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Modelling and evaluation of a biomethane truck for transport performance and cost☆

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ABSTRACT

This article compares a conventional diesel-fuelled heavy goods vehicle with one that runs on compressed gas (CG): either Compressed Natural Gas (CNG) or biomethane. It includes an evaluation of the transport performance, carbon emissions, and total costs. 41 CG trucks were trialled by a supermarket, delivering goods from their distribution centre. One of the vehicles was instrumented with a gas flow meter, which measured the gas consumption, and a smartphone based data logger, which collected data from the truck's Fleet Management System (FMS) interface. Similarly, a baseline diesel truck was instrumented. Based on the measurements that were collected in-service, fuel consumption models were developed and validated. Using the validated models, the CG and diesel trucks were compared for their transport performance, costs and carbon emissions. In addition, the vehicles were evaluated using telematics data and refuelling data from a year of transport operations for all 41 CG trucks and 9 diesel trucks. The results show that for a tonne.km of in-service (mostly long haul) transport work, compared to the diesel trucks, the CG trucks spend on average 22% more energy and their fuel cost is 30% lower for biomethane. When running on CNG, their equivalent carbon emissions is 10% lower than the baseline diesel, and when running on biomethane, their equivalent carbon emissions is 78% lower. Compared to long haul, the benefits are lower for regional operations, and are the lowest for city centre operations where using CNG, the CG truck's equivalent carbon emissions is higher than the diesel truck.

1. Introduction

During 2018–19, with support from the Innovate UK funding agency, John Lewis Partnership Plc, CNG Fuels Ltd and the Centre for Sustainable Road Freight (SRF) trialled 41 spark ignition compressed gas (CG) trucks. These vehicles can run on compressed natural gas (CNG) or biomethane produced from food waste (CNG Fuels, 2019). The main project objectives were to model the CG and diesel trucks, and to evaluate the CG trucks' transport performance, carbon emissions and costs (fuel and capital), against the baseline diesel trucks. This article also shares the fuel consumption modelling and analysis from the project. The main contributions of this article are as follows.

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- An evaluation of the CG and diesel trucks for in-service and standard drive cycles, when the CG truck uses biomethane or CNG.
- A fuel consumption modelling method using in-service data. This method does not require the vehicle to be taken out of service.

Both contributions used in-service data collected from Heavey Goods Vehicles operated by the fleet operator, John Lewis Partnership Plc, and from the fuel supplier, CNG Fuels Ltd.

Methane can be used as a fuel for reducing CO2 emissions from trucks (Thiruvengadam et al., 2018). Although electrification can also offer significant reduction of CO2 emissions from heavy vehicles, researchers are working to overcome the major challeneges caused by the limited energy density of current battery pack technologies (Nicolaides et al., 2019; Madhusudhanan and Na, 2020). Compared to diesel, as methane has fewer carbon atoms for a given number of hydrogen atoms, it can be used as truck fuel to reduce carbon emissions (Kay and Hill, 2012). If methane is generated by anaerobic digestion of biological waste or from landfill sites, the equivalent 'well to wheel' CO2 emissions can be very low. In the EU, Liquid Natural Gas (LNG) and diesel-methane dual fuel vehicles have been trialled with support from the European Commission (European Commission, 2019). Compared to a diesel truck, due to an LNG truck's lower engine efficiency, its equivalent 'tank to wheel' emissions was only 5–10% lower (Vermeulen et al., 2017; Song et al., 2017). A recent study on the performance of LNG Heavy Goods Vehicles (HGVs) in the UK (Langshaw et al., 2020) showed spark-ignited LNG engines to be 18% lesser efficient than its diesel equivalent, which causes a 7% higher Well-to-Whell (WTW) Greenhouse Gas (GHG) emissions. A similar conclusion was reached in a study in the US on LNG short-haul trucks (Cai et al., 2017). An evaluation of 'dual fuel' (diesel-methane) trucks in the UK found that 'methane slip', due to incomplete combustion of the gas, caused the vehicle's equivalent carbon emissions to be 50–127% *higher* than the baseline diesel vehicle (Stettler et al., 2016). Potential use of Natural Gas Vehicles (NGVs) to reduce GHG emissions in trucks was studied in Speirs et al. (2020), which showed a wide range of potential GHG emissions due to various factors such as engine efficiency, methane slip and the drive cycles. In Vojtšek-Lom et al. (2018), experimental comparison of Euro VI light-duty utility vehicles running on CNG against diesel was performed. This study showed slightly lower GHG emissions for CNG during laboratory testing, whereas it showed higher GHG emissions during on-road testing, possibly due to longer urban driving scenarios. Compared to diesel vehicles, evaluation of WTW GHG emissions of CNG short-haul trucks and refuse trucks in Cai et al. (2017) showed slightly higher emissions from CNG vehicles due to WTW methane leakage.

When it comes to biomethane as transport fuel, in thoery, its usage can reduce GHG emissions significantly. However, there are limitations to its usage (Uusitalo et al., 2015). In O'Shea et al. (2016), an interesting study, on how much natural gas in Ireland can be substituted by biomethane produced by anaerobic digestion of residues and wastes, was done. This study showed that, according to the energy requirements in 2013, only 7% of transport energy in Ireland can be from biomethane, which was equivalent to 52% of HGVs' fuel consumption in Ireland in 2013. Nevertheless, potential benefits of biomethane usage in trucks and buses were studied in Alamia et al. (2016) and Ryan and Caulfield (2010). But these studies on biomethane as a transport fuel did not involve in-service evaluation with a fleet operator, which is important as performance for in-service drive cycles can significantly differ from standard drive cycles. In addition, there are multiple factors such as fuel and capital costs, which influence a fleet operator while deciding which type of vehicle to buy (Anderhofstadt and Spinler, 2019).

