

École polytechnique de Louvain

Do the NO_x emissions in real driving conditions meet the European emission standards?

Influence of the driving behaviour

Authors: **Gauthier CORBISIER, Guillaume LACAVE**

Supervisor: **Francesco CONTINO**

Readers: **Hervé JEANMART, Benoît HERMAN**

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Abstract

European Emission Standards (EURO) have evolved over the years with increasingly stringent pollutants emission limits for new vehicles. Driving cycles have been developed under the Worldwide harmonised Light vehicles Test Procedure (WLTP) to simulate real driving conditions on a roller test bench in a laboratory. Since 2017, the Real Driving Emissions (RDE) test completes the WLTP by continuously measuring several parameters such as NO_x under real driving conditions.

In this work, four types of RDE tests have been implemented in order to characterise driving behaviour, using data analysis from an on-board accelerometer. A criteria tree defining different driving styles has been created.

Finally, the influence of different driving behaviours on the production of NO_x is studied by means of an exhaust gas analyser. The RDE tests are compared with each other to determine the optimal driving behaviour regarding NO_x production. Three out of four behaviours are EURO compliant, while a more aggressive driving has a direct impact on the NO_x emissions which could be more than two times above the EURO limit.

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Acronyms

EGR Exhaust Gas Recirculation.

EURO European Emission Standards.

IQR Interquartile Range.

N₂O Nitrous Oxide.

NEDC New European Driving Cycle.

NO Nitric Oxide.

NO₂ Nitrogen Dioxide.

NO_x Nitrogen Oxides.

OBD On-Board Diagnostics.

RDE Real Driving Emissions.

SCR Selective Catalytic Reduction.

TWC Three-Way Catalysts.

WLTP Worldwide harmonised Light vehicles Test Procedure.

Introduction

In the context of global warming and of a major ecological crisis, it has become essential to minimise the air pollution. The number of cars in the world is increasing every year as transport has become a key sector for many countries. Indeed, there was a 25% increase in car production between 2010 and 2018 [1].

Despite the energy transition, a major part of vehicles still runs on internal combustion engines and forecasts show that these engines will continue to be used in the majority of light vehicles in the medium term [2]. These engines present the disadvantage of emitting several substances that are harmful to the environment such as Nitrogen Oxides (NO_x). Standards have therefore been developed to regulate the amount of pollutants released into the atmosphere.

Any car sold in Europe since September 1992 must theoretically comply with European Emission Standards (EURO), which have become increasingly stricter over the years [3]. These standards impose maximum concentrations of pollutants emitted by cars on the road. Tools were therefore developed to certify that a car is compliant with the EURO regulation. These driving cycles are performed on a roller test bench in a laboratory. These tests have evolved to better simulate real driving conditions.

The Worldwide harmonised Light vehicles Test Procedure (WLTP) is a more representative driving cycle of the typical usage of a car, but it is still conducted in a laboratory. Since 2017 in Europe, a Real Driving Emissions (RDE) test has been added to the WLTP test in order to check the car emissions. This RDE test continuously measures several parameters such as the amounts of harmful gases in the exhaust (e.g. NO_x) but does not include the analysis of the driving behaviour of the driver.

In previous years, a research team at UCLouvain has developed dataloggers that can connect to the On-Board Diagnostics (OBD) socket of vehicles, allowing the recording of data from a car in real driving conditions. These dataloggers are

equipped with, among other things, an accelerometer. Through an in-depth analysis of the accelerometer data, specific driving behaviours are highlighted.

In the framework of this thesis, several RDE tests were carried out in order to study *the influence of the driving behaviour on the NO_x production of a WLTP homologated car*. These RDE tests reproduced a conventional WLTP under real driving conditions and were performed by measuring data with an exhaust gas analyser and a datalogger.

The first chapter intends to give a background of the different parameters involved in this thesis such as NO_x , driving cycles and driving behaviours defined with an accelerometer. The second chapter will focus on the characterisation of a driving style using an accelerometer. Finally, the relation between the driving behaviour and the NO_x emissions is detailed allowing to identify the EURO compliant driving behaviours.

Chapter 1

General Context

1.1 Nitrogen Oxides (NO_x)

1.1.1 What are the NO_x ?

NO_x is a generic term which refers to Nitrogen Oxides, an important family of air polluting chemical compounds. These gases are produced during the combustion of fuel with air, which happens in all gasoline and diesel engines. In 2018, 39 [%] of the emitted NO_x in the European Union (EU) was coming from the road transport and this was the largest share of NO_x emissions. So, this environmental issue is still in the spotlight of the fight against air pollution, especially in road transport.

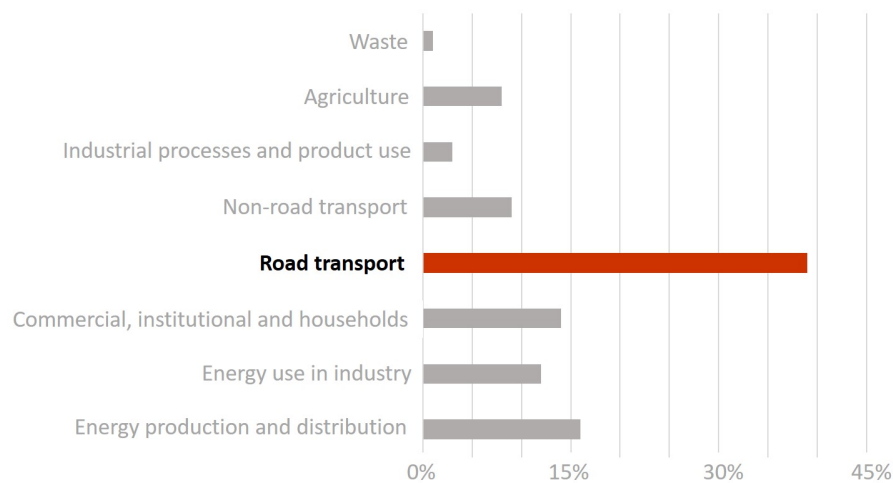


Figure 1.1: Road transport is the sector emitting most of the NO_x in the EU in 2018 [4].

Different types of NO_x

There are three types of NO_x:

1. **Thermal NO**: high temperatures are required for the formation of this type of NO_x, as shown in FIGURE 1.2. Thermal NO_x are the most abundant in combustion engines.
2. **Fuel NO**: the formation of fuel NO goes through the formation of HCN (Hydrogen cyanide) and NH_i. It appears when nitrogen is present in the composition of the fuel (e.g. coal), which is not the case for gasoline and diesel engines. Temperature has a slight influence on its formation (FIGURE 1.2).
3. **Prompt NO**: the prompt NO_x are generated with N₂ and CH_i radicals in fuel-rich environment at the flame front. This source of NO_x is less important in car engines because the "volume of high-temperature burned gases is much larger than the instantaneous volume of the flame front" [5].

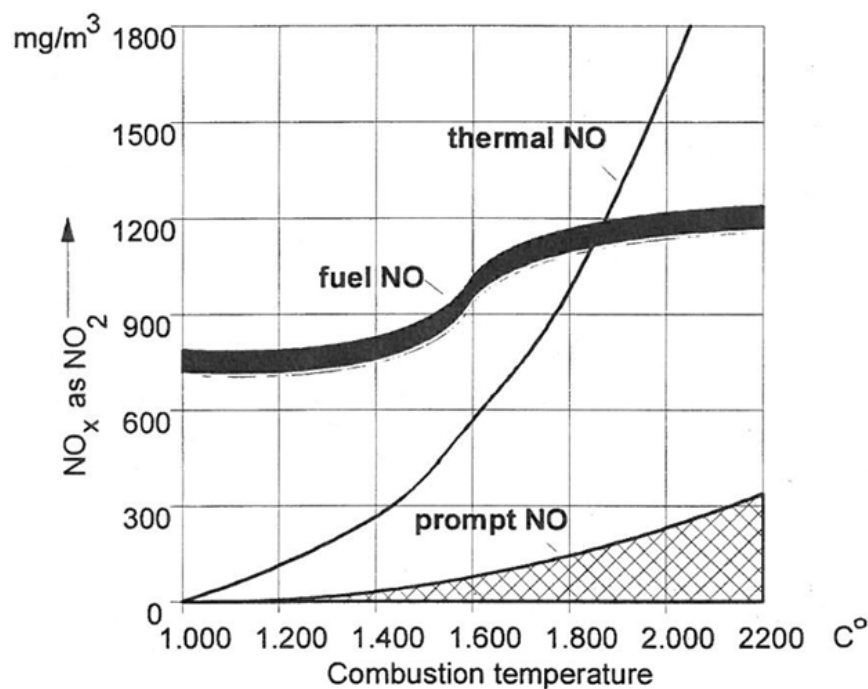


Figure 1.2: Influence of temperature on NO_x formation [6].

