Journal of Physics: Conference Series

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To cite this article: Teresa Donateo *et al* 2024 *J. Phys.: Conf. Ser.* **2893** 012103

Analysis of the Heat Content of Exhaust Gases from a Heavy-Duty Diesel Engine under Real-world Driving Conditions and Cold Start Operation

Teresa Donateo[1*], Paolo Cutuli[2], Niccolò Vilotta[2], Angelo Algieri[2], Pietropaolo Morrone[2]

[1] Department of Engineering for Innovation, University of Salento, Lecce, Italy
[2] Department of Mechanical Engineering, Energy Engineering and Management, University of Calabria, Arcavacata di Rende (CS), Italy

[*]E-mail: teresa.donateo@unisalento.it

Abstract

European Commission is currently working on defining new Euro 7 standards for light and heavy-duty vehicles, which will set severe restrictions on emissions in real driving conditions, and under cold-start operations. It is well known that about 60% of fuel energy converted in a diesel engine is lost in exhaust flow, coolant, and other forms of loss. A more efficient vehicle usage can be achieved by exploiting such dissipated energy content to produce additional mechanical or electrical energy. Several solutions can be adopted for Waste Heat Recovery (WHR) systems. Among them, exploiting the synergy between Organic Rankine Cycles (ORCs), thermal storage with Phase Change Materials (PCM), and electric hybridization is the solution adopted in the research project IRIDESCENT (biodIesel hybRID Electric buS with waste heat reCovEry aNd sTorage). The efficacy of recovering heat content from exhaust gases in reducing fuel consumption has already been demonstrated under stationary conditions. However, one of the challenges in applying WHRs to the powertrain of road vehicles is the fast dynamics of the engine load that determines fast variations in the flow rate and temperature of the exhaust gases. This makes it difficult to optimize energy recovery and explains the need to adopt PCM thermal storage systems. In this framework, the goal of the present work is to characterize the variability of temperature and flow rate in the exhaust gases of a diesel engine for heavy-duty applications under real-world driving conditions. To this end, a dataset of information retrieved from the scientific literature for the Isuzu FTR850 truck was used. The dataset consists of twenty-eight trips performed with the same driver over the same route. It includes both hot-start and cold-start trips and three different values of trailer load (0, 1500, 3000 kg). For each trip, data from GPS, ambient sensors, onboard diagnostics (OBD) systems, and portable emissions measurement systems are made available with a frequency of 1 Hz. In this investigation, a statistical analysis of the data set and a preliminary selection of the ORC and PCM technologies are performed.

Introduction

Heavy-duty vehicles (HDVs) like trucks and buses are responsible for about 25% of CO_2 emissions from road transport in the EU. The European Commission recently introduced two sets of limits, for hot and cold emissions; according to these regulations, new large trucks should emit 30% less CO_2 than today, with an intermediate target of 15% by 2025. Finding viable solutions to reduce environmental impacts in the coming years is a priority because HDVs entering the market before 2035 will remain in service for many years.

The solutions adopted in this investigation are the recovery of waste heat and its conversion into mechanical or electrical energy [1]. Organic Rankine Cycles (ORC) are a promising technology for this purpose [2], offering net efficiencies of up to 8% [3,4] [5], but on a smaller scale, such as in transportation, they are challenging because of their footprint.

To manage the high dynamicity of engine load and speed in the real-world operation of HDVs, Phase Change Materials (PCMs) can be adopted. PCMs have much higher thermal storage capacity than sensible heat storage systems [6],[7]. PCM-based heat exchangers can smooth out exhaust gas temperature variation of Internal Combustion Engines (ICEs) and improve WHR system efficiency by storing thermal energy for up to twelve hours with proper insulation and therefore, avoiding cold-start operation.

In hybrid electric vehicles (HEVs), compared to conventional powertrains in which cold-start occurs only once per driving mission, the ICE works discontinuously and is subject to more cold-starting. Lack of proper heating decreases engine efficiency [8] and affects the behavior of the after-treatment devices; using a PCM-based storage system would make it possible to keep the engine warm post-shutdown, exploiting the heat produced at the last start.

Real Driving Emissions (RDEs) ensure that a vehicle operates within acceptable emission standards during normal driving conditions and are a necessary certification tool for the environmental impacts of light and heavy-duty vehicles. RDE. In RDE test measurements are made using a Portable Emissions Measurement System (PEMS), which is connected to the vehicle exhaust to record pollutant concentrations, simultaneously exploiting data collected via On Board Diagnostic (OBD) and GPS systems, while the vehicle drives a standardized route [9]. In this investigation, PEMS measurements are used not only to assess the environmental impact but also to characterize the mass flow rate and temperature of exhaust gases in a heavy-duty vehicle under real-world conditions. This is the main novelty of these studies compared to the scientific literature where chassis dynamometer measurement [10] or model-based analysis of standard driving cycles [11] are performed to quantify exhaust gases mass flow rate and temperature in ICEs.

1. Project description

This investigation is performed in the framework of the IRIDESCENT project (biodIesel hybRID Electric buS with waste heat reCovEry aNd sTorage), funded by the European Union – NextGenerationEU through the Italian Ministry of Ministry of University and Research (MUR). This project is aimed at reducing the environmental impact, in particular at cold start operation, of heavy-duty vehicles by exploiting the synergy between:

- On-board Waste Heat Recovery (WHR) with Organic Rankine Cycle (ORC);
- Hybridization;
- Use of biodiesel fuel;
- Adoption of Thermal Energy Storage (TES) systems.

