x</sub> emissions were up to 10 times higher when compared to the emissions measured on the NEDC. In another study in Europe it was reported that on-road vehicle emissions exceeded the respective emission level of the Euro emission standard of the respective vehicle (Weiss et al., 2011). Furthermore, the on-road vehicle dynamics had higher magnitudes of acceleration than WLTC, spending up to 42% of the time decelerating and 46% accelerating; thereby, increasing emissions causing transients (Pathak et al., 2016). The authors also suggest that sharp braking at high speeds are a significant emissions contributor. However, in standard cycles, such as WLTC, these kinds of high acceleration and deceleration events are not represented.

There are several techniques of real-world measurements, such as: tunnel, remote sensing, road-side or on-board measurements. This study focuses on using PEMS to measure real-world emissions. Portable measurements can be carried out on-board a vehicle to provide instantaneous environmental, emission, vehicle and location information (Vojtisek-Lom and Cobb, 1997; Frey et al., 2003; Liu et al., 2011). PEMS systems have been utilised by several researchers to study different factors on vehicle emissions, such as: driver behaviour (Nam et al., 2003), traffic signals (Unal et al., 2003, 2004), speed and acceleration (Chen et al., 2007). Chen et al. (2007) reported that congestion conditions in Shanghai, China, resulted in low-speed with frequent acceleration and deceleration, increased emissions of CO and THC (total hydrocarbons). Frey et al. (2008) utilised PEMS in North Carolina, USA and found significant variation of NO emissions due to variations in average speed and travel duration. Kwon et al. (2017) showed that the route a diesel vehicle is driven on can have a substantive impact on the NO<sub>x</sub> emissions, owing to differences in engine loads. In another study, conducted in the localities of Shoreham-by-Sea, Hove and Brighton, England, PEMS was used to study effect of the driving route on emissions (Andersson et al., 2014). For this study two driving routes were developed, one route contained 60% urban whereas the other contained 60% motorway; both routes had urban, rural and motorway sections. Another key difference between these two routes was that one route started with motorway driving while the other started with urban driving. The average minimum route duration was one hour. The results obtained from these two routes concluded that driving style as well as the testing route influenced vehicle emissions.

Rapidly diminishing petroleum resources and ever growing public concern related to climate change and global warming has driven research into alternative fuel sources (Dhar et al., 2014). Researched alternatives include bio- and waste-derived diesel fuels. There has been several publications of on-road experiments evaluating the effect of different biodiesels on vehicle performance. In one on-road durability study in Thailand, Jatropa H-FAME was in-line blended at 10% (v/v) with Thai commercial diesel base (without lubricity additive) of Euro 4 fuel quality (sulphur content <50 ppm) (Chollacoop et al., 2015). For this work, the driving route was selected to represent the various driving characteristics of Thailand, including three different terrains: mountainous, suburban and urban areas. Across the test,

the vehicle was operated for 50,000 km of driving with periodic oil changes and assessments on the NEDC in a laboratory. There was no abnormal wear reported nor was the lube oil found to have any abnormal contamination. Similarly, at the conclusion of the 50,000 km of testing, no abnormal wear of the inspected engine parts was noted. With the biodiesel, all of the NEDC tests complied with the vehicles Euro standard (Euro 3). It was noted that NO<sub>x</sub> emissions systematically increased as the engine aged, but this was deemed to be normal.

Durbin et al. (2007) evaluated in-use performance of two different biodiesels: vegetable oil/yellow-grease biodiesel fuel (YGA) and soy-based biodiesel (SOY). These biodiesels were used to operate a Perkins Forklift, Harlan aircraft tow and a GM Humvee. The forklift was operated at 4 different conditions which comprised of hydraulic usage while idling, forklift usage while idling, and driving with and without hydraulic usage over a 5.8 km test route. The aircraft tow was driven over a 2.4 km route and on each run it obtained maximum speed at the same point. The Humvee was driven on a highway route (on Maryland State Highway 40 from the Aberdeen Proving Ground to White Marsh and back). Despite being on a highway, this route contained stop and go driving owing to the presence of traffic lights. The US EPA's (Environmental Protection Agency real-time On-road Vehicle Emissions Reporter was used to record in-use HC, NO<sub>x</sub>, CO<sub>2</sub> and CO as well as other key vehicle operating parameters). The results showed an increase of 20% for CO emission when the forklift was operated using a B20-Soy fuel. For the aircraft tow vehicle and the Humvee, the results showed no significant variance between ULSD and the B20-YGA for CO and NO<sub>x</sub> emissions. This approach used by Durbin et al. (2007) shows the utility of on-road emission measurements for evaluating the effect of fuels on vehicle emissions in realistic driving situations.