Thermal NO_x

Dinitrogen N₂ is the major component of our atmosphere since it represents about 80% of the air (by volume). It is a relatively inert gas. However, in engines it can react at high temperatures with the oxygen leading first to the formation of NO and other NO_x afterwards. In this case, the NO_x are called *thermal NO_x*, following the extended Zeldovich mechanism [7]:



The third equation appears in fuel-rich conditions. The formation of NO is linked to the combustion temperature and the presence of oxygen: the higher the combustion temperature and available oxygen, the higher NO formation.

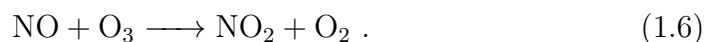
As said earlier, the NO_x stand for a large family of nitrogen oxides compounds. This family contains all the following molecules: N₂O, NO, N₂O₂, N₂O₃, NO₂, N₂O₄, N₂O₅ [7]. In the context of this work, the NO_x produced from vehicles with internal combustion engines were targeted. This includes mainly Nitric Oxide (NO) and Nitrogen Dioxide (NO₂). Some catalytic converters may produce Nitrous Oxide (N₂O).

1.1.2 Why are the NO_x harmful?

NO_x emissions lead to environmental and health problems. Indeed, these emissions induce the formation of ground-level ozone, it contributes to the formation of acid rains and eutrophication of waters and soils.

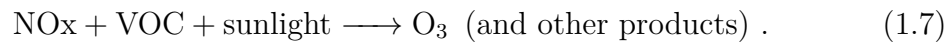
Nitric Oxide (NO) In the concentrations found in the atmosphere, this gas itself causes no health problem. However, it oxidises quickly in the very toxic and reactive NO₂.

Nitrogen Dioxide (NO₂) NO₂ can cause a lot of health and environmental problems, in particular regarding the ozone formation due to NO_x and Volatile Organic Compounds (VOC) in the troposphere [8], which accounts for a major part of smog.



Ozone formation involves first the photodissociation of NO_2 by the sunlight, followed by the recombination of the oxygen atom with the dioxygen. In a last step, a final reaction forms back NO_2 and dioxygen.

All these reactions do not lead to ozone generation. However, the interaction of the VOC and NO_x with sunlight lead to a net gain of ozone in the troposphere [8]:



The equation 1.7 is a "highly simplified version of tropospheric ozone formation" [8].

Nitrous Oxide (N_2O) This gas is an analgesic (known as laughing gas) and it is one of the most important greenhouse gases, so it is also an issue in the fight against global warming. In the vehicle industry, N_2O is produced in some catalytic converters, even though these prevent NO and NO_2 at the exhaust.

1.1.3 How are the NO_x prevented?

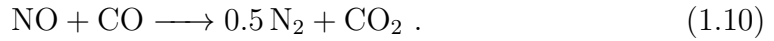
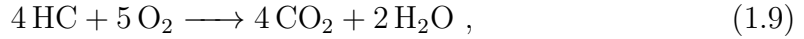
A lot of research has been done to reduce the amount of NO_x created. Nevertheless, it is almost impossible to eliminate the NO_x emissions. Several systems were invented to remove the NO_x from the exhaust by using an aftertreatment device. Here are some theoretical methods implemented to reduce the NO_x [7]:

- Reducing peak temperature;
- Reducing residence time at peak temperature;
- Chemical reduction of NO_x ;
- Oxidation of NO_x with subsequent absorption;
- Removal of nitrogen;
- Using a sorbent;
- Combination of these methods;

The chemical reduction of NO_x is mainly happening with the help of catalysts. It is more complicated to reduce the NO_x in the exhaust of diesel engines than in gasoline engines. Indeed the compression-ignition process in diesel engines requires more air. But if there is not enough oxygen, it is becoming more complicated to get rid of other pollutants like CO and unburned hydrocarbons [6].

Three-Way Catalysts (TWC)

The TWC is an exhaust aftertreatment technology used to recombine toxic gas molecules into less harmless substances like water vapour, oxygen and carbon dioxide. Theoretically, it allows to get rid of CO, unburned hydrocarbons (HC) and NO_x by oxidation and reduction reactions, as follows [9]:



To work efficiently, the catalytic converter must be at around 425 [°C] and ideally it should work at equivalence ratio Φ of 1 [9], as in most gasoline engines. This means it is not efficient for short trips where the catalytic converter does not have enough time to heat up.

Furthermore, if the equivalence ratio is below 1, there is an important quantity of air in the exhaust gases (leaner conditions), where these catalysts become less effective to treat the NO_x. This explains why other technologies have been implemented to treat in particular the NO_x [10] in modern diesel engines.

Exhaust Gas Recirculation (EGR)

The EGR is a technique allowing to recirculate a portion of the exhaust gases in the cylinder. The goal is to reduce the level of NO_x at the exhaust by mixing fresh air and exhaust gases. By doing that, the level of oxygen in the mixture will be lower than fresh air and the peak temperature in the cylinder will be decreased because the exhaust gases will act as an inert gas with a high specific heat capacity [11].

As illustrated in FIGURE 1.3, the exhaust gases go through a cooler to decrease their temperature and increase their positive effect on NO_x emissions. The negative consequence of this recirculation is the reduction of the volumetric efficiency of the engine. Actually, this problem never occurs because when there is a high demand for power, the Electronic Control Unit (ECU) closes the EGR valve completely and therefore the driver cannot notice it.

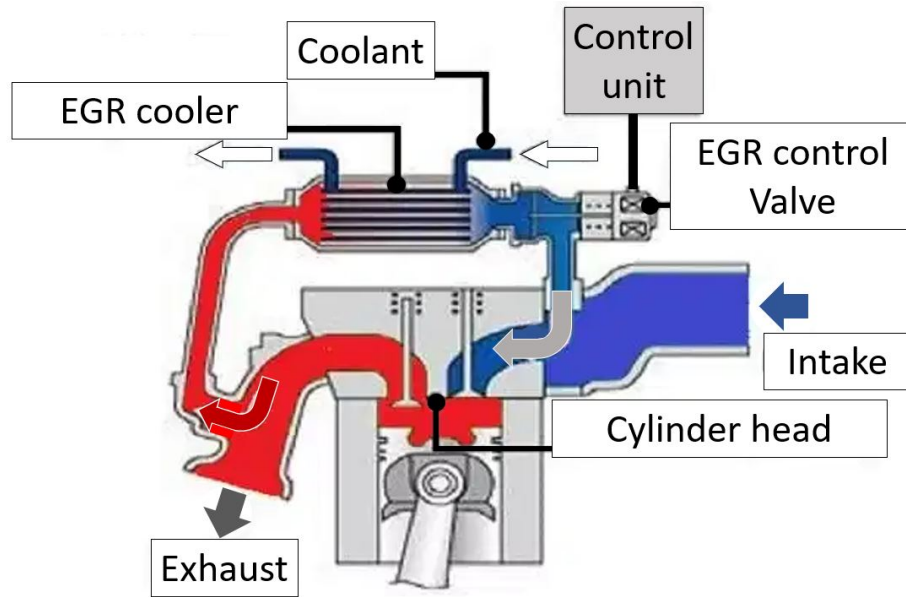


Figure 1.3: Location of the EGR and circulation of the gases [12].

Selective Catalytic Reduction (SCR)

SCR is a technology using a reductant to transform NO_x present in the exhaust gases in N_2 and H_2O . The reductant is added to the exhaust gases flow. The oxidation-reduction reaction can be realised with (SCR) or without a catalyst (SNCR) but the efficiency is lower in the case of SNCR. As for the TWC, the catalyst needs to be at a certain temperature ($250\text{ }^{\circ}\text{C}$)– $450\text{ }^{\circ}\text{C}$) to be efficient [13].

The most common reductant today is the *AdBlue*, a solution of 32.5 [%] urea diluted in water. This technology can reduce the NO_x production up to 90 [%] [14]. SCR is generally combined with TWC to get the lowest possible amount of NO_x in the exhaust gases. The SCR is placed after the TWC in the exhaust pipe (FIGURE 1.4). This technology is now preferred to meet the latest EURO 6 diesel emissions standards. The main disadvantage of SCR is that the tank must be refilled with urea at different time intervals.