The proposed integrated system is shown in Figure 1. System components, together with the thermal, electrical, and mechanical power flows, are displayed. As concerns the WHR system, both high-temperature waste heat from exhaust gases and low-temperature waste heat from coolant should be considered as thermal sources. However, this investigation focuses on high-temperature waste heat. More specifically, the present investigation describes the first activity of the project which includes the choice of a reference vehicle and the analysis of the thermal flows under real-world driving cycles.

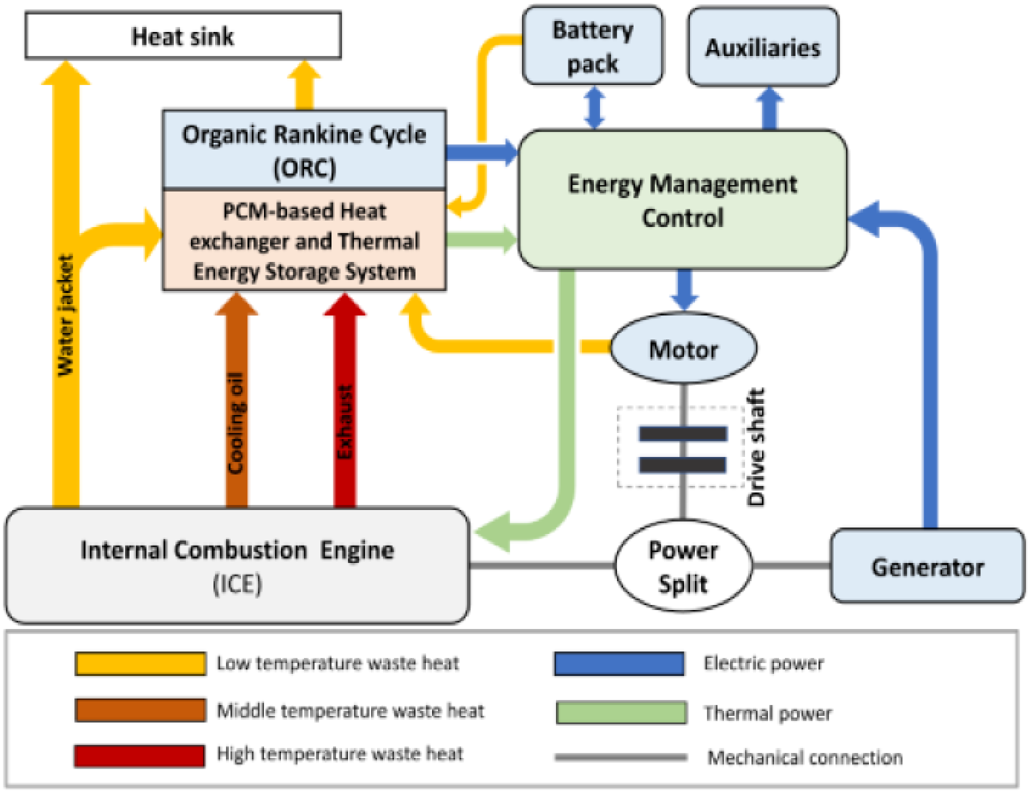

Fig. 1. Proposed hybrid WHR integrated powertrain - series/parallel hybrid electric

1.1 The benchmark vehicle

The benchmark vehicle is the Class 6 truck Isuzu FTR850 ATM equipped with a Euro III turbocharged intercooled diesel engine. The main specifications of the vehicle are in Table 1. This vehicle was chosen after a scouting of the available open data about RDE tests on heavy-duty vehicles equipped with diesel engines.

The estimated performance curves of the engine are shown in Figure 2.

Model	Isuzu FTR 850
Mass permissible body + payload gross vehicle mass (GVM) total mass during tests + load	 10410 kg 24000 kg 10740 kg + {0 kg; 1500 kg; 3000 kg}
Overall length	9255 mm
Overall width	2400 mm
Wheelbase	5500 mm
Engine model displacement power torque	 Isuzu 6HK1-TCN 7.79 liters 176 kW @ 2400 rpm 706 Nm @1450 - 2400 rpm
Transmission and drive type number of gears forward gear ratios final ratio	 manual 6 {8.51, 4.66, 2.73, 1.78, 1.27, 1.00} 5.875
Fuel capacity	400 liters
Tires	11 R22.5-16PR

Table 1. Benchmark vehicle data and specification

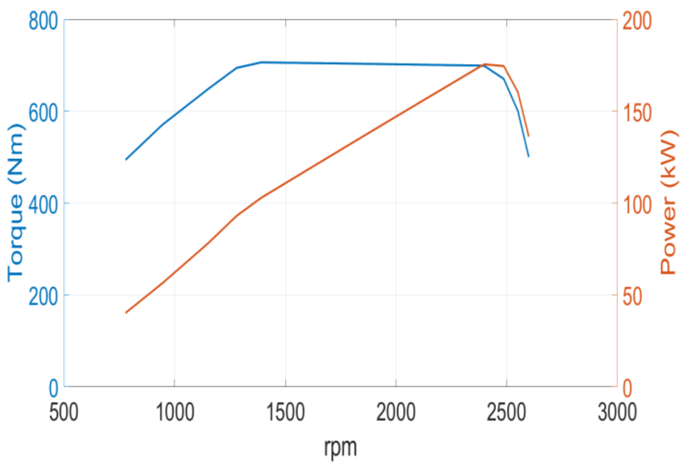

Fig. 2. Estimated engine performance map

2. Description of the dataset

The dataset analyzed in this investigation is made available by Joubert et al. [9] and contains a comprehensive collection of variables measured on the reference vehicle. These include spatial data recorded by GPS (latitude, longitude, altitude, and speed), trip identification details (date, trip number, and trailer load), and environmental conditions (temperature, pressure, and humidity). Engine-related parameters acquired via the OBD port include actual speed, intake manifold pressure and temperature, coolant temperature, and air-fuel ratio. Additionally, the exhaust flow rate and concentrations of CO, CO2, and NOX are recorded by the exhaust flow Meter. For the tests, the cargo bed of the Isuzu FTR850 AMT was equipped with a crane and a small cab. The rail subassembly that allows the vehicle to operate on rails and auxiliary equipment does not directly affect the vehicle transmission but adds additional weight to the truck. The total weight including equipment and driver was 10,740 kg, 4830 kg on the front axle and 5910 kg on the rear axle.