To develop fuel consumption models, there are several methods in the literature (Rakha et al., 2011; Wang et al., 2008; Duarte et al., 2016; Hunt et al., 2011; Xiao et al., 2012; Song et al., 2009; Ahn et al., 2002; Zhou and Jin, 2017; Bifulco et al., 2015; Skog and Händel, 2014; Oh et al., 2014). In Rakha et al. (2011), second order polynomials were proposed to predict fuel consumption. In these polynomial based models, engine maps, representing the fuel flow rate as a function of engine torque and speed, were not considered. Effect of different driving patterns on fuel consumption was studied in Wang et al. (2008) using a polynomial based model. An interesting piece of work was done in Duarte et al. (2016), where in-service evaluation of light duty vehicles showed higher fuel consumption compared to the standard certification drive cycles, which supports the need for in-service evaluation. In Hunt et al. (2011), fuel consumption model, including an engine map, was developed using dedicated tests, which requires the vehicle to be taken out of business operations. In Xiao et al. (2012), a vehicle weight dependent fuel consumption model was developed using statistical data. Fuel consumption factors such as engine map, road elevation, aerodynamic drag and rolling resistance were ignored in this work. Fuel consumption rate as a function of vehicle speed and acceleration was proposed in Song et al. (2009). The model development involved fuel consumption estimation using data from a Portable Emission Measurement System (PEMS), and it did not consider engine map and road slope variations. In Ahn et al. (2002), a fuel consumption map, as a function of vehicle speed and acceleration, was developed using fuel consumption and emission measurements, which required laboratory testing using a chassis dynamometer. In addition to vehicle speed and acceleration, the model proposed in Zhou and Jin (2017) uses a steady state engine map. The engine map was created using test data from a chassis dynamometer, and the model neglects road slope and variations in vehicle mass. In Bifulco et al. (2015), data from a vehicle's On-Board Diagnostic (OBD) port, which can be measured on-road, was used to develop a fuel consumption model as a function of vehicle speed, acceleration and gas pedal position. This model does not consider engine map, road slope profile and variations in vehicle weight. In Skog and Händel (2014), a fuel consumption model using vehicle speed and height data from a GPS receiver was proposed. This model development assumed constant engine efficiency. In Oh et al. (2014), a commercial power train simulation software, AVL Cruise, was used to develop a fuel consumption model using longitudinal equations of motion and an engine map. This work used test data from a chassis dynamometer to create the engine map, and the number of data points in the engine map was limited to less than 40 considering the experimental costs. In addition, the model does not consider road slope profile.

In this article, using the data collected in-service, a semi-empirical fuel-consumption model was developed for one of the CG trucks, a 'Scania P340 Gas'. The vehicle was instrumented with a gas flow meter and a smartphone based data logger, which collected high-resolution data from the truck's Fleet Management System (FMS) interface. Similarly, a fuel consumption model was developed for a baseline diesel truck, a ‘Scania P320 Diesel’. This vehicle was instrumented with a diesel flow meter and the same smartphone based data logger. Unlike the fuel consumption model developments in Hunt et al. (2011), Ahn et al. (2002), Zhou and Jin (2017), Oh et al. (2014), the models described in this article were created and validated using only in-service data and didn’t require any special testing. Therefore, the modelling and evaluation method in this article is useful to study the impact of different vehicle types on transport performance and emissions without affecting the commercial transport operations. In addition, unlike the models in Rakha et al. (2011), Wang et al. (2008), Xiao et al. (2012), Song et al. (2009), Zhou and Jin (2017), Bifulco et al. (2015), Skog and Händel (2014), both models in this article consider longitudinal equations of motion, engine map, road slope profile and gross vehicle weight variations.

The fuel consumption models were developed in a MATLAB simulation environment. They were validated using in-service fuel consumption measurements. The validated fuel consumption models were then used to compare the CG truck’s performance against the diesel truck for in-service drive cycles and standard drive cycles. Bespoke fuel consumption models were developed as existing models in the literature were not developed using data from this project vehicles. Therefore, performance of the existing models may significantly differ from those of this project vehicles. Development of custom-made fuel consumption models can prevent corruption of the evaluation resutls from such performance differences.

Telematics data and refuelling data from 41 CG trucks and 9 diesel trucks were also collected over a period of one full year. These data, along with the capital costs, were used to show that compared to the diesel trucks, the CG trucks are more cost effective and clean.

Finally, this article also describes the limitation of using biomethane as truck fuel.

2. Instrumentation and data collection

This section describes the data loggers, which were fitted to the CG and diesel trucks, and the data collection from these two trucks. Fig. 1 shows a schematic diagram of the instrumentation system used on both vehicles. The two installations were the same apart from the details of the fuel flow meter (right hand side of the figure).

The CG truck (Scania P340 Gas), shown in Fig. 2, was instrumented with a MASS-STREAM D-6300 Gas Flow Meter (GFM), which uses a constant temperature anemometer principle. It can measure in the range [2.5, 125] kg/h within 2% full scale accuracy and comes with a factory calibration certificate. Its output signal is in the range [0, 10] V and was connected to an analog input of a Bluetooth Data Logger (BDL), BTH-1208LS. The BDL was connected via Bluetooth communication to an electronic logging device developed at the Centre for Sustainable Road Freight (SRF), University of Cambridge. The logging device, known as ‘SRF Logger’, consists of a software app written for a smartphone and a VIACONT Bluetooth dongle. The Bluetooth dongle connects to the truck’s FMS interface and transmits the FMS data to the smartphone via the Bluetooth dongle. The FMS data includes the accelerator pedal position, brake pedal position, vehicle speed, engine torque, engine speed and the gear number. The smartphone senses the Global Positioning System (GPS) coordinates, translational accelerations along the x, y and z axes, and the angular velocities around the x, y and z axes.