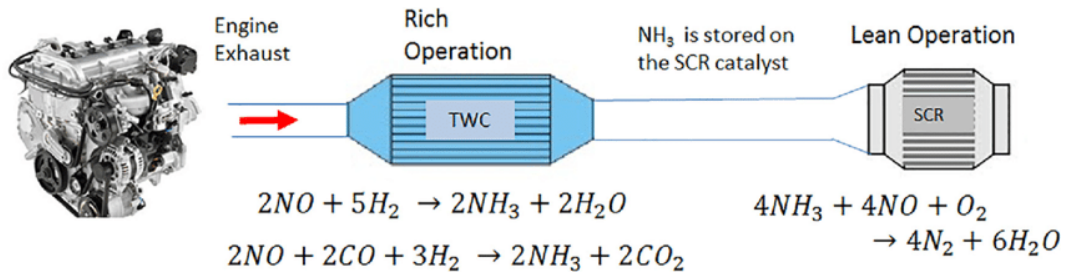


Figure 1.4: Evolution of chemical composition through the exhaust pipe [15].

NO_x adsorbers

The NO_x adsorbers, also called lean NO_x traps (LNT), is a complementary technology used for exhaust gases under lean conditions, when the catalytic converters are not in ideal operating conditions. For example, this is the case when there is too much oxygen present in diesel (meaning that the equivalence ratio is below 1), or when the catalyst has not reached a minimum temperature yet [16]. LNT adsorb and store NO_x using an adsorbant such as zeolite during lean exhaust conditions.

Then, there are two releasing strategies:

- **Active NO_x adsorbers:** the release happens periodically during a short period of rich air-to-fuel ratio operation called the *regeneration*. During these short rich operations, the released NO_x are converted to N₂ as in TWC [17].
- **Passive NO_x adsorbers:** the release happens when a certain exhaust gas temperature is reached [16].

1.2 Driving cycle

With the increasing use of automobiles at the end of the 1960s, the members of the EEC¹ wanted to legislate the production of pollutants from cars. In order to achieve this, they have introduced the European Emission Standards (EURO). It sets a maximum limit for pollutant emissions from vehicles.

To test that these standards were being met, a driving cycle was developed, the New European Driving Cycle (NEDC) cycle. The aim of this cycle was to simulate the behaviour of drivers as defined in the European Directive 70/220. This cycle was carried out on a roller test bench in a laboratory and was used between 1973 and 2017 to approve new vehicles put into circulation in Europe. After 2017, the NEDC was replaced by the Worldwide harmonised Light vehicles Test Procedure (WLTP). The WLTP is also a laboratory test that aims to correct the defects of the NEDC test. These driving cycle tests and the European Emission Standards (EURO) are detailed in the following sections.

1.2.1 European Emission Standards (EURO)

The EURO regulation was established by the EU to fix a limitation on car emissions. It aims to limit the main pollutants emitted by cars, namely the NO_x, to comply with the EURO standards.

This regulation has evolved over the years with increasingly stringent emission limits. The "EURO 1" was introduced in 1992 while the recent "EURO 7" was introduced on the 1st of January, 2021.

Diesel	Date	CO	NO _x
Euro 1	July 1992	2.72	–
Euro 2	January 1996	1.0	–
Euro 3	January 2000	0.64	0.50
Euro 4	January 2005	0.50	0.25
Euro 5a	September 2009	0.50	0.180
Euro 5b	September 2011	0.50	0.180
Euro 6	September 2014	0.50	0.080

Figure 1.5: Evolution of the EURO standards between 1992 and 2014 [18]. These are expressed in $[g/km]$.

¹European Economic Community

To determine the level of emissions, the car was put on a roller test bench to simulate a NEDC. During the cycle, the car emissions were monitored to check the compliance with the EURO standard. Until 2017, the NEDC was used to check if cars respected the legislation. After that, cars were tested following the WLTP. It is worth noting that the EURO regulation do not consider the CO₂ emissions until 2021. In April 2019, the European parliament voted the *2019/631 regulation* [19] which imposes that the average emissions of new light commercial vehicles registered in the Union, must at most emits 95 [g/km] of CO₂. The WLTP cycle is the new reference for the CO₂ emissions and the fuel consumption of cars.

FIGURE 1.5 shows the evolution of the EURO standards. CO and NO_x emissions were divided by six over a period of 24 years. The complete table for diesel and gasoline engines is available in APPENDIX F.

1.2.2 New European Driving Cycle (NEDC)

To measure consumption and pollutant emissions, EU decided to define a driving cycle modelling real driving conditions. The first part of the driving cycle (800 [s]) simulates typical driving conditions in a European city, it is the *urban* part. The second part (800 [s] to 1200 [s]) represents more aggressive and high speed driving modes, it is the *extra-urban* part. Until 2017, this cycle was used to calculate fuel consumption and determine the composition of the exhaust gases. The NEDC is illustrated in FIGURE 1.6.

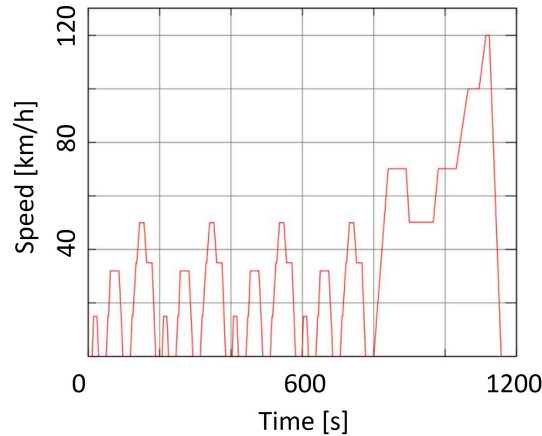


Figure 1.6: Speed versus time during a NEDC cycle. The behaviour of the first 200 seconds is repeated four times [20].

However, these cycles have several degrees of freedom on which manufacturers optimise the consumption and CO₂ emissions of their vehicles. This explains the difference between the consumption levels announced by automotive constructors and the actual consumption of drivers in real driving conditions.

Firstly, constructors could choose flexible parameters that could influence the production of car emissions until 4.5 [%] [18]:

- Wheel and tyre specification;
- Tyre pressure;
- Adjustment of brakes;
- Vehicle preconditioning;
- Running-in period;
- Test track design.

Secondly, the test did not depend on the power of the car. The difference between the cycle and reality was even bigger for more powerful cars.

Thirdly, the test was highly repeatable. Constructors could optimise the conditions to decrease the emissions of the car:

- Vehicle test mass;
- Laboratory instrumentation;
- Test cell temperature;
- Dynamometer load;
- Gear shift schedule;
- Driving techniques.

The final degree of freedom lies in the fact that the test did not consider obvious parameters such as air conditioning, additional load, aggressive driving or roof rack. Indeed these parameters should be taken into account as shown in FIGURE 1.7

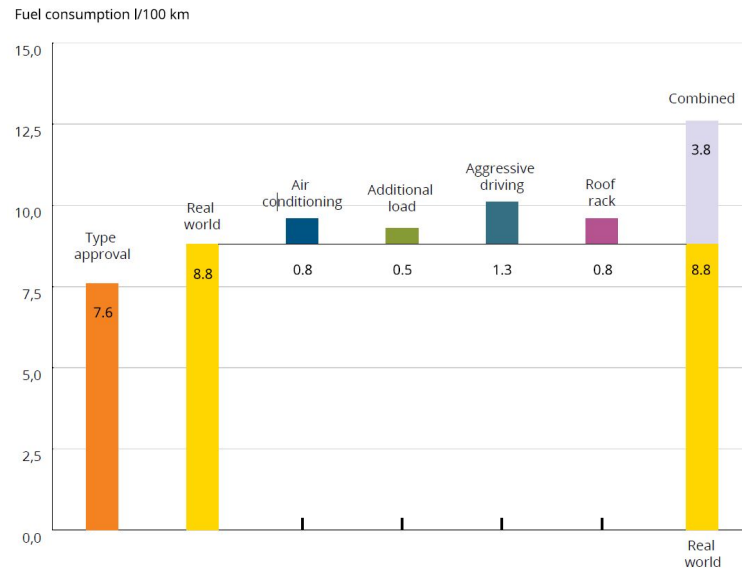


Figure 1.7: Impact of selected vehicle and driving conditions on fuel economy for a typical mid-sized petrol car [18].

1.2.3 Worldwide harmonised Light vehicles Test Procedure (WLTP)

The WLTP has been developed to address all the NEDC limitations. Like the NEDC, this cycle is realised on a roller test bench in a laboratory. It is based on real-driving data and has a better matching with on-road performance [21]. The cycle is also more dynamic and more varied (FIGURE 1.8), which better represents the real driving conditions. There are several types of WLTP cycle. In the following, focus will be only on the WLTP 3b cycle, the one that represents vehicles driven in Europe and Japan [22].