Twenty-eight trips were made by the same driver and following a standard route, with coincident starting and ending points, located at the University of Pretoria's Hatfield campus (Pretoria, South Africa), totaling 61.7 km. The following sections can be identified in the route:

- urban road (A), which runs around the city center;
- highway (B), with allowed speeds up to 120 km/h;
- steep road (C), busy with stop-and-go traffic conditions.

Among the twenty-eight trips, the first eight were conducted with the flatbed unloaded, the next ten with a load of 1500 kg, and the last ten with a load of 3000 kg. The tests are further distinguished by whether they involve data acquisition with a cold-start or a hot-start. Specifically, in the former case, emissions are measured while the engine is running below its operating temperature. In the latter, the test begins when the coolant temperature is stabilized at its steady-state value above 70 °C. Trips with cold-start acquisitions will be three in the case of zero load, two in the case of intermediate trailer load, and three in the case of maximum load on the cargo bed.

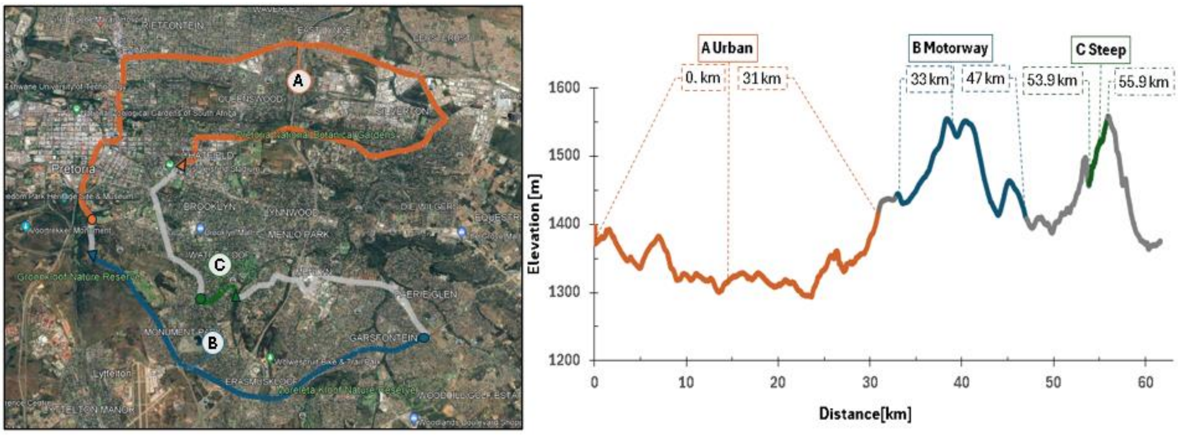

Fig. 3. Road section map (on the left) and road section elevation (right).

Figure 4 (a) shows the longitudinal profile of the standardized path and the instantaneous vehicle speeds measured by OBD; Figure 4 (b) reports exhaust gas temperatures and flow rates along the path carried out for a generic trip. These figures evince the high variability of exhaust temperature and mass flow rate during the trip.