The baseline diesel truck (a Scania P320 Diesel) had similar instrumentation to the CG truck (also shown in Fig. 1). This included an AIC-4008 Diesel Flow Meter (DFM) which uses direct flow measurement. It is accurate to 1% of full scale and comes with factory calibration. It generates 804 open collector pulses per litre of diesel flow. The open collector output was connected to the digital counter input of a BDL via a 10 kΩ pull-up resistor. The BDL was connected via Bluetooth communication to an SRF Logger, which was also connected to the truck’s FMS interface.

The data were collected while the vehicles performed their usual transport operations between the distribution centre and supermarkets. This did not disturb the transport operations and did not require any intervention from the truck drivers. Once the trucks started to move, the SRF Loggers acquired and uploaded the data to internet via 3G or 4G mobile data connection. This process continued until the trucks’ journey ended. The uploaded data was automatically downloaded and stored in a server at the Centre for Sustainable Road Freight (SRF), University of Cambridge.

3. Fuel consumption model

This section describes the fuel consumption models for the CG and diesel trucks and their validation using the measured data. Fig. 3 shows a schematic diagram of the fuel consumption model used for both vehicles. It contains a *Driver* model block to track a target speed profile, an *Engine Power Profile* block to determine the engine power as a function of the current engine speed and throttle input, an *Engine FFR Profile* block to calculate the Fuel Flow Rate (FFR) as a function of the engine speed and engine torque, a *Vehicle Motion* block to compute the vehicle’s longitudinal equations of motion, a *Gearbox* block, and a *Fuel Consumption* block to find the

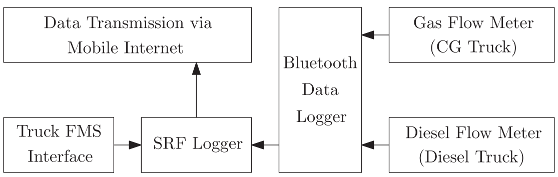

Fig. 1. A schematic diagram of the truck instrumentation.

Fig. 2. One of the instrumented vehicles.

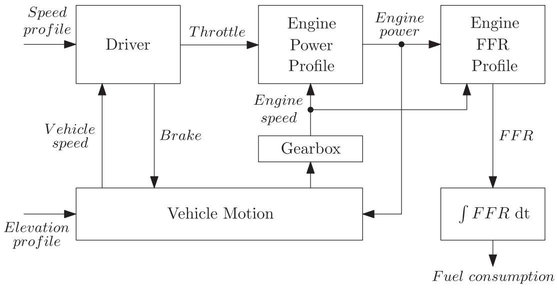

Fig. 3. Schematic diagram of the fuel consumption model.

total fuel consumption by integrating the FFR.

3.1. Driver and drivetrain

The *Driver* block contains a Proportional-Integral (PI) controller, which generates the throttle and brake inputs to track the vehicle speed profile:

$$e_v(t) = v_p(t) - v(t) \tag{1}$$

$$u_d(t) = k_p e_v(t) + k_i \int_0^t e_v(t)dt \tag{2}$$

$$\widehat{P}_{thr}(t) = \begin{cases} u_d(t), & \text{if } 0 < u_d(t) \leqslant 1 \\ 1, & \text{if } 1 < u_d(t) \\ 0, & \text{otherwise} \end{cases} \tag{3}$$

$$P_{thr}(t) = \widehat{P}_{thr}(t)G_{gcd}(t) \tag{4}$$

$$P_{br}(t) = \begin{cases} -u_d(t), & \text{if } -1 \leqslant u_d(t) < 0 \\ 1, & \text{if } u_d(t) < -1 \\ 0, & \text{otherwise} \end{cases} \tag{5}$$

Here, t is time, v is the vehicle speed, v_p is the reference speed, e_v is the speed error, k_p and k_i are the PI control gains, u_d is the PI control input, $\widehat{P}_{thr}$ is an intermediate variable, $0 \leqslant P_{thr} \leqslant 1$ is the throttle pedal position, $G_{gcd} \in \{0, 1\}$ is a digital signal to consider the gear change delay, and $0 \leqslant P_{br} \leqslant 1$ is the brake pedal position. G_{gcd} is 1 except for a brief period after each gear shift, when it is 0.

The *Engine Power Profile* block contains a one dimensional lookup table with maximum engine torque as the output and engine speed as the input. The lookup table was created using maximum engine torque versus engine speed data points, which were read from the truck's On-Board Diagnostic (OBD) port using the SRF Logger. Fig. 4 shows the relationship between the engine speed and maximum engine torque for the CG truck. Multiplying the engine speed, nominal throttle input and the maximum engine torque gives the engine power:

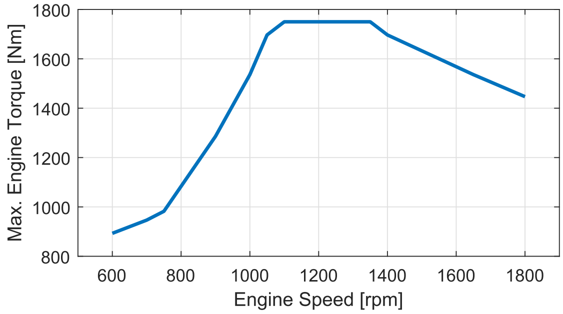

Fig. 4. The relationship between the engine speed and maximum engine torque (obtained from the vehicle's OBD port).

$$P_e(t) = T_{max}(w_e(t))P_{thr}(t)w_e(t) \tag{6}$$

Here, P_e is the engine power, w_e is the engine speed and $T_{max}(w_e)$ is the maximum engine torque as a function of the engine speed, shown in Fig. 4.