To validate the WLTP cycle, a real-life test is performed, the RDE. This test is no longer carried out in the laboratory but on road. During the RDE, pollutant emissions are monitored to ensure that they do not exceed by more than 50 [%] the levels obtained during the WLTP cycle in the laboratory [23].

Overall, the WLTP cycle gives more accurate and significant results of real driving conditions and it does not allow automotive constructors to optimise the cycle because all the parameters of the test as the tyre pressure or temperature are fixed.

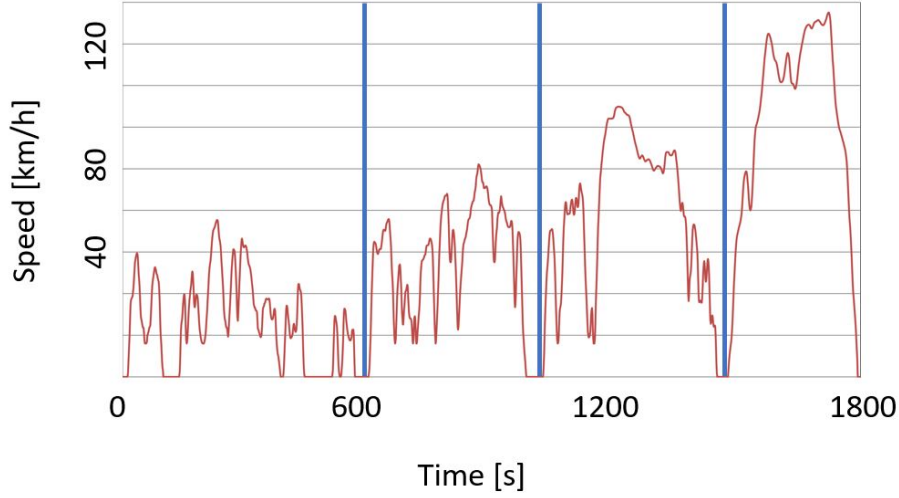


Figure 1.8: Worldwide harmonised Light vehicles Test Procedure (WLTP) [24].

1.3 Driving behaviour

Driving behaviour can have a major influence on parameters such as safety, fuel consumption or engine wear. The driving behaviour can be characterised by various parameters such as intensity of braking, speed in curves or acceleration [25]. Since the latter has an impact on the production of pollutants such as NO_x [26], this master thesis measured the acceleration by using an accelerometer. This allows different driving styles to be determined in order to analyse their impact on NO_x production.

Accelerometers calculate the acceleration in $[g]$, where g is the gravitational acceleration on earth which equals $9.81 [m/s^2]$. Accelerometers cover a wide range of uses: the acceleration of a car, the vibration of industrial machines, seismic activities, inclination and even the energy spent by animals in the wild [27].

Working principle

The working principle of an accelerometer is based on the conversion of mechanical energy into electrical energy. To calculate this mechanical energy, an accelerometer uses the principle of a mass-spring system. The force to stretch a spring of stiffness k by x metres is given by:

$$F = k \cdot x [N] , \quad (1.11)$$

where k [N/m] is the stiffness and x [m] the distance. The acceleration is given by Newton's second law as

$$\sum F = m \cdot a \text{ [N]} , \quad (1.12)$$

where m [kg] is the mass of the accelerated body and a the acceleration in [m/s^2]. Knowing k and m from combining equations 1.11 and 1.12, the acceleration is proportional to the displacement of the mass in the accelerometer:

$$a = \frac{k \cdot x}{m} \text{ [m/s}^2\text{]} . \quad (1.13)$$

Accelerometers use two main methods to calculate the displacement, namely capacity and piezoelectric material.

In the first case, the variation of the distance x will generate a variation of the electrical capacity. The formula for the voltage between the plates of a capacitance is given by:

$$V = \frac{q \cdot d}{\epsilon_0 \cdot S} \text{ [V]} , \quad (1.14)$$

where V [V] is the voltage, q [C] the charge, ϵ_0 [F/m] the vacuum permittivity, S [m^2] the surface of the plates and d [m] the distance. q , ϵ_0 and a are known. It is therefore possible to deduce the distance between the two plates of the capacitance by passing an electric current through it and measuring the output voltage.

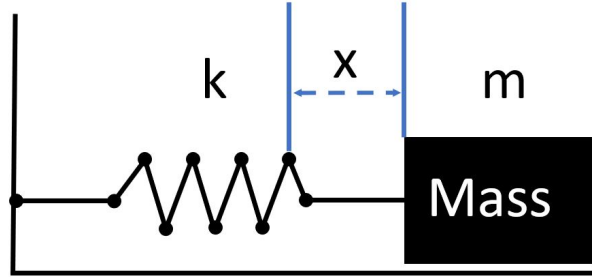


Figure 1.9: Distance between plates with mass displacement.

In the second case, the accelerometer uses the piezoelectric effect of certain materials to measure the acceleration. "Piezoelectric effect is the ability of certain materials to generate an electric charge in response to applied mechanical stress" [28]. With the measurement of this electric charge and by knowing the property of the piezoelectric material, it is possible to determine the distance and so the acceleration (FIGURE 1.10).

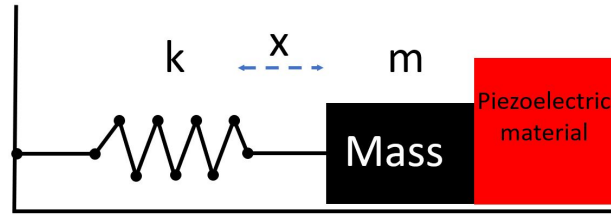


Figure 1.10: Configuration of the piezoelectric crystal with the mass-spring system.

One of the main interest of piezoelectric accelerometers is their ability to determine acceleration in three dimensions. As it can be seen in FIGURE 1.11, the mass is enclosed in a cube with piezoelectric faces. When the accelerometer is at rest, the only acceleration experienced by the accelerometer is the gravity in z direction. In the case of a horizontal acceleration, the piezoelectric accelerometer can calculate the gravitational and the horizontal accelerations in the same time.

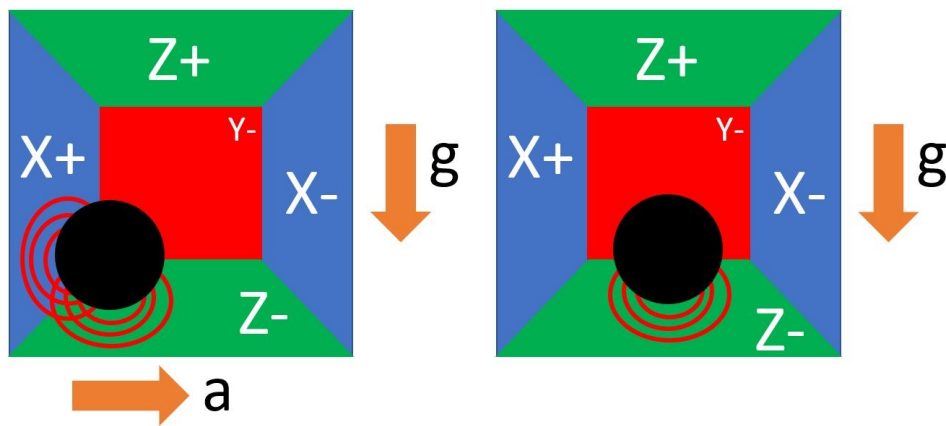


Figure 1.11: Schematic view of the interior of a piezoelectric accelerometer. On the left, the accelerometer is under a horizontal acceleration and gravitational acceleration. On the right, it is only subject to gravitational acceleration.

Chapter 2

Driving behaviour characterisation

2.1 Characterisation method

2.1.1 Datalogger

During our experiments, we used dataloggers developed in a previous master thesis about the RDE subject [29]. The final objective is to highlight the influence of a driving behaviour on the NO_x production. This is achieved by using data coming from the datalogger and an exhaust gas analyser, the Testo 350 XL which will be described in CHAPTER 3.

The datalogger consists of three parts: a microcontroller, a GPS chip and an accelerometer (FIGURE 2.1). The datalogger is powered by the OBD socket of the car. A light-emitting diode (LED) indicates whether the datalogger is working properly when in use. The lack of written documentation during the implementation of the datalogger makes it difficult to use. A datalogger user guide has therefore been written.

Microcontroller

The microcontroller gathers the data of the accelerometer, the GPS chip and the car OBD socket. After processing those data, it writes the results on a SD card every tenth of a second in a CSV file. It was originally developed to acquire precise data such as speed or engine water temperature on a large number of cars. Contrary to its original purpose, the experiments carried out during this master thesis concerned a specific car and were intended to collect a large and varied amount of data for further analysis on the driving and vehicle behaviours.