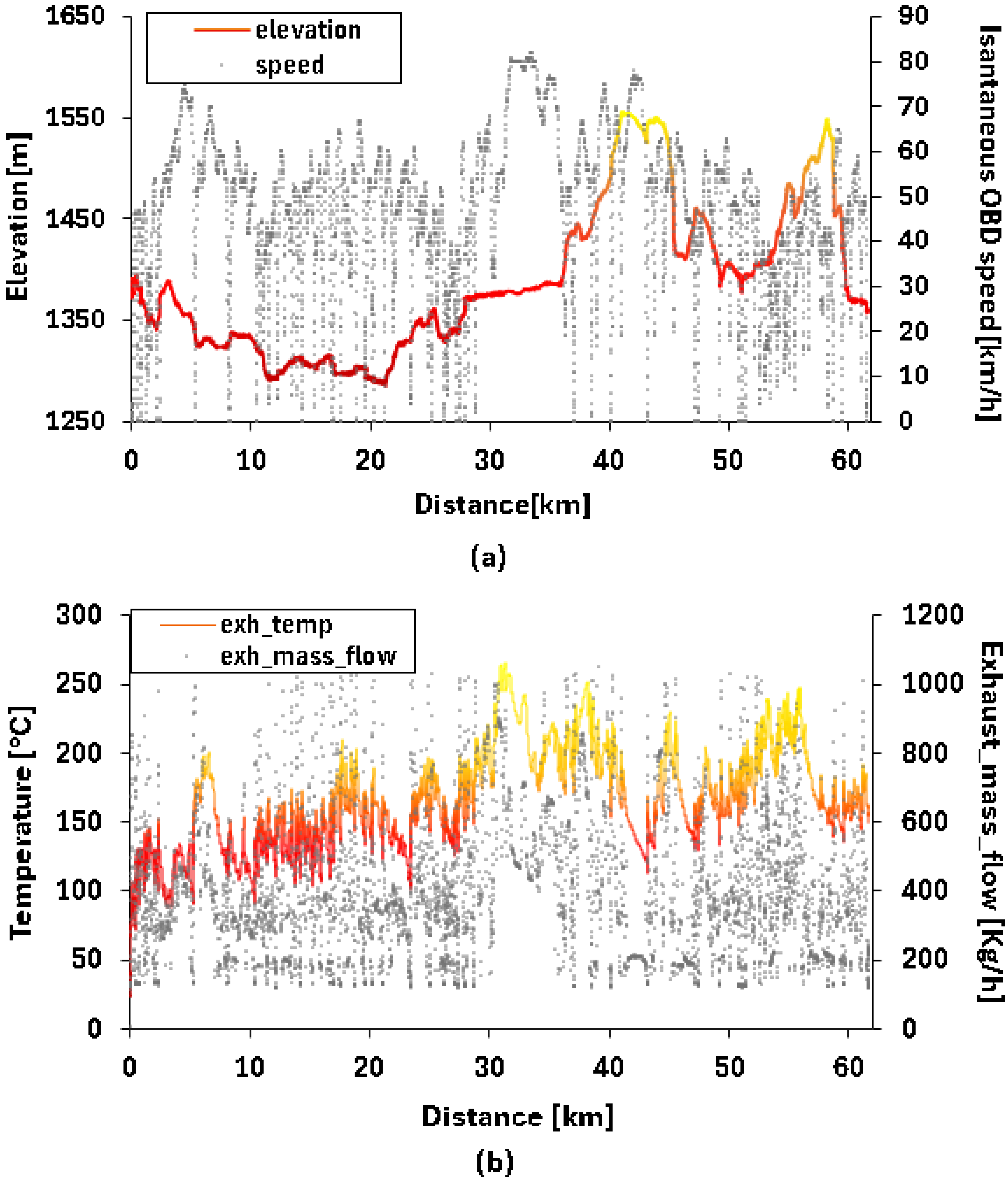

Fig. 4. Road elevation and vehicle speed (a), exhaust temperature, and mass flow rate (b).

3. Methodology and results

A statistical analysis of the most relevant quantities was carried out to characterize engine behavior in terms of load, fuel flow rate, exhaust gas temperatures, and emissions.
The first step of the investigation was the choice of a limited number of representative cycles after excluding those that would reduce data repeatability, cause significant variation in averages, or alter correlations between variables. To achieve this, the Relative Positive

Acceleration (RPA) parameter was chosen, which relates to the dynamicity of a driving cycle within the framework of RDE, defined in Commission Regulation (EU) 2016/427 on pollutant emissions [12].
The RPA is defined as follows:

$$RPA_k = \frac{\sum_j \Delta t \cdot \left(v \cdot a_{pos}\right)_{j,k}}{\sum_j d_{i,j}}$$

Where $d_{i,j}$is the distance related to the route section $k = \{u, r, m\}$ refers to the urban, rural and motorway path; Δt is the time interval corresponding to an acquisition frequency of 1 Hz; v is the vehicle speed. a_{pos} is the positive acceleration defined as:

$$a_{pos} = \frac{v_{i+1} - v_{i-1}}{2\Delta t}$$

It is worth noting that decelerations are excluded from the computation of this parameter since they do not contribute to the driving cycle dynamism.

Considering the speeds for each trip, always lower than 90 km/h, the RPA by type of road stretch was calculated. More specifically, based on recorded speed the values of RPA_u and RPA_r were determined, characterised by $v \leq 60\ km/h$ and 60$\leq v \leq 90\ km/h$, respectively [9].

Another benchmark for driving cycle dynamics is $v \cdot a_{pos}$, i.e., the RPA numerator as prescribed by regulations [12,13]. The parameter $v \cdot a_{pos}$[95], which corresponds to the ninety-fifth percentile of the product between velocity and positive accelerations, was also evaluated.

The values obtained for this parameter and RPA are shown in Figure 5 as a function of speed. From the graphs of $v \cdot a_{pos}$ and RPA, it can also be verified that almost all tests remain below the upper limit and above the lower limit imposed by current regulations for validation of RDE tests. The average values are also reported.

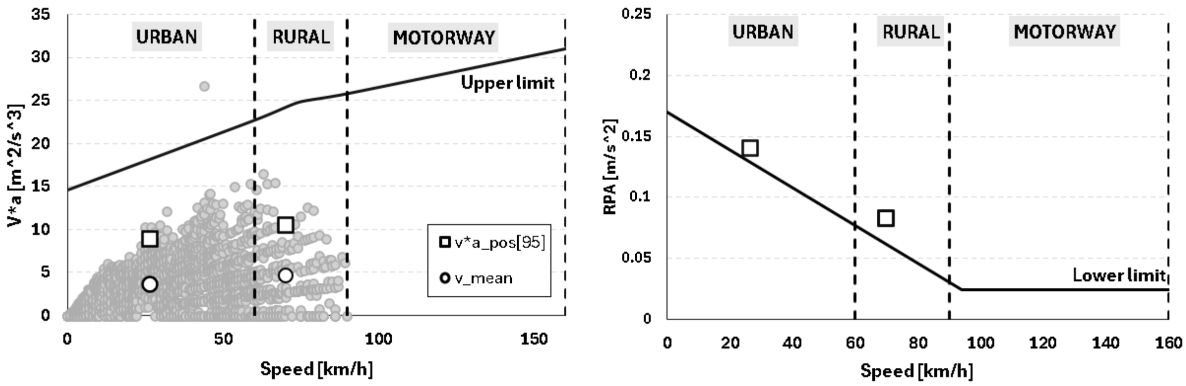

Fig. 5. Dynamism parameters of a driving cycle and boundary conditions.