Tyre pyrolysis oil (TPO) is another alternative fuel which is produced from waste tyres. There has been 48.5 million tyre Equivalent Passenger Units (EPUs) of waste in Australia alone in 2009–2010 and this will keep increasing with time (Verma et al., 2018). Similarly, in 2015 the US generated 246 million end of life waste tyres (Anon, 2015). Globally, there is strong motivation to reduce waste tyre stockpiles for environmental and health issues. Waste tyres are hazardous to human health as they hold water and therefore create breeding sites for mosquitoes and bacteria (Torretta et al., 2015) and large stockpiles have the potential to catch on fire (Nadal et al., 2016; Downard et al., 2015; Singh et al., 2015). Fires from waste tyres are difficult to extinguish and cause significant environmental degradation (Singh et al., 2015). If TPO is used to fuel vehicles, it could form part of a solution to reducing waste associated with waste tyres (Verma et al., 2018).

There have been several studies in which TPO was used to operate a diesel engine in an engine-dynamometer test setup. It has been reported that the use of TPO reduced engine performance such as reduced brake thermal efficiency (BTE), engine power and increased brake specific fuel consumption (BSFC) (Ilkilic and Aydin, 2011; Wang et al., 2016; Verma et al., 2018). These reductions are largely contributable to TPO having a heating value ~3.5% lower than neat diesel. This is mostly visible at lower loads because of poor fuel atomisation and difficulties mixing with air at low temperatures in the combustion chamber (Martinez et al., 2014). The higher density of TPO (910 kg/m<sup>3</sup>), compared to diesel (830 kg/m<sup>3</sup>), is partly responsible for the poor atomisation and spray characteristics of TPO (Murugan et al., 2005; Wamankar and Murugan, 2014; Tudu et al., 2016). Additionally, TPO has higher nitrogen and oxygen content than diesel, which also contributes to higher NO<sub>x</sub> emissions. It is also reported that TPO increases CO emission (Ilkilic and Aydin, 2011; Aydin and Ilkilic, 2015; Tudu et al., 2016), which can be attributed to higher fuel density—higher fuel density can result in an increase in fuel injection,

leading to a decrease in the air-to-fuel ratio. Coupled to relatively poor atomisation, owing to the higher viscosity, these factors result in incomplete combustion.

Although in recent years there have been studies which focused on evaluating the performance of TPO on engine performance and emissions, most of these studies were conducted in laboratory conditions (Ilkic and Aydin, 2011; Martínez et al., 2014; Tudu et al., 2016; Wang et al., 2016). To date, no studies have been conducted in order to evaluate the on-road emissions of a vehicle being operated with TPO. Therefore, this study focuses on this research gap. In order to investigate this, a vehicle will be driven through Brisbane, Queensland, Australia, while being operated using both a TPO/diesel blend and diesel with a PEMS measuring NO<sub>x</sub> emissions in addition to data captured through the on-board diagnostics port (OBDII).

## 2. Experimental setup

The experiments in this work were conducted on a 2.5 ℓ diesel 2017 Hyundai iLoad van. Hyundai iLoad vans make up ~25% of the Australian market share of sales for new vans, owing to good fuel consumption and competitive sale price; they are regularly seen driven by couriers and trades people. The iLoad tested in this work was unmodified and in original form. However, Australia is behind Europe and the US in terms of emissions regulations (currently Euro 5 emissions limits are enforced). As such, vehicles such as the iLoad have some changes to the variants sold elsewhere. In this case, the key difference is the absence of the LNT (lean NO<sub>x</sub> trap) found on the European variant of this vehicle. Otherwise, this vehicle is representative of the same engine technology as the European variant. As a benefit to this study, given the lack of a NO<sub>x</sub> after-treatment system, there was no need to pre-condition the vehicle between tests nor be concerned about the impact of LNT purging on the feedgas emissions during the experiments.

It is widely accepted that while biodiesel use reduces CO<sub>2</sub>, CO, PM (particulate matter) and THC emissions, it causes an increase in NO<sub>x</sub> emissions (Mahmudul et al., 2017). Some studies, however, have shown that the change in NO<sub>x</sub> emissions is highly dependent on the fuel chemistry and characteristics, which can ultimately lead to a reduction or an increase in NO<sub>x</sub> emissions, compared to diesel fuel (Karavalakis et al., 2009). In addition to this, it has been shown that NO<sub>x</sub> emissions measured on-road are significantly higher than those in the laboratory (Weiss et al., 2012). European regulations are aiming to reduce ambient NO<sub>2</sub>, particularly in urban areas, by homologating new vehicles on-road with portable emissions measurement systems (European Commission, 2016; Triantafyllopoulos et al., 2018). Further, Jonson et al. (2017) estimate that NO<sub>x</sub> emissions caused approximately 10,000 premature deaths in Europe (including Norway and Switzerland) in 2013. It is, therefore, particularly important to investigate NO<sub>x</sub> emissions when evaluating an alternative fuel.

In this study, the NO<sub>x</sub> emissions were measured in the exhaust pipe ~70 cm downstream along the centre-line of the exhaust from the turbo-charger using an ECM ceramic NO<sub>x</sub> sensor coupled to a pressure compensator kit through an ECM miniPEMS system at 10 Hz. The manufacturer stated accuracy is given as: ±5 ppm (0 to 200 ppm), ±20 ppm (200 to 1000 ppm) and ±2% (1000 ppm to 5000 ppm). The response time is less than 1 s. Prior to this experiment the sensor was new and therefore calibrated by the manufacture—this calibration was further confirmed before the experiments using a span gas with a 2500 ppm concentration of nitrogen oxide and found to still hold. During testing of this equipment it was found that the measured NO<sub>x</sub> emission from 2 sensors did not vary by more than 2%. Therefore, it can be assumed that the NO<sub>x</sub> concentration measurements are accurate within the stated 2%.