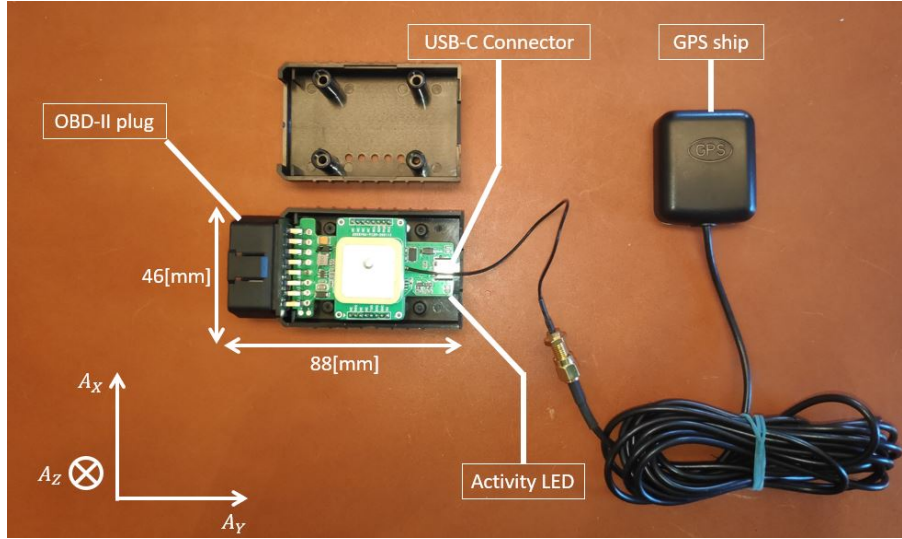


Figure 2.1: Size and design of the datalogger. At the bottom left are the directions of the accelerometer axes.

The datalogger was modified to obtain precise data that were not recorded in its previous version. The microcontroller is running with Arduino software.

GPS chip

The GPS chip enables the datalogger to obtain the longitude, latitude and altitude of the car at any time. This chip is connected to the datalogger via a 1.5 [m] long cable, which allows it to be placed on the roof of the car in order to obtain an optimal signal quickly.

Accelerometer

One of the most interesting sensors of the datalogger is its accelerometer. It is potentially possible to deduce remarkable properties by analysing the signal returned by the accelerometer, such as driver behaviour, road quality or potential mechanical failure. The piezoelectric accelerometer calculates acceleration in all three dimensions of space.

However, the datalogger is limited by its power and memory. It is therefore not possible to access more than four OBD socket data simultaneously and some OBD addresses are not available. To overcome this problem and to perform a deeper analysis of the driving and the vehicle behaviours, a solution is presented in APPENDIX C.

2.1.2 Outliers managing

This section explains how to treat the outliers present in the acceleration signal from the accelerometer.

As plotted in FIGURE 2.2, a portion of the data from the accelerometer is considered as outlier. Indeed, it is impossible to undergo 10000 [g] of acceleration in a car. These outliers can come from malfunctioning instruments or they may represent a specific driving behaviour due to an obstacle (e.g. speed bumps, roundabout, road narrowing). In fact, when the acceleration exceeds a threshold (when it is outside the operating range of the accelerometer), the device stops writing consistent data in the CSV file, but it writes data between 10000 [g] and 14000 [g]. More details about the measurement range of the accelerometer can be found in APPENDIX C.

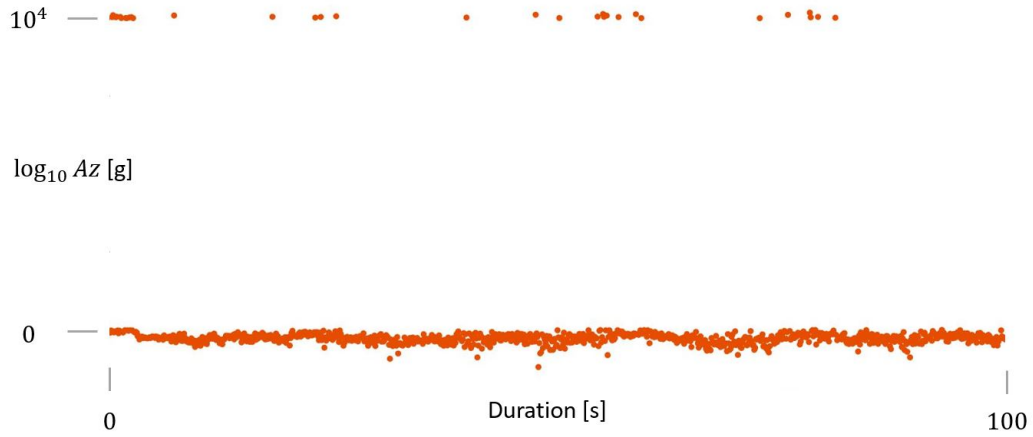


Figure 2.2: Outliers in raw data for the acceleration in z direction are above 10000 [g].

These outliers must be processed in order to work with coherent signals afterwards. The function *filloutliers* implemented in Matlab was used to remove them from the raw signals [30] and the method used to detect and replace the outliers was the Interquartile Range (IQR) rule method.

With the IQR method, outliers are defined as data elements (1.5 times IQR) greater than the third quartile (75 [%]) or below the first quartile (25 [%]) [31].

Once the outliers are found, they are replaced by a linear interpolation of the neighbouring, non-outlier values. FIGURE 2.3 shows the boxplots of the acceleration in the y and z directions (A_y and A_z) once the outliers have been replaced by the interpolation of their neighbouring values.

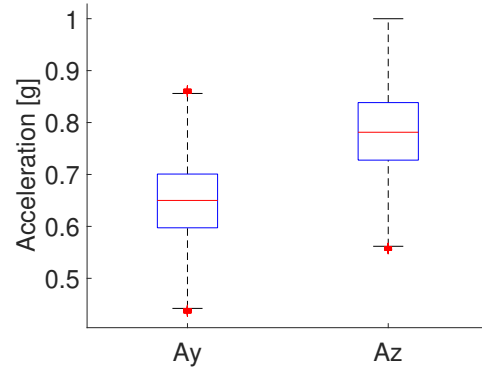


Figure 2.3: Boxplot of data after the replacement of the outliers

The boxplots of the accelerations in the y and z directions have an offset because of the position of the datalogger in the car, connected to the OBD socket. So, the datalogger is already tilted, even if the car is stationary.

2.1.3 Noise filtering methods

Once the outliers are filtered out, the signal is still noisy (see FIGURE 2.4). This section compares different filters to remove this noise. The idea is to apply a filter to the data which will remove the noise and highlight different behaviour types. FIGURE 2.5 illustrates four typical behaviours expected through filtering. The spikes must be preserved to keep all the accelerations in order to highlight a certain driving behaviour, such as aggressive driving for example.

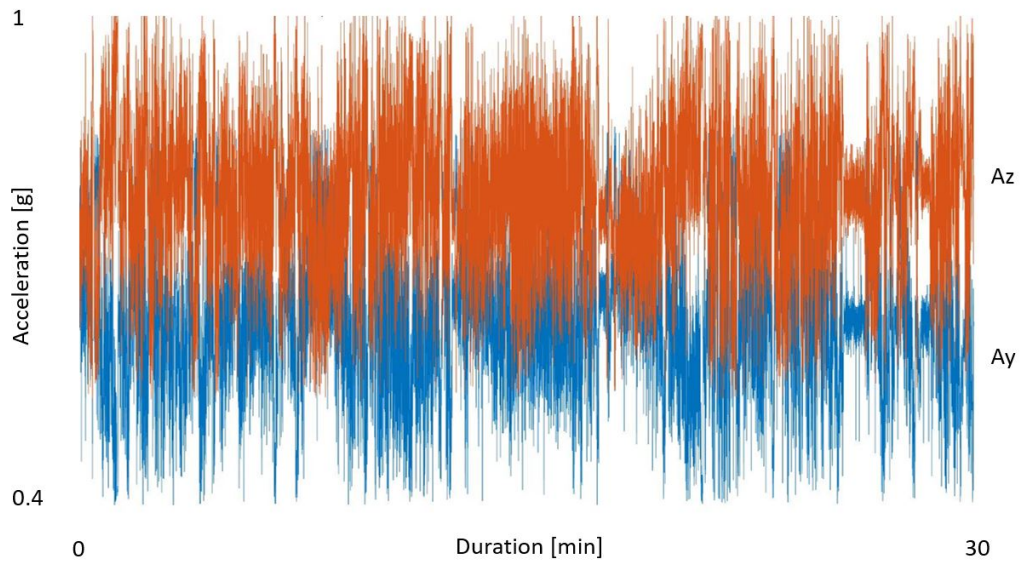


Figure 2.4: Signals to be treated are noisy.