3.1 Choice and analysis of the representative cycles

The parameters $v \cdot a_{pos}$ and RPA were calculated for all trips and the values plotted in the respective diagrams, as shown in Figure 6. From these plots, a trip with intermediate dynamical characteristics is chosen for sets of similar trips obtaining a total of 6 reference trips.

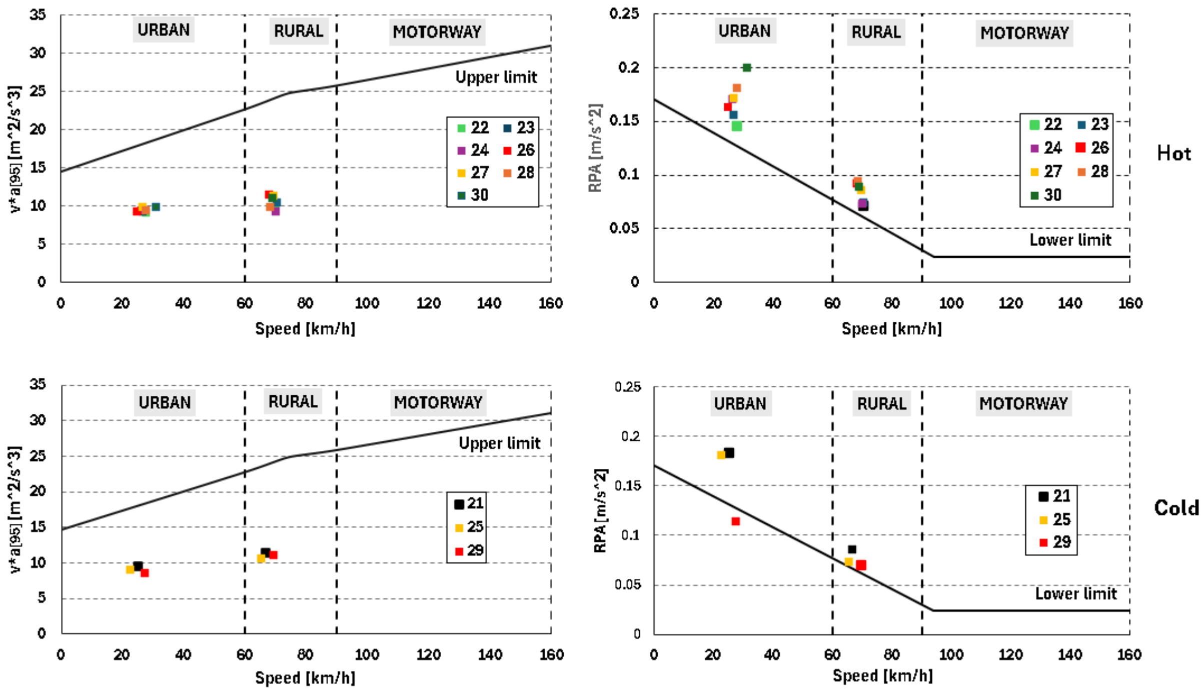

Fig. 6. Evaluation of trip dynamism with 1500 kg load under hot start and cold start.

The selected representative trips are reported in Table 2 where they are identified by the number, type of start, and load on the cargo bed.

	Cold start	Hot start
0 kg	#5	#4
1500kg	#23	#24
3000 kg	#15	#14

Table 2. Reference trips for trailer load and hot/cold start.

Following this, the exhaust gas temperature and fuel flow rate data were analyzed for each of the six typical trips to choose the PCM and estimated the potentiality of thermal energy recovery with ORCs. In the future development of the project, the data of these cycles will be analyzed to obtain correlations between driving conditions and/or engine operating points and available thermal power.

The average values of temperature and mass flow rate of all cycles are reported in Figure 7 where the selected 6 cycles are highlighted in blue and red for the hot start and cold start, respectively. It is possible to observe that the average mass flow rate is almost the same for all cycles while the exhaust temperature is affected mainly by the load and tends to increase with the vehicle's total mass, as expected because of the higher torque request to the engine.