Through the same system, the NO<sub>x</sub> sensor also measures O<sub>2</sub>. The manufacturer stated accuracy is given as 0.2% with a response time of less than 150 ms. This system performs a calculation to estimate the air-to-fuel ratio with a manufacturer specified accuracy of 0.8% at stoichiometric and 1.8% elsewhere.

The vehicle speed and flow rates are estimated from the OBDII data. The sampling rate of the OBDII data is not consistent; however, it is typically higher than 1 Hz. Although the emission equipment contained a GPS device for the purpose of measuring vehicle speed, the GPS signal was unable to reliably penetrate the vehicle. Therefore, the OBDII vehicle speed was used. The greatest source of potential error in this work arises from the use of the OBDII estimate for air flow. Exhaust mass flow rate in this work is estimated from the OBDII air intake estimate (MAF — manifold air flow) and the air-to-fuel ratio measured by the NO<sub>x</sub> sensor, shown in Eq. (1).

$$\dot{m}_{\text{exhaust}} \approx \dot{m}_{\text{intake}} + \frac{\dot{m}_{\text{intake}}}{AFR} \quad (1)$$

where,  $\dot{m}_{\text{exhaust}}$  is the estimated exhaust mass flow rate (kg/h),  $\dot{m}_{\text{intake}}$  is the air intake (from OBDII) (kg/h) and  $AFR$  is the air-to-fuel ratio. The NO<sub>x</sub> mass flow rate was calculated using the process in Ref. European Commission (2016), shown in Eq. (2).

$$\dot{m}_{\text{NO}_x} \approx \dot{m}_{\text{exhaust}} \times \text{Conc}_{\text{NO}_x} \times 4.40833 \times 10^{-7} \quad (2)$$

where  $\dot{m}_{\text{NO}_x}$  is the mass flow rate of NO<sub>x</sub> (g/s) and  $\text{Conc}_{\text{NO}_x}$  is the NO<sub>x</sub> concentration (ppm).

## 3. Fuel

On-road testing with diesel was conducted with fuel whose properties are shown in Table 1, denoted as “Reference Diesel” and the corresponding data for pure tyre oil is also shown. On-road testing was undertaken with a tyre oil/diesel blend in order to ensure the final properties of the fuel remained within the specifications required by the relevant standard. Because refuelling of the vehicle during the on-road testing with the tyre oil/diesel fuel was conducted in a range of locations, the diesel used for blending with the tyre oil did not have exactly the same properties as that of the Reference Diesel. In order to avoid confusion when interpreting Table 1, properties of the tyre oil/diesel blend are shown in the last column (obtained by calculation). Properties reported in Table 1 were obtained from fuel certificates provided by the suppliers. The diesel fuel was from the pump at Caltex service stations and the tyre oil was supplied by Green Distillation Technologies. From the table it can be seen that tyre oil has a slightly higher density, viscosity and significantly higher flash point. Furthermore, it has lower HHV (42.3 MJ/kg) compared to that of neat diesel (45.3 MJ/kg).

The blended fuel properties were assumed from a linear combination of the diesel and tyre oil properties. Consequently, those values which were higher in the tyre oil caused an increase in the blend, compared to diesel, and those values which were lower in the tyre oil caused a decrease, compared to diesel. However, given that the difference between the tyre oil properties and the diesel fuel properties was low and that the blend was not high, the blended fuel properties are similar to that of the reference diesel. The largest difference between the reference diesel and the blended fuel is in the Cetane Index. This difference has more to do with the difference between the reference diesel and the diesel used in the blend, than the tyre oil.

GDT tyre oil is produced in a continuous-batch and destructive distillation process, where the vapourised oil condenses into liquid oil and carbon and steel collects together as an end product. The sample oil used in this experiment was produced from end-of-life truck tyres. After extraction, a universal common rail diesel

**Table 1**  
Fuel properties.

Properties	Units	ASTM method	Reference diesel	Tyre oil	Blend <sup>1</sup>
Density	kg/l	D4052	0.835	0.847	0.849
Viscosity	mm <sup>2</sup> /s	D445	3.043	3.430	3.082
Flash point	°C	D93	73.0	97.0	75.4
HHV	MJ/kg	D240	45.3 <sup>1</sup>	42.3	45.0
Cetane index	–	D4737	55.3	51.7	49.6 <sup>2</sup>
Carbon <sup>1</sup>	%	–	87.0	84.1	86.7
Hydrogen <sup>1</sup>	%	–	13.0	15.9	13.3
C:H <sup>1</sup>	–	–	6.69	5.29	6.55
Ash content	mg/kg	D482	0.001	0.001	0.001

<sup>1</sup>Calculated.

<sup>2</sup>The Cetane index of diesel used for the blend calculated was 49.4.