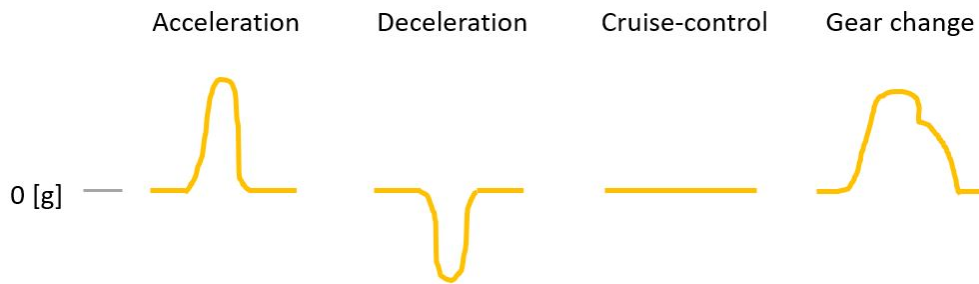


Figure 2.5: Illustration of four typical behaviours expected to emerge from filtered data.

Median filter

This filter uses a window of a particular dimension (n) which slides along the vector and takes the median of the window at a specific location index. This function sorts the data, finds the median value and returns it in a new vector. The function applies a n th-order one-dimensional median filter to an input vector [32].

For example, a median filter of size n on a sequence $\{x_i, i \in \mathbb{Z}\}$ (with n odd and $v = \frac{n-1}{2}$) is defined as [33]:

$$y_i = \text{medfilt1}(x_i, n) = \text{Median}_n(x_{i-v}, \dots, x_i, \dots, x_{i+v}) . \quad (2.1)$$

The advantage of this filter is that it preserves sharp edges (if n is low) because it is a non-linear filter. It is worth noting that this filter can also be used to remove spikes, however the function *filloutliers* is more appropriate for the signal to be treated. FIGURE 2.6 illustrates the median filter applied to the accelerometer in the y direction with the order $n = 5$ and $n = 15$. The higher the order, the higher the smoothing but also the less sharp edges. In our case, a median filtering with a low order is more appropriate because it preserves more sharp edges while smoothing the signal.

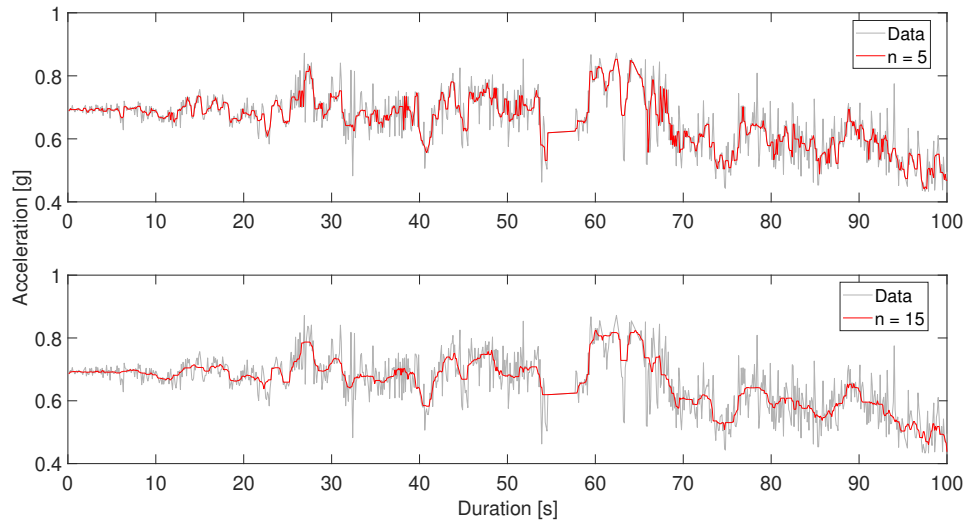


Figure 2.6: Median filter of order 5 and 15 applied to data without outliers. The case $n = 15$ smooths data too much, while the case $n = 5$ preserves more sharp edges.

Moving average filter

This filter uses a window of a particular dimension (n) that slides along the vector and computes the average of the window at a specific location index. This filter is an adequate means of rejecting noise but it has two major drawbacks:

- First, it introduces delay effects in the process [34]. Indeed, a zoom of the signal is visible in FIGURE 2.7 and it indicates that the larger the size of the

window, the larger the delay introduced by the smoothing filter. For $n = 5$ or $n = 10$, a delay appeared and it needs to be handled explicitly to use the filter efficiently.

- Second, there are additional end-effects associated with moving average filter. Indeed, for $n = 5$ there are two points at the beginning and at the end for which a complete smoothing cannot be computed.

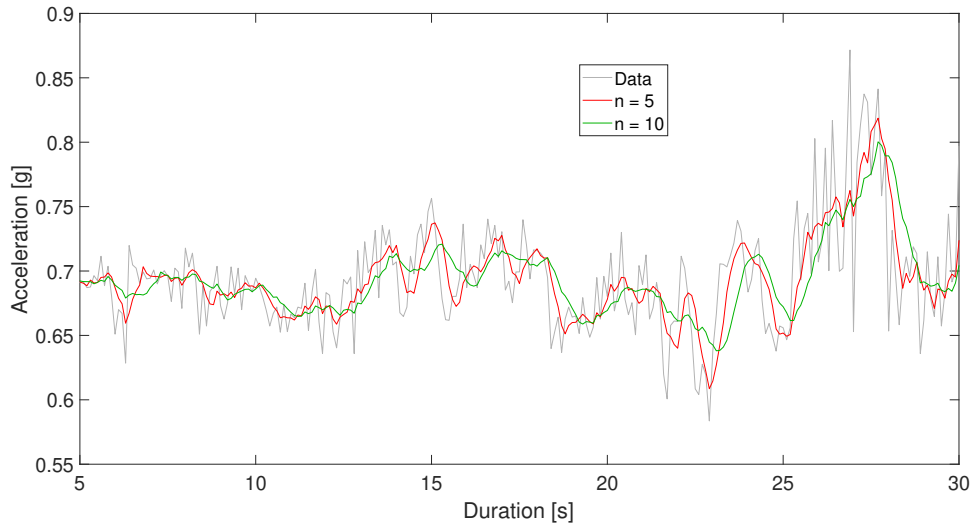


Figure 2.7: A zoom on the moving average filtering with a size of window of 5 and 10 illustrates the delay effect introduced by the filter.

Savitzky-Golay filtering

The Savitzky-Golay filter allows to track data more closely and to take into account transient effects. It also uses a sliding window and as before, the higher the window size, the higher the smoothing of the data. The function *sgolayfilt* internally computes the smoothing polynomial coefficients of a low-degree polynomial for adjacent data points contained in the current frame and the best coefficients are found by the linear least square method [35]. This function takes three argument inputs: the vector to be filtered, the order of the polynomial and the frame length. The frame length must be odd (to maintain symmetry) and higher than the order for the function to operate properly. The pros and cons of this filter are the following:

- First, it retains sharp edges as illustrated in FIGURE 2.8 after 32 [s] for example, but it follows noise fluctuations too [34]. As a consequence, this filter flattens peaks less than moving average, which is good to find a driving behaviour from the accelerometer. However, when applying parameters that preserve peaks well, smoothing may not be effective at all.
- Second, the delay found in the moving average filter is removed with the Savitzky-Golay filter.

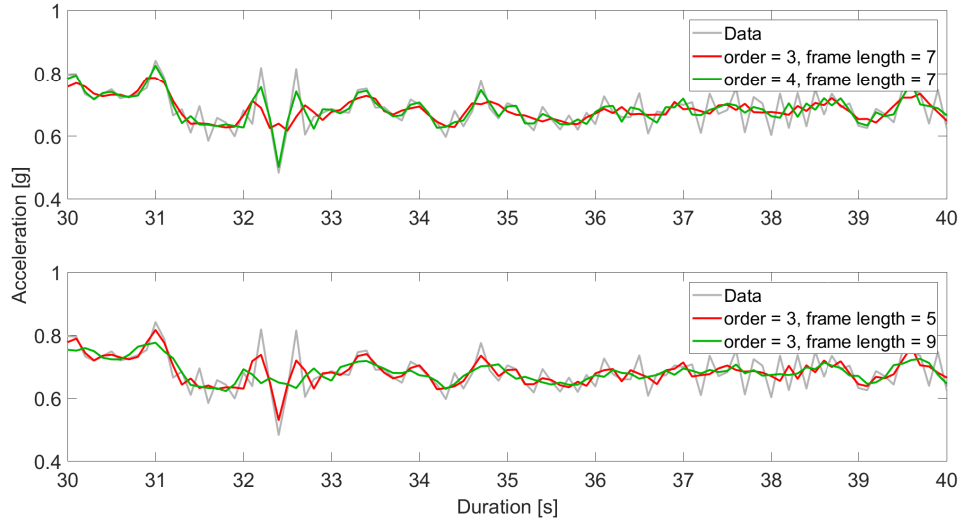


Figure 2.8: Zoom on the Savitzky-Golay filtering applied with varying order (3^{rd} and 4^{th}) with fixed frame length (7) and fixed order (3^{rd}) with varying frame length (5 and 9).