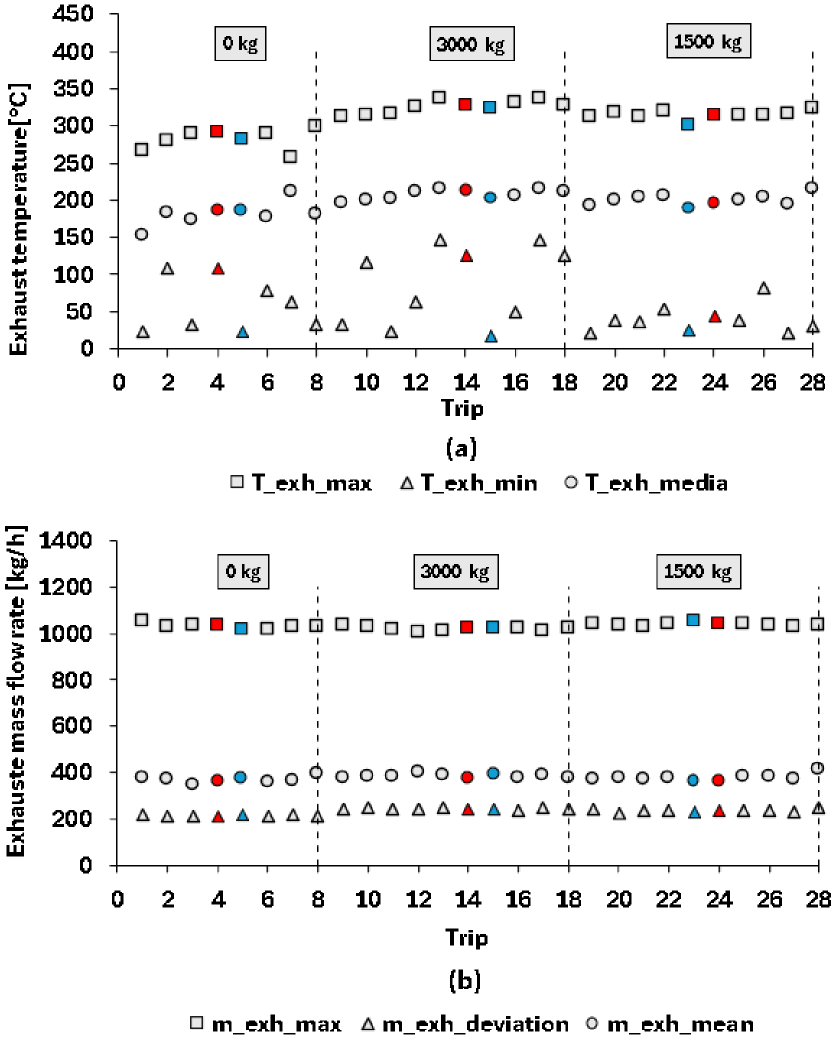

Fig. 7. Range of exhaust temperatures (a) and flow rates for each trip (b). Selected trips are highlighted (red and blue for hot start and cold start respectively).

Note that the range of exhaust temperature shown in Figure 7 is significantly lower than the range of 500 K - 900 K reported in the scientific literature for heavy-duty engines [11]. However, the values of exhaust temperature recorded in the dataset refer to the tailpipe exit section where the temperature sensor is located while the WHR system is generally located before the exhaust after-treatment and after the turbocharging device [14] where temperatures are higher. In future development, literature values and models will be used to estimate the temperature in different sections of the exhaust system under stationary and dynamic conditions [15] to develop a simple Mean Value Model (MVM) to predict the temperature drop and the delay between the turbine outlet and the tailpipe exit.

3.2 Analysis of the selected cycles

Using reference trips, the exhaust temperature trends in the cold start/hot start cases are displayed in Figure 8. Note that these plots display only the first 5 km since after this distance the cooling liquid has reached the normal operating temperature so there is no longer any difference between the trends.

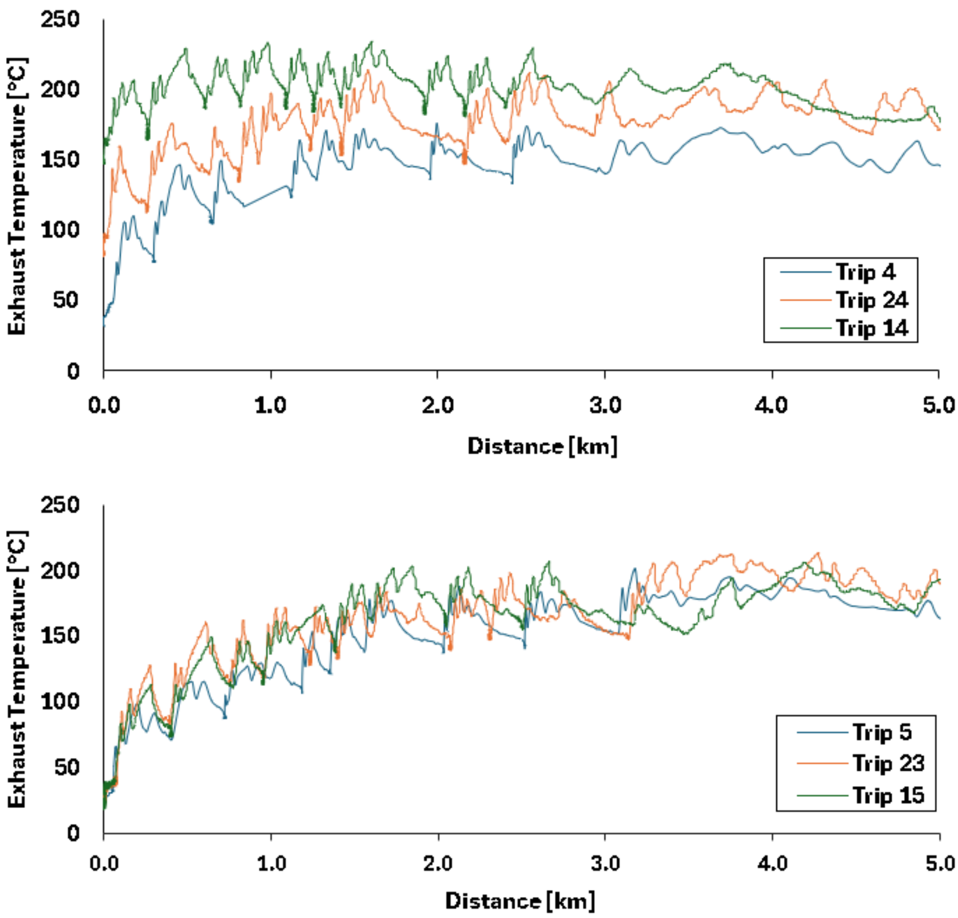

Fig. 8. Exhaust gas temperature after 5 km in hot start (above) and cold start (below).

Next, an analysis of emissions was conducted, comparing the amount of CO2, NOx, and CO produced under cold-start and hot-start cases.
The graphs in Figure 9 prove that in cold-start cases, the emissions produced are higher. As for the exhaust temperature, after the first 10 km, corresponding to an average travel time of about 20 min, there is no longer any difference between the trends, which overlap. In addition to pollutant emissions, Figure 9 also shows the trips selected by the type and underlines the increase of emissions with load.