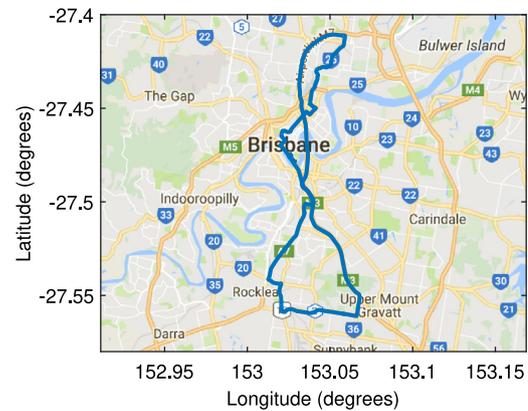
fuel filter (5 micron) was used to separate the particle and water. Physical properties, including: HHV, density, viscosity and surface tension of the waste tyre oil were tested at Queensland University of Technology (QUT). Chemical properties, such as: chemical composition of carbon, hydrogen and sulphur were tested at Elemental Microanalysis Laboratory at the University of Queensland (UQ). The elemental composition, carbon and hydrogen content of tyre oil compare well with those for diesel fuel; however the sulphur content of tyre oil is high compared to the Caltex ultra low sulphur diesel, as would be expected.

The tyre oil used in this study contains a relatively small level of oxygen compared to conventional tyre pyrolysis oils. Fuel oxygen leads to an error in the calculation of the air-to-fuel ratio, which assumes zero fuel oxygen. Pham et al. (2014) following Mueller et al. (2003) quantitatively estimate the change in air-to-fuel ratio with fuel oxygen (see Pham et al. (2014, Figure 3). They show that this change is approximately a linear function of fuel oxygen and ranges from 3% to 7% change for fuel oxygen levels of 10% to 20%, respectively. Since the tyre oil blends used in this study have fuel oxygen levels less than 1%, the corresponding change in the calculation of the air-to-fuel ratio will have an error of significantly less than 1% and has therefore been neglected in this study.

#### 4. Driving route

Given the commercial nature of the light-duty vehicle utilised in this study, the driving route was compiled to be representative of the type of driving a courier is likely to do—city driving that primarily utilises the main urban connecting roads. Additionally, the route was aimed to be approximately 1 h in duration, which should give sufficient data for a fair comparison while allowing for multiple repeats. The route begins and finishes at the city campus of QUT (Queensland University of Technology), Brisbane Australia, contains a mix of urban (<60 km/h), rural (<90 km/h) and motorway (>90 km/h) roads and also utilises Brisbane's tunnel system. QUT is located at the southern side of the city CBD (central business district), the route travels north toward Brisbane Airport on the urban streets through the city and northern suburbs before returning south through Brisbane's tunnel system (Airport Link and CLEM7) back to the main highway heading south. From the south side of Brisbane, the route then travels west before returning north to QUT via a major arterial road (A7). For illustrative purposes, a map of this route is shown in Fig. 1. The entire route was approximately 46.7 km and took between 1 h and 6 min and 1 h and 18 min to complete.

The experiments were performed on the 9th–11th of November 2017. The route was driven 3 times with neat diesel (from the pump) and 5 times with a 10% blend of tyre oil. Owing to corrupt OBDII data for 2 of the neat diesel experiments, the exhaust flow



**Fig. 1.** Route representative of a light-duty commercial vehicle driving around Brisbane. The map in this figure was queried from Google Static Map APIs (<http://code.google.com/apis/maps/>) using plot\_google\_map version 2.0 (<https://au.mathworks.com/matlabcentral/fileexchange/27627-zoharby-plot-google-map>) in MATLAB R2015b (<http://www.mathworks.com/>).

rate was unable to be calculated. Therefore, the remaining neat diesel experiment, henceforth denoted as the Reference Diesel trip, is included for comparison only. Further testing was not conducted owing to the potential for latent fuel contamination from the experiments with the tyre oil. The tyre oil experiments had 1 trip where the OBDII data was corrupted and flow rate data was not able to be extracted. The 4 successful trips, denoted Trips 1–4, will be discussed in Sections 5–6 with respect to each other and to the Reference Diesel trip. The driver was constant for all of the tests and has had substantive (2 years) industry experience working in real driving emissions for a major OEM (original equipment manufacturer).

#### 5. Driving dynamics

As the route spends a significant portion of time travelling through the centre of Brisbane city, there is substantial idle time in each trip, see Table 2. Similarly, owing to the central nature of the route, despite a significant portion of the route being on 100 km/h roads, very little driving was done above 90 km/h. However, all of the successful trips had a similar make-up with a fairly even split between urban and rural driving, see Table 2. The Reference Diesel trip did have substantially more high speed driving when compared to the trips with the tyre oil blended fuel and Trip 2 did not have any driving greater than 90 km/h and Trip 2 also had substantially more urban driving when compared to the other trips.