A trade-off needs to be found between the two degrees of freedom (i.e. order and frame length) to get usable filtered data. FIGURE 2.8 shows that a higher order allows to preserve more sharp edges (see just after 32 [s]). Furthermore, if a smaller frame length is taken, sharp peaks are preserved but with the drawback that the noise is less smoothed. Indeed, if a filter of 4^{th} order with a frame length of 5 is applied, there is no filtering at all. Therefore, as a compromise, the filter chosen is the one with 3^{rd} order and frame length of 7 because it preserves overall trend with relevant peaks while applying a good smoothing of the data.

Comparison between filters

Finally, FIGURE 2.9 illustrates the three different filters developed above with the following characteristics:

- Median filtering of 5^{th} order;
- Moving average filtering with $n = 10$, where n is the window size;
- Savitzky-Golay filtering of 3^{rd} order and of frame length of 7.

The Savitzky-Golay filter seems to be more interesting for the purpose of this work because it smooths the data while preserving the overall trend of the driving cycle. The median filtering of 5^{th} order could also be used but the Savitzky-Golay filter is more interesting because it has two degrees of freedom and retains better the sharp edges. This is the reason why the Savitzky-Golay filter was selected in this study.

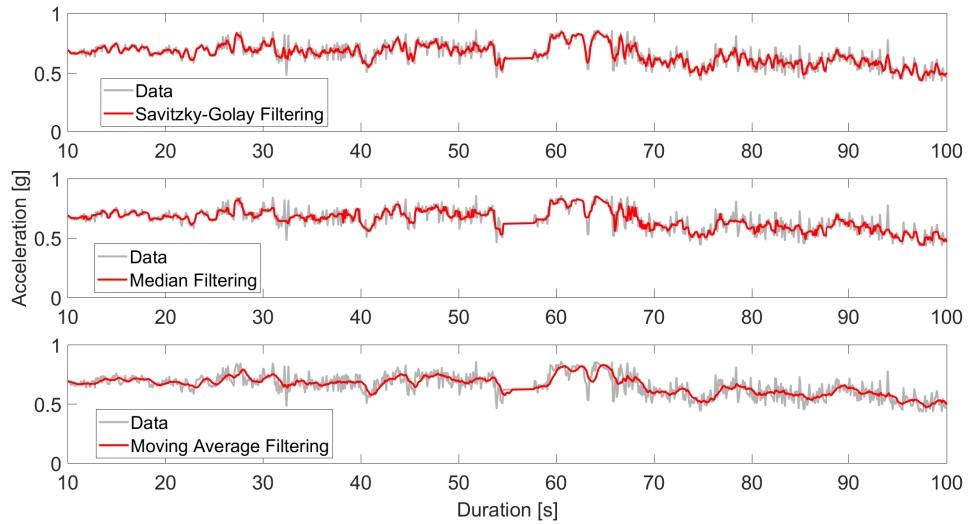


Figure 2.9: Comparison between the 3 filters computed: the Savitzky-Golay filtering is selected because it is the best trade-off between data smoothing and relevant peaks highlighting in order to study the driving behaviour.

2.1.4 Two ways of computing the acceleration

Now that the various filters have been discussed, attention is focused on the way to get the acceleration. There are two different ways to obtain the acceleration from the datalogger. Firstly, the car speed $[km/h]$ can be obtained from the OBD socket with the datalogger. Then, by derivating this speed, the longitudinal acceleration can be calculated.

Secondly, the signals of the accelerometer in the y and z direction are corrected to get as close as possible to the actual accelerations in both directions.

Acceleration from the On-Board Diagnostics (OBD)

The acceleration consists of the derivative of the speed, so the function *gradient* implemented in Matlab can be used on the speed vector coming from the OBD socket. Indeed, in a coordinate system, the gradient of a function $f(x_1, x_2, \dots, x_n)$ is defined in n-dimensional space as the vector of components $\partial f / \partial x_i$ for $i = (1, 2, \dots, n)$:

$$\nabla f = \begin{bmatrix} \frac{\partial f}{\partial x_1} \\ \vdots \\ \frac{\partial f}{\partial x_n} \end{bmatrix} . \quad (2.2)$$

The gradient of f illustrates the rate of change of f in any direction. If this gradient is of first-order ($n = 1$), then $\nabla = \frac{\partial}{\partial x}$. The gradient becomes in the case of $f(x) = v(t)$:

$$a = \nabla v = \frac{\partial v}{\partial t} = \frac{dv}{dt} \approx \frac{\Delta v}{\Delta t} \left[\frac{m}{s^2} \right] , \quad (2.3)$$

where $a [m/s^2]$ is the longitudinal acceleration, $v [m/s]$ the velocity of the car and $t [s]$ the duration. In equation 2.3, $\Delta t = 0.1 [s]$ and the *gradient* function is called by specifying a uniform spacing between points of $0.1 [s]$ ¹. Furthermore, the algorithm of the gradient function implemented in Matlab uses the central difference for interior data points and it computes with single-sided differences for the edges of the vector [36]. It means that it computes the different indices of the acceleration as follows:

$$Ay_i = \frac{v_{i+1} - v_{i-1}}{3.6 \cdot (t_{i+1} - t_{i-1})} = \frac{v_{i+1} - v_{i-1}}{3.6 \cdot 0.2} \left[\frac{m}{s^2} \right] , \quad (2.4)$$

¹This time interval is due to the data acquisition frequency of the datalogger.

for $i = (2, 3, \dots, n - 1)$. These represent the interior data points. The edges of the acceleration vector are computed as follows:

$$Ay_1 = \frac{v_2 - v_1}{3.6 \cdot (t_2 - t_1)} = \frac{v_2 - v_1}{3.6 \cdot 0.1} \left[\frac{m}{s^2} \right] , \quad (2.5)$$

$$Ay_n = \frac{v_n - v_{n-1}}{3.6 \cdot (t_n - t_{n-1})} = \frac{v_n - v_{n-1}}{3.6 \cdot 0.1} \left[\frac{m}{s^2} \right] , \quad (2.6)$$

where n is the length of the vector v .

The upper graph in FIGURE 2.10 illustrates the longitudinal acceleration (in the y-direction) expressed in $[g]$, result of the gradient applied to the vector speed. An upper and lower limits appear and are shown on this graph at the values $0.14 [g]$ and $-0.14 [g]$. These values are due to the fact that the speeds coming from the OBD are whole numbers without decimal places and sometimes vary slightly. For example, the data recorded can pass from 24 to $25 [km/h]$ in the measuring interval of $0.2 [s]$, this means that the acceleration is equal to:

$$Ay_i = \frac{25 - 24}{9.81 \cdot 3.6 \cdot 0.2} = 0.14 [g] , \quad (2.7)$$

where dividing per 9.81 allows to express the acceleration in $[g]$.

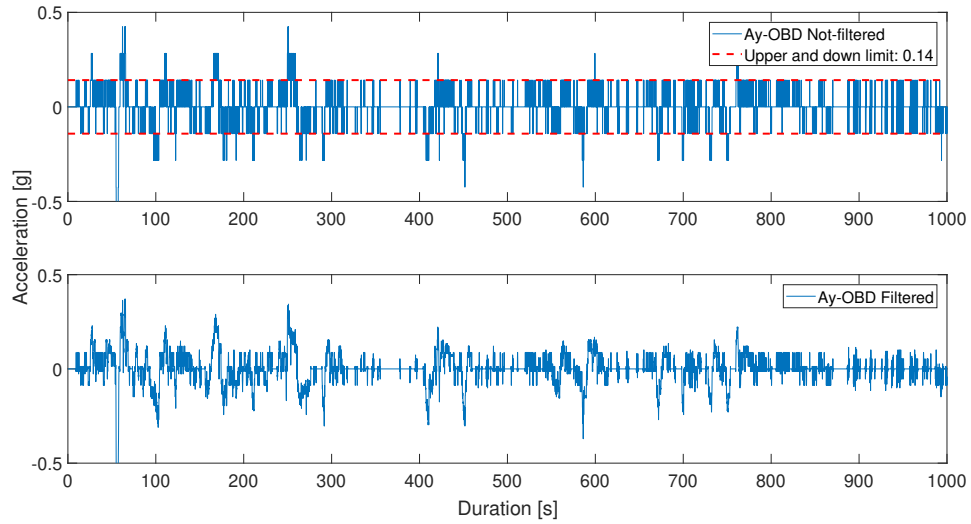


Figure 2.10: Comparison between the acceleration from the OBD without filter and using Savitzky-Golay filtering.