More in-depth statistical analyses were also carried out to better assess the reliability of the results obtained at each stage of the data analysis. Figure 10 shows the average CO_2 and NO_x emissions for each trip. It can be seen that in the case of maximum trailer load, the average emissions are higher.

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doi:10.1088/1742-6596/2893/1/012103

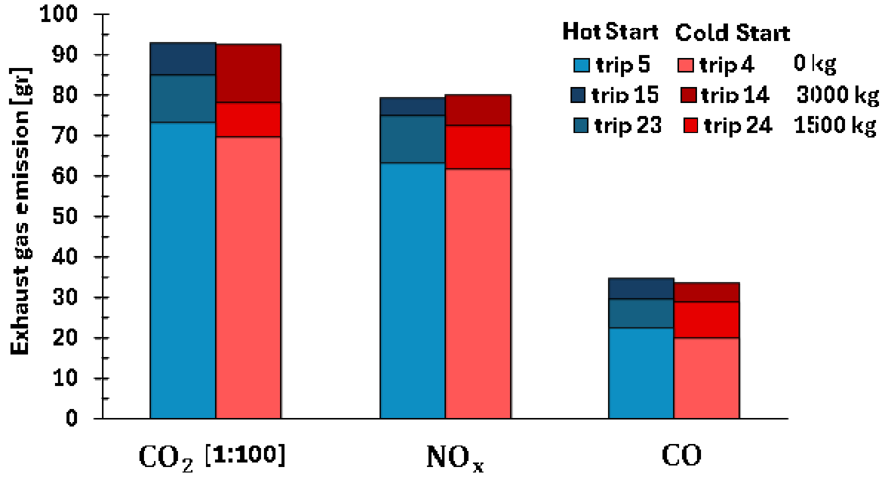
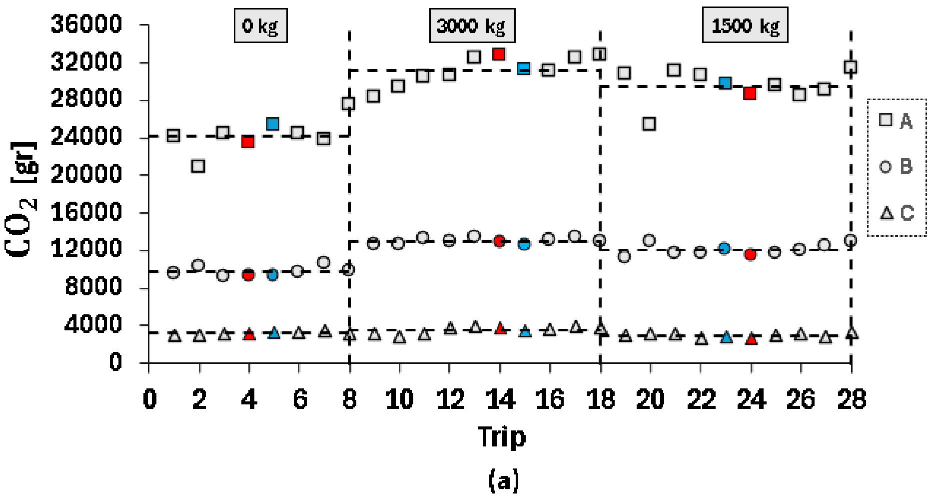


Fig. 9. Pollutant emissions with cold start and hot start for selected trips in the first 10 km.



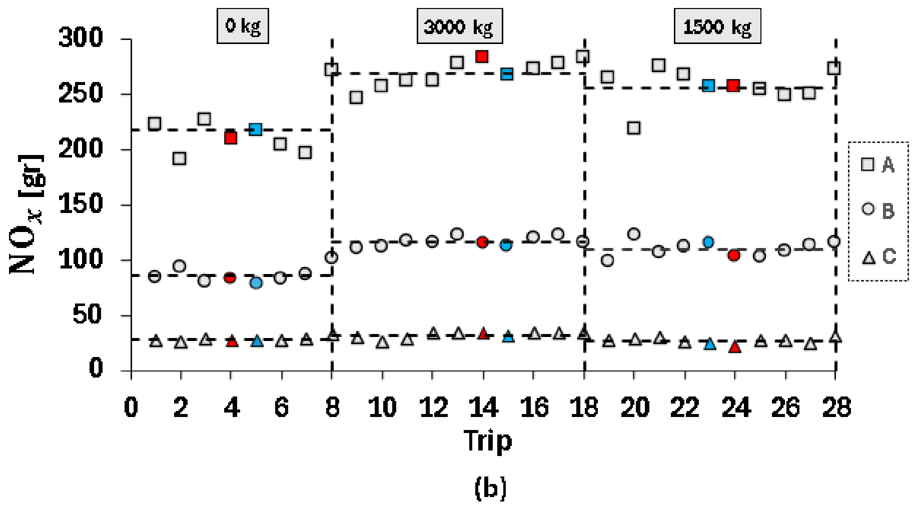


Fig. 10. Average pollutant emissions per trip. Selected trips are highlighted (red and blue for hot start and cold start respectively).

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Finally, Figure 11 displays the average fuel economy and the average vehicle speed per trip. The average speed is comparable for different loads, so the maximum one (3000 kg) corresponds to an higher average fuel consumption [km/l], as expected.