The power applied to the wheels, P_w, is either from the engine through the drivetrain or from the brake actuators:

$$P_w(t) = \begin{cases} P_e(t)\eta_{dt}, & \text{if } 0 < P_{thr}(t) \\ P_{br}(t)G_{br}\frac{v(t)}{R_t}, & \text{otherwise} \end{cases} \tag{7}$$

Here, η_{dt} is the drivetrain efficiency, G_{br} is the brake gain and R_t is the effective rolling radius of the tyre.

The test vehicles had automatic gearboxes that were observed to change gear at essentially fixed vehicle speeds for the in-service drive cycles. Consequently, the *Gearbox* model utilized a simple lookup table (Table 1) with the gear numbers, gear ratios and vehicle speeds at which the gear shifts occur. For example, the model shifts from gear 4 to gear 5 when the speed is above $9.03 + 0.5 = 9.53$ km/h and shifts from gear 5 to gear 4 when the speed is below $9.03 - 0.5 = 8.53$ km/h. The hysteresis band of $\pm$ 0.5 km/h prevents chatter during the gear shifts. The model includes a gear change delay of 1.5 s. The speeds at which the gear shifts occur were determined from the measured vehicle data and they represent the average gear shift speeds. The final drive gear ratio of the CG vehicle is 2.92. The gear ratios in Table 1 and final drive gear ratios for the two vehicles were obtained from the vehicle manufacturer.

Using the gear ratios, the engine speed was modelled as follows:

$$w_e(t) = r_g(t)r_{fd}\frac{v(t)}{R_t} \tag{8}$$

Here, r_g is the gear ratio and r_{fd} is the final drive ratio.

For the diesel vehicle, the gear box parameters, coefficient of aerodynamic drag, coefficient of rolling resistance and longitudinal equations of motion are the same as for the CG vehicle. The final gear drive ratio of the diesel truck is 2.71, which was obtained from the vehicle manufacturer.

The *Vehicle Motion* block in Fig. 3 contains the standard longitudinal equations of motion of a vehicle (Hunt et al., 2011; Heißing and Ersoy, 2011):

$$ma(t)v(t) = P_w(t) - P_a(t) - P_r(t) - P_g(t) \tag{9}$$

$$P_a(t) = \frac{1}{2}\rho_{air}C_dAv(t)^3 \tag{10}$$

$$P_r(t) = C_r mgv(t) \tag{11}$$

Table 1
The gear box parameters.

Gear Number	Gear Ratio	Shift Speed [km/h]
4	9.16	9.03 ± 0.5
5	7.19	11.88 ± 0.5
6	5.82	15.08 ± 0.5
7	4.63	19.35 ± 0.5
8	3.75	23.62 ± 0.5
9	3.02	30.46 ± 0.5
10	2.44	38.27 ± 0.5
11	1.92	48.34 ± 0.5
12	1.55	61.76 ± 0.5
13	1.24	71.98 ± 0.5
14	1.00	99.00 ± 0.5

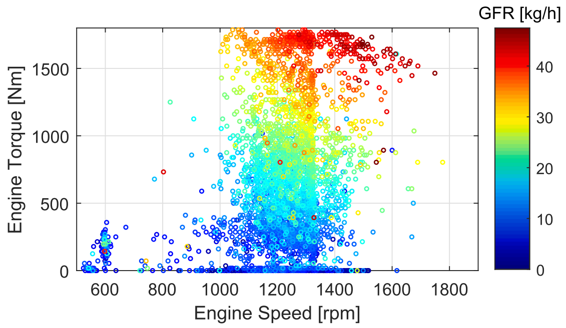

Fig. 5. The relationship between the engine speed, engine torque and biomethane flow rate (GFR) for the CG vehicle. The colour scale shows the GFR in kg/h. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

$$P_g(t) = mg\sin\theta(t)v(t) \tag{12}$$

$$v(t) = \int_0^t a(t)dt \tag{13}$$

$$d(t) = \int_0^t v(t)dt \tag{14}$$

Here m is the vehicle mass, a is the longitudinal acceleration, P_a is the power dissipated by aerodynamic drag, P_r is the power dissipated by rolling resistance, P_g is the power required to ascend the road gradient, $\rho_{air} = 1.225$ kg/m^3 is the density of air, C_d is the coefficient of aerodynamic drag, A is the vehicle's frontal area, C_r is the coefficient of rolling resistance, $g = 9.81$ m/s^2 is the acceleration due to gravity, θ is the road gradient and d is the distance travelled by the vehicle. The values, $C_r = 0.0066$ and $C_dA = 6.62$ m^2, were obtained from Odhams et al. (2010) for a similar tractor-trailer combination.