The manner in which a vehicle is driven will have a substantive impact on the subsequent emissions. It is, therefore, important to interpret emissions results from on-road testing in-conjunction with the driving dynamics. With respect to distance, using a threshold of 0.1 m/s<sup>2</sup>, the proportion of driving with respect to distance that was spent decelerating, cruising and accelerating is shown in Table 3. Also shown in Table 3 is the proportion of the distance travelled under hard acceleration (using a threshold of 1 m/s<sup>2</sup>). Acceleration for this work is defined as Barlow et al. (2009), as shown in Eq. (3).

$$a_i = \frac{v_{i+1} - v_{i-1}}{2 \times 3.6} \quad (3)$$

where,  $a$  is vehicle acceleration (m/s),  $v$  is the vehicle speed (km/h),  $i$  is the  $i$ th time step and is contained between 2 and  $N-1$ , where  $N$  represents the total number of samples, noting that the sample rate is 1 Hz and  $a_0 = a_N = 0$ . Whilst the trips do have similar profiles, Table 3 does show that the reference trip did the

**Table 2**  
Driving proportions by distance and total proportion of idle time.

	Reference diesel	Trip 1	Trip 2	Trip 3	Trip 4
Idle time (<1 km/h)	23.7%	21.4%	22.1%	20.5%	17.5%
Urban driving (<60 km/h)	44.1%	44.0%	59.6%	48.2%	41.9%
Rural driving (<90 km/h)	47.3%	53.2%	40.4%	50.9%	55.9%
Motorway driving (≥90 km/h)	8.56%	2.82%	0.00%	0.86%	2.14%
Total distance (km)	46.6	46.7	45.1 <sup>a</sup>	46.7	46.7

<sup>a</sup>The trip variation occurred here because of driver error.

**Table 3**  
Proportion of driving route spent decelerating, cruising and accelerating with respect to distance travelled.

	Reference diesel	Trip 1	Trip 2	Trip 3	Trip 4
Decelerating (<-0.1 m/s <sup>2</sup> )	30.3%	29.8%	30.3%	32.6%	29.9%
Cruising (~0 m/s <sup>2</sup> )	36.2%	34.6%	32.3%	28.0%	35.2%
Accelerating (>0.1 m/s <sup>2</sup> )	33.5%	35.6%	37.4%	39.4%	34.9%
Hard acceleration (>1 m/s <sup>2</sup> )	2.90%	2.77%	2.29%	2.35%	3.10%

least accelerating and the most cruising. However, the distance covered under hard acceleration was comparable to Trips 1 and 4 and substantially higher than Trips 2 and 3.

Other dynamics parameters of interest, for understanding how the vehicle was driven on each trip, are the: velocity×positive acceleration (VA), relative positive acceleration (RPA) and relative cubic speed (RCS). Of interest is also the number of stops per km, average stop duration and the average distance between stops—in this study, the vehicle will be considered stationary if the vehicle speed is less than 1 km/h. For this work, VA is defined by Eq. (4).

$$VA_i = \begin{cases} \frac{a_i \times v_i}{3.6} & a_i > 0.1 \\ 0 & a_i \leq 0.1 \end{cases} \quad (4)$$

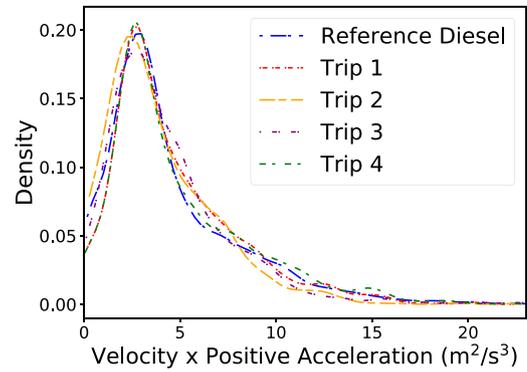
and RPA, Eq. (5), is calculated as (de Haan, 2004; Barlow et al., 2009):

$$RPA = \frac{1}{distance} \sum_{i=1}^N \begin{cases} \frac{a_i \times v_i}{3.6} & a_i > 0 \\ 0 & a_i \leq 0 \end{cases} \quad (5)$$

where *distance* is the total distance travelled in metres. RCS, Eq. (6), is calculated as (Barlow et al., 2009):

$$RCS = \frac{1}{distance} \sum_{i=1}^N \left( \frac{v_i}{3.6} \right)^3 \quad (6)$$

Fig. 2 shows the distribution of VA (excluding acceleration values less than or equal to 0.1 m/s<sup>2</sup>). Higher values of VA can indicate aggressive driving, similarly low values of VA can indicate subdued driving. From this, it can be seen that Trip 2 had the most subdued driving—the peak of the density plot is at the lowest value and beyond ~8 m<sup>2</sup>/s<sup>3</sup> contains the least density. Trip 3 is interesting, the lower peak is indicative that this trip had the least acceleration that was very subdued; however, much like Trip 2 there is very little residency beyond ~8 m<sup>2</sup>/s<sup>3</sup>, compared to the other trips. The difference is made up with increased residency at ~5 m<sup>2</sup>/s<sup>3</sup>. Indicative that Trip 3 was not aggressively driven, but nor was it completely subdued. Trip 4 is the inverse of this, there is high residency at both the subdued and the aggressive ends of the plot, with low residency in the middle ~5 m<sup>2</sup>/s<sup>3</sup> point. This could be interpreted that Trip 4 was very transient and contained many examples of both soft and hard acceleration. The presence of a greater proportion of hard acceleration is in agreement with Table 3. The profile of the reference trip is not as aggressive as Trip 4, but does have a similar profile. Outside of the ~5–7 m<sup>2</sup>/s<sup>3</sup> range, where this reference trip had the least residency, the reference trip is predominately near the middle of the other trips.