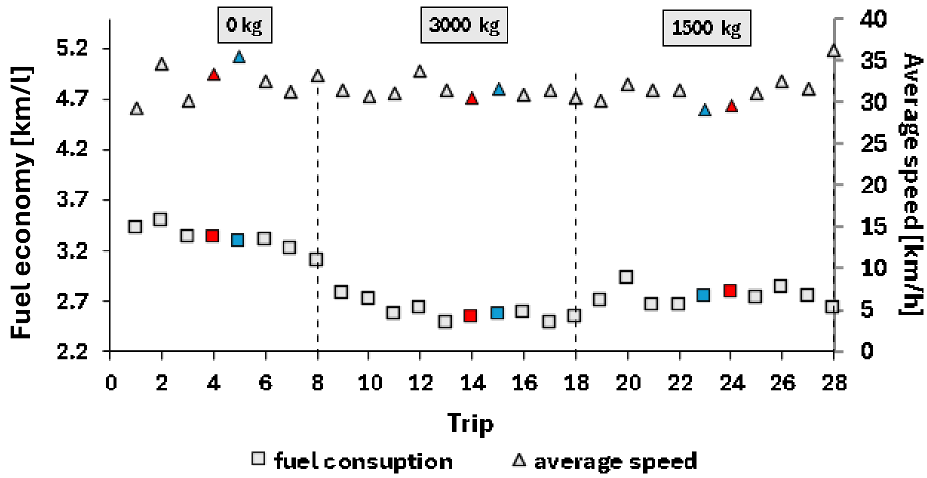

Fig. 11. Average fuel consumption and average speed per trip. Selected trips are highlighted (red and blue for hot start and cold start respectively).

4. Waste Heat Recovery Section

A thermal energy storage system, containing the phase change material, is proposed in the IRIDESCENT project to smooth out power fluctuations. In this investigation, a preliminary analysis of the PCM was performed by using the average values of exhaust temperature data shown in Table 3 together with their large range of variation.

	Temperature [°C]	Exhaust flow rate [kg/h]
0 kg	180.09 ± 37.76	361.07 ± 213.50
1500kg	203.76 ± 37.29	384.17 ± 242.29
3000 kg	208.22 ± 35.77	380.56 ± 235.01

Table 3. Exhaust temperature and flow rate (expressed as mean value ± standard deviation).

Considering the literature on PCM and the exhaust temperature range, between 200-300°C, the choice will fall on nitrate, as listed in Table 4.

	Melting temperature [°C]	Laten fusion heat [kJ/l]
Parafines	0÷150	150÷200
Salt hydrates	50÷110	250÷580
Nitrates	150÷330	250÷650
Hydroxides	180÷420	450÷700

Table 4. Melting temperature and latent fusion heat for typical PCM.
$\eta_{ORC} = 15\%$

The temperature and flow rate data of the exhaust gases were used also to estimate the recovery potential of an Organic Rankine Cycle (ORC) system installed downstream of the engine. This preliminary estimate does not encompass a dynamic analysis, which will be conducted in future studies. However, the use of a PCM-based heat storage system is assumed to compensate for variations across the entire route, thereby enabling the ORC system to effectively recover most of the energy.

A comprehensive literature review was conducted to determine the typical efficiency values of ORC systems based on the temperature of the hot source, with efficiencies ranging from 5% to 15% [16], [17]. By evaluating the available energy within the exhaust gases over the entire selected route, the recoverable energy range of an ORC system was assessed. The results of this evaluation are presented in Table 5 for the different trailer load values and considering the range of minimum and maximum efficiency. The table shows the ratio between the energy delivered by the ORC and the average energy produced by the engine, calculated according to the literature [18]. In particular, for a 10% average ORC efficiency, the percentage ORC power ranges from 7.1% to 9.3% when the load goes from 0 kg to 3000 kg. The maximum energy recovery is 13.9% for an ORC with a 15% efficiency revealing interesting capabilities for the waste heat recovery unit.

	E_{exh} [kWh$_{th}$]	P_{ele} $\eta_{ORC} = 15\%$	$P_{ele}/\overline{P}_{ICE}$ [%]	P_{ele} $\eta_{ORC} = 10\%$	$P_{ele}/\overline{P}_{ICE}$ [%]	P_{ele} $\eta_{ORC} = 5\%$	$P_{ele}/\overline{P}_{ICE}$ [%]
0 kg	29.52	4.43	10.66	2.95	7.11	1.48	3.55
1500 kg	35.59	5.34	12.85	3.56	8.57	1.78	4.28
3000 kg	38.64	5.80	13.95	3.86	9.3	1.93	4.65

Table 5. Energy recovered by the ORC unit from exhaust in the efficiency range of 5%-15%.

5. Conclusions

In this paper, a preliminary analysis of fuel consumption, CO2 and pollutant emissions, temperature, and mass flow rate of exhaust gases from a heavy-duty vehicle equipped with a diesel engine was performed to stress the variability of these parameters under real-world conditions. An open dataset containing 28 cycles was considered for the investigation but, after a detailed analysis of cycle dynamicity, 6 representative cycles were selected, one for each condition of load (0, 1500kg, and 3000kg) and hot/cold start.

The results of this analysis were used to analyze the variability of exhaust temperature and flow rate to quantify the expected recovery of power with a PCM-ORC system with literature values of ORC efficiency and to choose the best material for the PCM. It was found that the recovered electric power ranges between 1.6 and 8.5% of the engine brake power.

The selected representative cycles will be used for the remaining activities of the IRIDESCENT project including the development of a dynamic model of the engine able to predict the temperature and flow rate of exhaust gases as a function of dynamically variable driving conditions or engine operating points (speed and load time histories).

6. Acknowledgements

We acknowledge financial support under the National Recovery and Resilience Plan (NRRP), Mission 4, Component 2, Investment 1.1, Call for tender No. 1409 published on 14.9.2022 by the Italian Ministry of University and Research (MUR), funded by the European Union – NextGenerationEU– Project Title IRIDESCENT – P2022YB8HY CUP F53D23009880001 - Grant Assignment Decree No. 5 adopted on 01/09/2023 by the Italian Ministry of University and Research (MUR).

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