3.2. Engine maps

The main difference between the models of the CG and diesel vehicles is in the *Engine FFR Profile* block. This contained a two dimensional lookup table (engine map) with 'steady-state' values of the engine speed and engine torque as the inputs and the fuel flow rate (FFR) as the output. The lookup table data points were obtained from the in-service measurements by locating data segments of three seconds or longer for which the vehicle speed was essentially constant. Whenever such an operating condition was found, the corresponding engine speed and engine torque, which were read from the FMS port, and the FFR, which was obtained from the fuel flow meter, were saved as a data point in the lookup table. This procedure was performed over all data collected for a period of one week. Fig. 5 shows the resulting colour-map of the CG engine's gas flow rate (GFR). Fig. 6 shows the corresponding map for the diesel engine. Considering the dynamic effects in the engine map is one of the future research directions as it can potentially increase the model accuracy.

An interesting observation from Fig. 6 is the accumulation of many data points around the engine speed of 1208 rpm. This engine speed corresponds to the use of cruise control at a speed of approximately 83 km/h (51.5 mph) in gear 14. This condition occurs often while driving on UK motorways. Similar accumulation is also present in Fig. 5. However, it is around a different engine speed due to the difference between the final drive gear ratios of the vehicles.

Using the engine map, the fuel consumed was modelled as follows:

$$FFR(t) = F_{em}(T_e(t), w_e(t)) \tag{15}$$

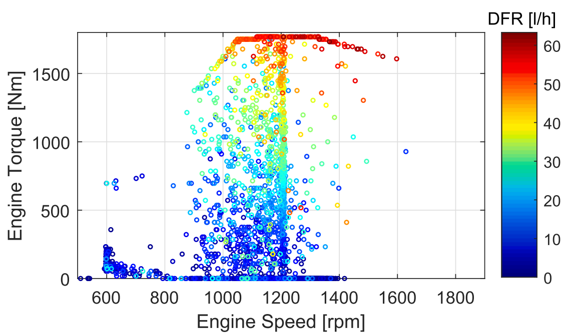

Fig. 6. The relationship between the engine speed, engine torque and diesel flow rate (DFR). The colour scale shows the DFR in l/h. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

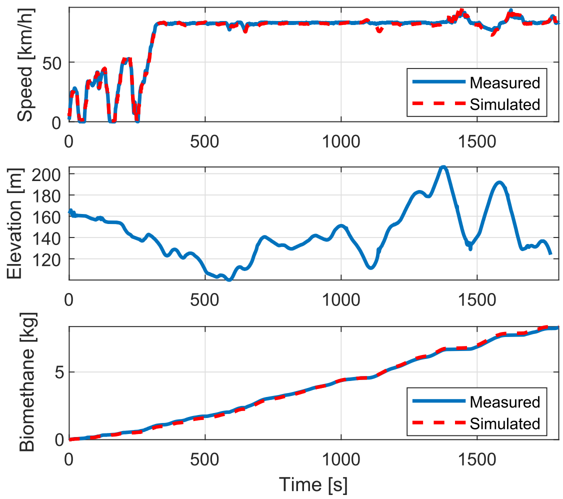

Fig. 7. Comparison of measured and simulated biomethane consumption for an in-service drive cycle.

$$FC(t) = \int_0^t FFR(t)dt \tag{16}$$

Here, F_{em} is the FFR engine map as a function of the engine torque and engine speed, and FC is the fuel consumed.

3.3. CG vehicle model validation

The CG model was validated using data from in-service drive cycles. The validation procedure compared the model's biomethane consumption with measured biomethane consumption. Fig. 7 shows the simulation results using an in-service drive cycle of duration 1800 s as the input. The measured speed profile in the top plot and the measured biomethane consumption in the bottom plot were collected using the instrumentation described in Section 2. The road elevation profile in the middle plot was obtained by looking-up the elevation corresponding to recorded GPS coordinates using the UK Environment Agency's Composite Digital Surface Model, which is available at data.gov.uk. This Digital Surface Model contains a LIDAR-based elevation model of more than 60% of England at 1 m spatial resolution (LIDAR Composite DSM , 2019).

In Fig. 7, the measured and simulated biomethane consumptions correlate well. The simulated biomethane consumption has less than 2% difference from the measured value. The simulation accuracy varied from test-to-test due to various factors, particularly changes in the ambient weather conditions - e.g. wind speed, air temperature and pressure, which all affect aerodynamic drag.

Table 2 shows the simulation model's biomethane consumption for 5 in-service drive cycles, the measured biomethane consumption in these drive cycles and the RMS error. In these drive cycles, which are each 1800 s long, the RMS error of the gas consumption model is less than 6%.

3.4. Diesel vehicle model validation

The diesel model was validated in the same way, using data from in-service drive cycles. The validation compared the model's diesel consumption against the measured diesel consumption, using different vehicle speed and road elevation profiles as input. Fig. 8 shows the simulation results for an in-service drive cycle of duration 1800 s.

In Fig. 8, the measured and simulated diesel consumptions correlate well. The simulated diesel consumption has less than 2% difference from the measured value.

Table 3 shows the simulation model's gas consumption in 5 in-service drive cycles, the measured diesel consumption in these drive cycles and the RMS error. In these drive cycles, which are 1800 s long, the RMS error of the diesel consumption model is less than 5%.

Table 2
The measured and simulated biomethane consumption in different drive cycles.