**Fig. 2.** Distribution of velocity times positive acceleration.

As a representative value, the 95th percentile of VA (excluding acceleration values less than or equal to 0.1 m/s<sup>2</sup>) can be used as a measure of driver aggressiveness. Table 4 shows the aforementioned driving dynamic measures along with the 95th percentile of VA and the stopping metrics. The 95th percentile of VA matches the trend shown at ~10 m<sup>2</sup>/s<sup>3</sup> from Fig. 2. These values can be explained by the increased motorway driving in the reference trip and Trips 1 and 4 compared to Trips 2 and 3. Taking the motorway portion into account, see Table 2, it can be concluded that Trip 4 was substantially more aggressive than the other trips and that the reference trip was likely not driven more aggressively than Trip 3. This difference in aggressiveness shown in the data, despite the vehicle being driven as consistently as possible by the same driver, was likely a consequence of factors outside the drivers control (for example, varying traffic conditions).

A similar story is evident with the RCS and RPA results. Parallels between the distribution of VA at different points, Fig. 2, and the RCS and RPA values are evident. The RCS values are clearly influenced by the proportion of motorway driving, where the RPA values appear to be better correlated with the ~4–10 m<sup>2</sup>/s<sup>3</sup> range. Clear is that no single value alone adequately quantifies aggressiveness.

The influence of traffic on Trips 2 and 3 can be clearly seen not only in the insignificant portion of motorway driving, but also in the number of stops. Interestingly, against intuition, this trend is not evident in the average stop duration. Stop duration can have a cooling effect, which for vehicles with NO<sub>x</sub> after-treatment systems can have a negative impact on tail-pipe emissions (Gosala et al., 2017), given the lack of NO<sub>x</sub> after-treatment in the vehicle utilised in this study this parameter should not significantly influence the measured NO<sub>x</sub> emissions. The average distance between stops is shorter for Trips 2 and 3, which clearly encountered more traffic than the other trips. However, with the exception of Trip 4, which had a substantially greater average distance between stops (likely as a consequence of stopping less frequently), there was not a substantial difference between the average distance between stops. This is likely because a large portion of the route was on roads with no opportunity to stop (the tunnel system, motorway and arterial roads).

Fig. 3 shows the distribution of the percentage engine load as reported through the OBDII port. Here, the influence of traffic is further evident in Trips 2 and 3 by the increased residency at higher loads. The time at high load is attributable to short increases in driver aggressiveness. With the exception of the high load residency shown for Trips 2 and 3, the engine load for all of the trips shows a very similar distribution. This is indicative that the change in fuel did not cause a significant difference in the way the vehicle was operated.

**Table 4**  
Driving dynamics.

	Units	Reference diesel	Trip 1	Trip 2	Trip 3	Trip 4
95%ile VA	$\text{m}^2/\text{s}^3$	11.3	10.8	9.09	9.80	11.8
RCS	$\text{m}^2/\text{s}^3$	422	414	270	398	414
RPA	$\text{m}/\text{s}^3$	0.135	0.138	0.140	0.143	0.139
Number of stops	–	34	35	38	37	28
Avg stop duration	s	28.3	22.9	24.4	23.6	24.5
Avg distance between stops	km	1.33	1.30	1.16	1.23	1.61

**Table 5**  
NO<sub>x</sub> emissions (mg/km).

	Reference diesel	Trip 1	Trip 2	Trip 3	Trip 4
Total	951	1390	969	805	1150
Urban	1100	1650	959	768	1050
Rural	592	843	589	721	1090
Motorway	633	1510	–	244	2620
Deceleration	377	516	554	323	482
Cruising	766	1320	1060	737	1060
Acceleration	1670	2190	1230	1250	1820
Hard acceleration	4820	5830	3730	3100	4080

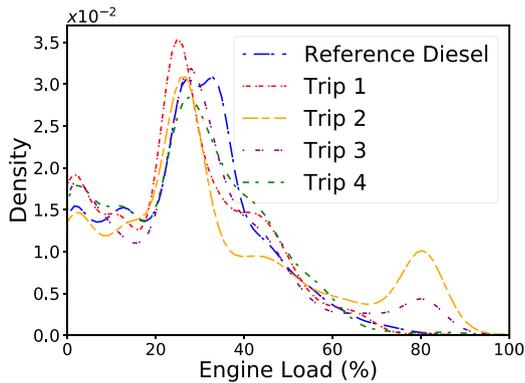
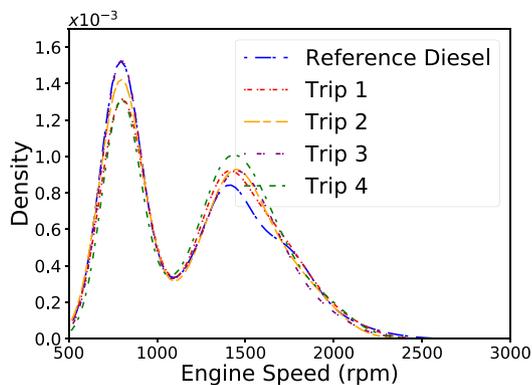
**Fig. 3.** Distribution of engine load.**Fig. 4.** Distribution of engine speed.