Drive Cycle	Simulated [kg]	Measured [kg]	RMS error [%]
1	7.93	7.49	5.84
2	8.26	8.30	0.51
3	5.77	5.77	0.02
4	7.77	7.89	1.56
5	8.52	8.71	2.16

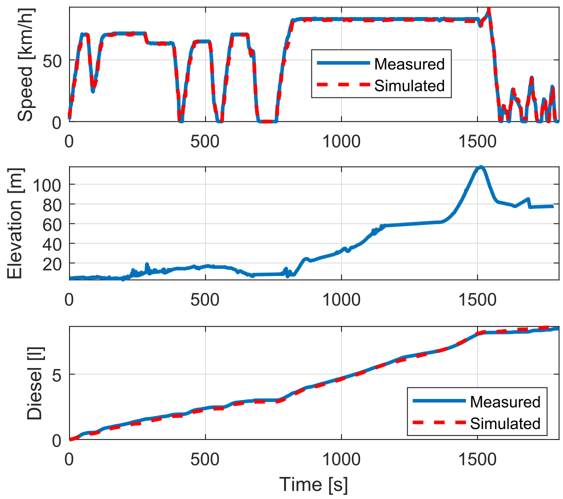

Fig. 8. Comparison of measured and simulated diesel consumption for an in-service drive cycle.

Table 3
The measured and simulated diesel consumption in different drive cycles.

Drive Cycle	Simulated [l]	Measured [l]	RMS error [%]
1	9.77	9.91	1.46
2	8.60	8.48	1.37
3	10.41	10.90	4.44
4	8.91	8.68	2.61
5	9.18	8.88	3.38

4. Vehicle comparison

This section compares the CG truck against the baseline diesel truck for transport performance, costs and equivalent carbon emissions.

4.1. Comparison of modelled performance

The models of the CG and diesel trucks described previously were used to predict the fuel consumption (diesel and CG) for various drive cycles. It was assumed that the CG engine's performance was the same for biomethane and CNG. In practice, this assumption may not be perfectly accurate because of small chemical differences between the two fuels (Langness and Depcik, 2016). According the biomethane supplier, CNG Fuels, the biomethane constitutes approximately 89.9% methane, 4.8% ethane, 1.9% carbon dioxide, 1.7% nitrogen, 1.3% propane, 0.2% butane and 0.1% i-butane.

The energy consumption, fuel cost and equivalent CO_2 content (gCO_2eq) were determined by multiplying fuel consumption values by appropriate conversion factors (Majer et al., 2020; UK Government greenhouse gas reporting: conversion factors, 2019; MacLeay et al., 2010). These factors are shown in Table 4. Alternatively, a model like COPERT could have been used to estimate the emissions (Ntziachristos et al., 2018). But to calculate the exhaust emissions, it uses vehicle distance, average speed and vehicle technology. In this article, instead of using an average speed and a generic vehicle technology, speed versus time profile and custom-made models of the vehicles, respectively, were used.

The fuel costs in Table 4 are average values for September 2018 as the in-service drive cycles, which were used for the comparison of modelled performance, were collected in this month. Variations in the fuel costs during March 2018 to February 2019 were considered in the comparison of measured performance, which are discussed in Section 4.2. According to the project partner, CNG

Table 4
Net calorific value (NCV), well-to-wheel (WTW) equivalent carbon emissions and cost comparisons for the three fuels (Majer et al., 2020; UK Government greenhouse gas reporting: conversion factors, 2019; MacLeay et al., 2010).

Fuel	NCV	WTW gCO_2eq/MJ	Cost
biomethane	44.80 MJ/kg	16.87	0.78 £/kg
CNG	44.80 MJ/kg	67.81	–
Diesel	35.99 MJ/L	91.87	1.05 £/l

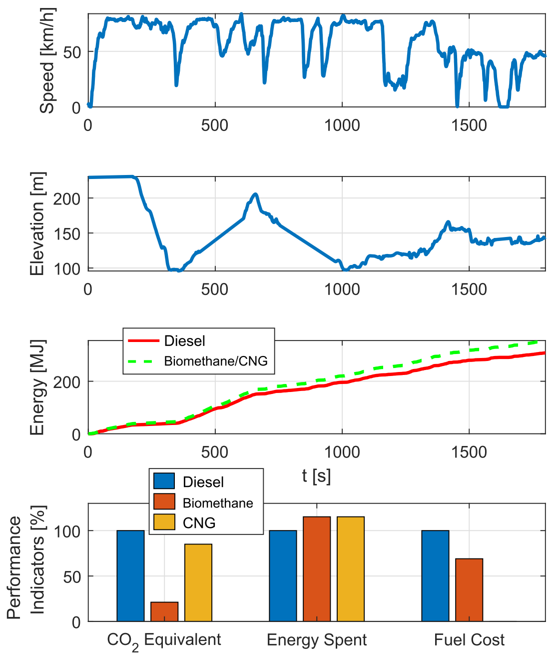

Fig. 9. Performance comparison of the diesel and CG trucks for one of the in-service drive cycles.

Fuels, the difference between the cost of CNG and biomethane is insignificant. However, as it was not possible to get the actual CNG cost, the cost of CNG was not considered in this work.

The vehicles were first compared for 10 in-service and 4 standard drive cycles. The standard drive cycles include the Heavy Heavy-Duty Diesel Truck (HHDDT) cruise mode drive cycle, LowCVP (Low Carbon Vehicle Partnership, UK) Long Haul drive cycle, LowCVP Regional Delivery drive cycle and the LowCVP City Centre drive cycle. Fig. 9 shows the comparison for one of the in-service drive cycles (DC).

The results in Fig. 9 show that using biomethane or CNG, the CG truck's energy requirement for the drive cycle is 355.2 MJ, which is approximately 15.2% more than that of the diesel truck. This is expected because the spark-ignition engine cycle of the CG truck has a significantly lower thermodynamic efficiency than the diesel engine cycle (Thiruvengadam et al., 2018). Using biomethane, the CG truck's fuel cost for the drive cycle is approximately 31% lower than the diesel truck's fuel cost. Compared to the diesel truck, the CG truck has 78.8% and 15% lower equivalent carbon emissions using biomethane and CNG respectively. As the energy content of CNG was assumed equal to that of biomethane, the CG truck's energy requirement is the same using either biomethane or CNG.

Table 5 shows a performance comparison for diesel and CG trucks over different in-service and standard drive cycles.

In the in-service drive cycles, similar to Fig. 9, the results in Table 5 show that the CG truck, using either biomethane or CNG, requires an average of 18.8% more energy than the diesel truck. The fuel cost for the CG truck using biomethane is approximately

Table 5
Compared to the diesel truck, performance of the CG truck using biomethane and CNG for different in-service and standard drive cycles.

Drive Cycle	biomethane $\Delta£$ [%]	biomethane/CNG ΔE [%]	biomethane ΔCO_2 [%]	CNG ΔCO_2 [%]
In-service DC 1	− 28.70	19.07	− 78.14	− 12.11
In-service DC 2	− 29.78	17.26	− 78.47	− 13.45
In-service DC 3	− 31.06	15.12	− 78.86	− 15.03
In-service DC 4	− 28.38	19.61	− 78.04	− 11.72
In-service DC 5	− 30.55	15.97	− 78.70	− 14.40
In-service DC 6	− 29.06	18.46	− 78.25	− 12.56
In-service DC 7	− 28.81	18.88	− 78.17	− 12.26
In-service DC 8	− 21.45	31.18	− 75.91	− 3.18
In-service DC 9	− 29.74	17.33	− 78.46	− 13.40
In-service DC 10	− 31.01	15.21	− 78.84	− 14.96
HHDDT cruise	− 26.93	22.02	− 77.59	− 9.94
LowCVP Long Haul	− 30.55	15.97	− 78.71	− 14.40
LowCVP Regional	− 26.24	23.18	− 77.38	− 9.08
LowCVP City Centre	− 18.30	36.43	− 74.95	0.70

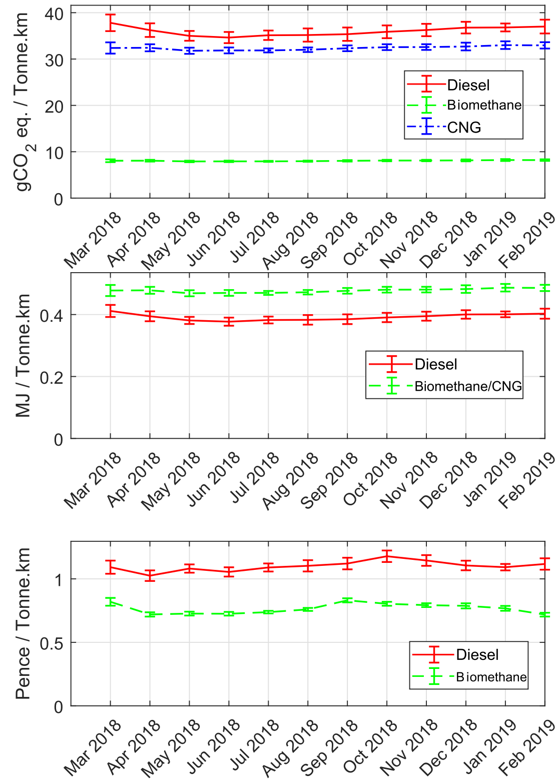

Fig. 10. Performance comparison of the diesel and CG trucks using telematics and refuel data. ‘Error bars’ show ± one standard deviation.

28.9% lower than diesel. Compared to the diesel truck, the equivalent carbon emissions of the CG truck is 78.2% lower using biomethane and 12.3% lower using CNG. Note that most of the in-service drive cycles are representative of motorway (highway) conditions.

From Table 5, looking at the results for standard LowCVP drive cycles, general conclusions about CG trucks can be drawn. It is clear that the CG truck offers the most carbon and financial benefits when used for long haul operations, where the truck mostly operates on motorways (highways). Compared to the long haul drive cycle, the carbon and financial benefits are lower for the regional drive cycle, and are the lowest for the city centre drive cycle. This is caused by the lower engine efficiency of the CG truck when operating in regional and city centre conditions, which causes higher energy consumption as shown in Table 5. The results in the last row of Table 5 show that if fuelled by CNG, the CG truck requires 36.4% more energy than the diesel truck and it’s equivalent carbon emissions is even higher than the diesel truck. This analysis shows that CG trucks are best suited for long haul transport operations to maximise the carbon and financial benefits.

Another project objective was to evaluate how air quality is affected by CNG. Dedicated tests were conducted at Millbrook Proving Ground in the UK by the Transport Research Lab (TRL) and Low Carbon Vehicle Partnership (LowCVP) in the UK. However, this analysis is outside the scope of this work and will be published by TRL in their Low Emission Freight Trial report.

4.2. Comparison of measured performance

In addition to the evaluation based on the fuel consumption models, telematics data (distances travelled, transport work and fuel consumption) and refuelling data (quantity and cost of biomethane and diesel, which varied month to month) were used directly to quantify performance. Data was collected and analysed for the 41 CG trucks and 9 diesel trucks, over a period of one full year. Conversion factors from Table 4 were used to calculate equivalent carbon emissions, energy and cost.

The transport work measure from the telematics data in tonne.km was used to calculate the performance metrics. Fig. 10 compares the performance of the CG trucks and the baseline diesel trucks.