Fig. 4 shows the distribution of the engine speed, as reported through the OBDII port. This distribution shows that the vehicle, regardless of the trip or the fuel used, had very similar engine speed residency. The distribution is clearly bimodal with the peak at  $\sim 800$  rpm corresponding to the engine speed at idle. The other peak, at  $\sim 1500$  rpm, is attributable to cruising—acceleration would cover a range of engine speeds and hence not contribute as strongly to a single point.

Anecdotally, the driver perception of the vehicle performance was not different when operating with the blend of TPO/diesel, compared to driving with neat diesel. This is reflected in the vehicle dynamics results, Table 4, and the distributions of engine load and engine speed, Figs. 3 and 4, which do not show a significant difference between the Reference Diesel trip and those where the vehicle was operated on the blend of TPO/diesel.

## 6. Emission results

Table 5 shows the NO<sub>x</sub> emissions for each trip across the whole route, during the instantaneous urban, rural and motorway portions and also during deceleration, cruising, acceleration and

hard acceleration. With the exception of Trip 1, which emitted substantially more NO<sub>x</sub> emissions than the other trips, there is a lot of similarities between these results. The reference trip had very similar total NO<sub>x</sub> emissions to Trip 2, did not perform as well as Trip 3 and performed better than Trip 4. On the more granular level, there are substantive differences worth discussing. Between the urban portions, with the exception of Trip 1, the trips that utilised the tyre oil blend emitted less NO<sub>x</sub> emissions. Trip 1 emitted more than twice the urban NO<sub>x</sub> emissions when compared to Trip 3. Similarly, the reference rural portion emissions were essentially the same as Trip 2, which were almost half that of Trip 4. The substantive differences between the motorway emissions can be explained by the differing proportions of motorway driving, see Table 2. With a significantly increased proportion of motorway driving, it can be assumed that much of reference trip's motorway portion was not as transient as the other trips; hence accounting for the lower measured NO<sub>x</sub> emissions, with the exception of Trip 3 whose motorway portion was arguably too short to derive a meaningful interpretation.

Interesting are the differences among the deceleration and cruising NO<sub>x</sub> emissions. It is intuitive to expect substantive differences between the acceleration and hard acceleration emissions owing to naturally different levels of accelerator pedal aggressiveness. However, on the other-hand, it is also intuitive to expect similar levels of deceleration and cruising given that across the same route it can be assumed that very similar amounts of accelerator pedal were used in those portions. The substantive differences, Trips 1 and 2 for example has approximately 1.5 times the cruising and decelerations emissions of Trip 3; this could only be explainable if the cruising portions occurred at different locations on the route. These results clearly demonstrate the unrepeatability nature of on-road testing, even with the same driver on the same route with similar traffic conditions the emissions and driver dynamics vary significantly.

The significant variability throughout the trips is observable graphically in Figs. 5 and 6. Careful inspection of Fig. 5 shows that each of the trips has locations with NO<sub>x</sub> emissions spikes. Interestingly, none of these spikes align with the spikes from any other drive. It is clear that the substantive portion of the NO<sub>x</sub> emissions from Trip 1 occurred in the first 10 km of the route and thereafter the rate of NO<sub>x</sub> emissions was not substantially different to the other trips. It is also evident that for the most of route, the rate of NO<sub>x</sub> emissions of the trips with the tyre oil blended fuel was not substantially different to that of the reference trip. This observation is clear in Fig. 6, where it can be seen that on some parts of the route some of the trips NO<sub>x</sub> emissions were lower than the reference trip and on other parts they were higher. At each portion of the route there are example trips with higher and lower emissions, and every trip has examples where it has higher and lower NO<sub>x</sub> emissions when compared to the reference trip. Suarez-Bertoa et al. (2019) also showed that NO<sub>x</sub> emissions with biofuels are not significantly different to diesel on-road. Their study used blends of hydrotreated vegetable

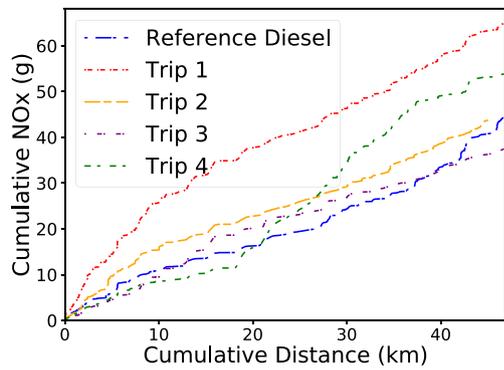


Fig. 5. Cumulative NO<sub>x</sub> emissions.