The results in Fig. 10 show that the fuel cost of the 41 CG trucks, running on biomethane, was consistently lower (30% on average) than that of the 9 diesel trucks, over the 12 months. On the other hand, the energy requirement of the 41 CG trucks, running on biomethane or CNG, was on average 22% higher than the 9 diesel trucks. The equivalent carbon emissions of the CG trucks was significantly lower than the diesel trucks. Over the 12 months, the average equivalent carbon emissions of the diesel trucks was 36.0 gCO_2eq/tonne.km, whereas for the CG trucks using biomethane, it was 8.05 gCO_2eq/tonne.km, i.e. 78% lower. For the CNG case, the average equivalent carbon emissions was 32.4 gCO_2eq/tonne.km, which is 10% lower than the diesel case. These trends agree with the observations from Fig. 9 and the in-service drive cycles in Table 5.

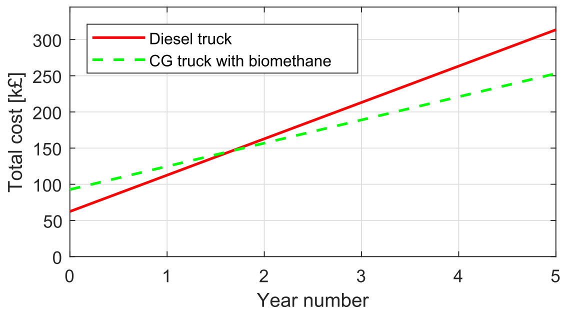

Fig. 11. Comparison of capital cost + fuel costs for a CG truck running on biomethane and a diesel truck.

In Fig. 10, fuel cost benefit of the biomethane case varies due to price variations of biomethane and diesel, which consistently have been in favour of biomethane. The UK government have also been playing a positive role here by applying significantly low fuel duty on biomethane and CNG, which enables use of CG trucks in a cost-effective manner.

As of 2019, the price of a CG truck was approximately £92750, while a diesel truck cost was approximately £62400. (Cost data provided by the fleet operator.) Based on the Telematics data and biomethane refuelling data for the 41 CG trucks, the average fuel cost estimate per year per CG truck was £32060. For a diesel truck, it was £50237. Considering both the capital cost and fuel cost (and noting that the operator does not use loan financing to purchase the vehicle), Fig. 11 shows a comparison between the 'total cost' of a CG truck running on biomethane and a diesel truck.

It is apparent that the total cost of owning a CG truck, fuelled with biomethane, (excluding driver costs) breaks even with that of a diesel truck approximately two years from purchase. Therefore, although the energy efficiency of a biomethane truck is lower than that of a diesel truck, it still offers a cost-effective goods transport solution with significantly lower equivalent carbon emissions. As the difference between the cost of CNG and biomethane is insignificant (information from the project partner, CNG Fuels), the cost of owning a CG truck, fuelled with CNG, is expected to break even with that of a diesel truck around the same time as the biomethane case.

An interesting study on how much natural gas in Ireland can be substituted by biomethane produced by anaerobic digestion of residues and wastes, was done in O'Shea et al. (2016). This study showed that, according to the energy requirements in 2013, only 7% of transport energy in Ireland can be from biomethane, which was equivalent to 52% of HGVs' fuel consumption in Ireland in 2013. Similarly, replacing all the diesel HGVs in the UK with CG trucks running on biomethane would be difficult due to the limited availability of biomethane - from landfill or anaerobic digestion. Nevertheless, use of biomethane clearly provides a cost-effective solution that reduces carbon emissions.

Where biomethane is available, substantial reduction of emissions is possible - using the same vehicle technology and much of the same infrastructure - as for CNG. However the limited availability of biomethane means that this solution is not scalable to all fleet operators and therefore it cannot be used as a solution for decarbonising all freight vehicles.

5. Conclusions

(i) Accurate fuel consumption models were developed and validated for compressed gas and diesel lorries, using vehicle performance data collected in-service. The RMS errors of both models were less than 6% for a range of operating conditions.

(ii) Over 10 in-service drive cycles studied in simulation, the CG truck was predicted to use approximately 18.8% more energy than the diesel truck. When fuelled with biomethane, the CG truck's fuel cost was estimated to be 28.9% lower than the diesel. The vehicle running on biomethane is predicted to emit approximately 78.2% lower equivalent carbon emissions than the diesel and the vehicle running on CNG emits 12.3% lower carbon emissions.

(iii) The transport performance and fuel costs of 41 CG trucks and 9 diesel trucks were monitored in-service using Telematics and refuelling data, collected over one full year of transport operations. For one tonne.km of transport work, the CG trucks consumed on average 22% more energy than diesel. In the biomethane case, the fuel cost was on average 30% lower than the diesel case. The vehicles running on biomethane emitted on average 78% lower than the diesel trucks, whereas the CG trucks, if fuelled using CNG, are expected to emit 10% lower equivalent carbon emissions than diesel trucks.

(iv) When considering the 'total cost' of running the CG vehicle (fuel cost + capital cost); neglecting labour costs and maintenance cost; the break even period is approximately 2 years.

(v) Using the results for standard drive cycles, general conclusions about the CG trucks were drawn. The CG truck offers the most carbon and financial benefits when used for long haul operations. Compared to long haul operations, the carbon and financial benefits are lower for regional operations, and are the lowest for city centre operations. This is caused by the lower engine efficiency of the CG truck when operating in regional and city centre conditions. For the city centre drive cycle, if fuelled by CNG, the CG truck's equivalent carbon emissions was even higher than the baseline diesel truck.

(vi) It would be difficult to run all trucks in the UK on biomethane due to limited availability. Nevertheless, given the significant carbon savings and proven business case, this mode of goods transport may be attractive to several fleet operators.

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