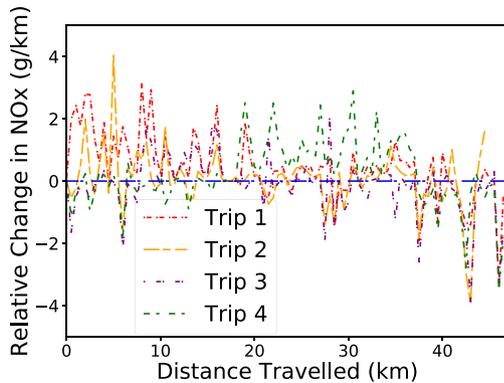


Fig. 6. Instantaneous per kilometre NO<sub>x</sub> emissions with a 0.5 km window relative to the reference trip.

oil (7%, 30% and 100% by volume) and reported NO<sub>x</sub> emissions of ~300 mg/km in all cases. The substantive difference in NO<sub>x</sub> emissions between their study and this one is owing to NO<sub>x</sub> emissions after-treatment systems.

Fig. 7 shows the distribution of NO<sub>x</sub> emissions. Much like the previous results, the distribution clearly shows the strong similarity between the reference trip and Trip 3. An interesting feature though is from Trip 4. It is clear that Trip 4 did not spend as significant a amount of time emitting high emissions as the other trips. When viewed in-conjunction with Fig. 5 it is also clear that the high aggregate emissions from Trip 4 are explainable by short transients, rather than a trend of higher emissions—such as is evident with Trip 1. Also interesting when viewed in-conjunction with Fig. 5 is that although Trip 2 did not have a significant portion of time emitting very low emissions, it had competitive aggregate NO<sub>x</sub> emissions. This could be explainable in a similar manner to Trip 4, except to conclude the Trip 2 had less transients. These conclusions are backed up by the proportion of distance covered under hard acceleration, Table 3 and the RCS, Table 4.

It should be noted that the results found in this study mirror that from other on-road emissions studies that show the large disconnect between on-road NO<sub>x</sub> emissions and manufacturer reported emissions (Weiss et al., 2011). The vehicle under-investigation here would have been homologated on the NEDC (new European driving cycle) and shown to be compliant to the Euro 5 emissions limits for light vehicles ( $\leq 3.5$  tonnes GVM), for a Class III vehicle (reference weight > 1760 kg) the NO<sub>x</sub> limit is 280 mg/km. It is clear from the results in Table 5 that this vehicle was emitting substantially more NO<sub>x</sub> emissions than the laboratory test would indicate, the total NO<sub>x</sub> emissions from the Reference Diesel trip was more than 3 times this limit.

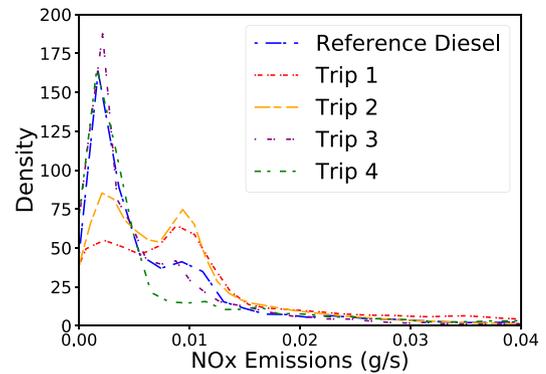


Fig. 7. Distribution of NO<sub>x</sub> emissions.

Table 6  
Estimation of fuel consumption.

Trip	Fuel consumption g/km
Reference	105
Trip 1	91
Trip 2	103
Trip 3	105
Trip 4	102

The second term of Eq. (1) is an estimate of the fuel flow rate from the air-to-fuel ratio measured by the NO<sub>x</sub> sensor and the intake air, as reported by the OBDII port. Although both measures come with significant uncertainty, they do allow for a relative reasonable comparison of efficiency. Table 6 shows an estimate of the average fuel usage for each trip. It is clear that the reference trip with diesel and those with tyre oil used had approximately the same average fuel consumption with the exception of Trip 1 which is attributable to the lower vehicle load residency, as shown in Fig. 3.

## 7. Conclusion

NO<sub>x</sub> emissions measured on-road with a modern commercial light-duty vehicle using neat diesel fuel and blended tyre oil have been described and analysed with the following major findings:

- There is substantive evidence that suggests that the NO<sub>x</sub> emissions are not significantly different when run with the tyre oil blend compared to neat diesel.
- Short transients have a significant impact on aggregate NO<sub>x</sub> emissions across a driving route.
- The variability in on-road emissions is significant and repeatability is unlikely.

This study has also shown that the manufacturer reported NO<sub>x</sub> emissions are not representative of the on-road reality. Given that biodiesel use is often attributed to higher NO<sub>x</sub> emissions, it is critical to note that the use of diesel fuel blended with tyre oil does not produce significantly different NO<sub>x</sub> emissions—thereby showing that repurposing waste tyres as fuel is not trading one environmental issue for another.

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