The below graph in FIGURE 2.10 represents the longitudinal acceleration coming from the OBD after Savitzky-Golay filtering. This acceleration is centered around 0 [g], illustrating the real behaviour of a car.

Limitation of the acceleration computed from the car speed

The previously calculated acceleration gives an idea of the shape the curve should have but is not the true acceleration of the trip either. Below are the limitations of this approach:

- Data encoded from the OBD is in whole numbers, which implies a lack of precision.
- The speed data is already treated internally by the vehicle computer.

Acceleration from the accelerometer

FIGURE 2.3 shows the boxplot of the signals of the accelerometer once the outliers are removed. They need to be corrected to represent the longitudinal acceleration in the y-direction² and the gravitational acceleration in the z-direction because for now they are respectively oscillating at around $Ay = 0.65$ [g] and $Az = 0.78$ [g], while they should oscillate around 0 [g] and 1 [g] respectively. To be able to adjust the signals, two angles must be taken into account: the angle of the datalogger with respect to the car and the angle of the slope of the road.

Angle related to the position of the datalogger in the car

Firstly, the position of the datalogger connected to the OBD socket in the car is already tilted, even when the road slope is zero. FIGURE 2.11 illustrates the position of the datalogger in the car. When the car moves from left to right in the diagram, the accelerations are counted positive in both directions shown. Knowing that the accelerometer measurements are very sensitive, the average of Ay and Az over ten seconds on flat ground is calculated. Then, the angle α can be computed as follows:

$$\alpha = \arctan\left(\frac{Ay}{Az}\right) [^\circ] . \quad (2.8)$$

The gravitational acceleration encountered by the accelerometer can also be calculated:

$$G = \sqrt{Ay^2 + Az^2} = 1.025 [g] . \quad (2.9)$$

With this gravitational acceleration, an error of 2.5 [g] is deduced.

²The acceleration parallel to the road.

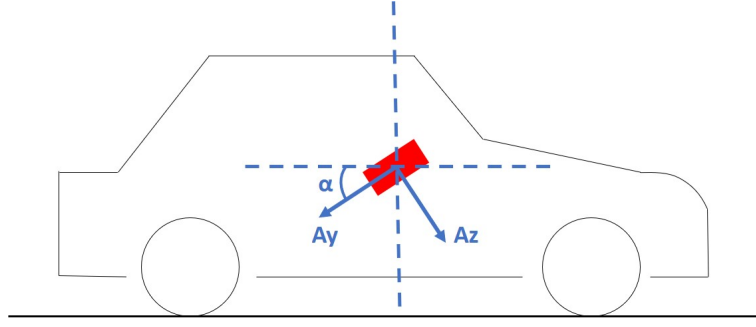


Figure 2.11: The datalogger illustrated in red is already tilted with an angle α . The y and z directions of the accelerometer are also shown.

The angle due to the road slope

Secondly, when the car moves on a slope, its inclination must also be taken into account in order to rectify the accelerometer correctly. FIGURE 2.12 shows the angle of the slope of the road θ that is calculated continuously during the trip using the following equation:

$$\theta = \arcsin \left(\frac{Alt_{i+1} - Alt_i}{v_i \cdot \Delta t} \right) [^\circ] , \quad (2.10)$$

with $\Delta t = 0.1 [s]$, $v_i [m/s]$ the speed at time t_i , $Alt_i [m]$ the altitude at time t_i and $Alt_{i+1} [m]$ the altitude at time t_{i+1} .

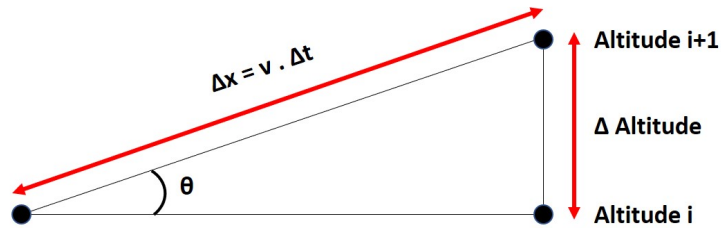


Figure 2.12: θ is computed by calculating $\Delta x [m]$ the distance travelled during $\Delta t [s]$ and $\Delta \text{Altitude} = Alt_{i+1} - Alt_i [m]$ the gain or loss of altitude during Δt .

The following conditions must be added to equation 2.10 in order to obtain angles consistent with real driving conditions.

Speed must be different from zero:

If the speed at time t_i is equal to 0, then θ is fixed at $i - 1$ to avoid dividing by 0 in equation 2.10.

The domain of $y = \arcsin(x)$ must be taken into account:

To obtain a real result, the domain of x for the inverse trigonometric function $y = \arcsin(x)$ is $-1 \leq x \leq 1$. So, for values where $\text{abs}\left(\frac{\text{Alt}_{i+1} - \text{Alt}_i}{v \cdot \Delta t}\right) \geq 1$ with $\text{abs}(x)$ the absolute value of x , θ is fixed at 0 to avoid imaginary results.

Limits have been set to obtain consistent data for real driving conditions:

The left graph in FIGURE 2.13 illustrates θ calculated as explained above. This graph shows angles that are too high for slopes that can be encountered in real driving conditions (e.g. 64.16 [°]). The steepest slope found during driving tests was 17 [%], which represents an angle of slope $\theta = \arctan(\frac{17}{100}) = 9.65$ [°]. Hence, the limit imposed for angles corresponding to $\text{abs}(\theta) \geq 9.65$ [°] has been set to $\theta = 9.65$ [°]. These limits are shown on the right graph in FIGURE 2.13.

Moreover, FIGURE 2.13 also shows that aberrant angles appear more often at low speeds. Indeed, according to equation 2.10, e.g. a small variation in altitude of 0.1 [m] at a low speed of 4 [km/h] (1.11 [m/s]) will lead to a calculated angle of 64.16 [°]:

$$\theta = \arcsin\left(\frac{\text{Alt}_{i+1} - \text{Alt}_i}{v \cdot \Delta t}\right) = \frac{0.1}{1.11 \cdot 0.1} = 64.16 \text{ [°]} .$$

Savitzky-Golay filtering

Finally, a Savitzky-Golay filter of 3^{rd} order and frame length of 7 (as discussed in SECTION 2.1.3) is applied to θ . FIGURE 2.14 shows the evolution curves of the altitude and θ . These two curves present an offset of approximately 20 [s]. This is the expected behaviour with the maximum value of θ in the middle of the slope.

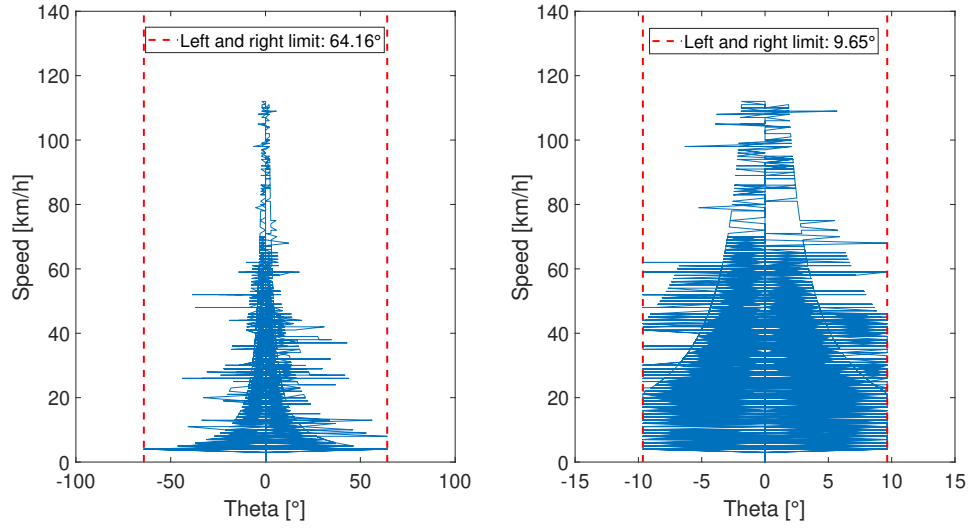


Figure 2.13: The inverse function $y = \arcsin(x)$ gives aberrant angles, especially at low speed (left graph). Angles are more coherent when limits are imposed (right graph).

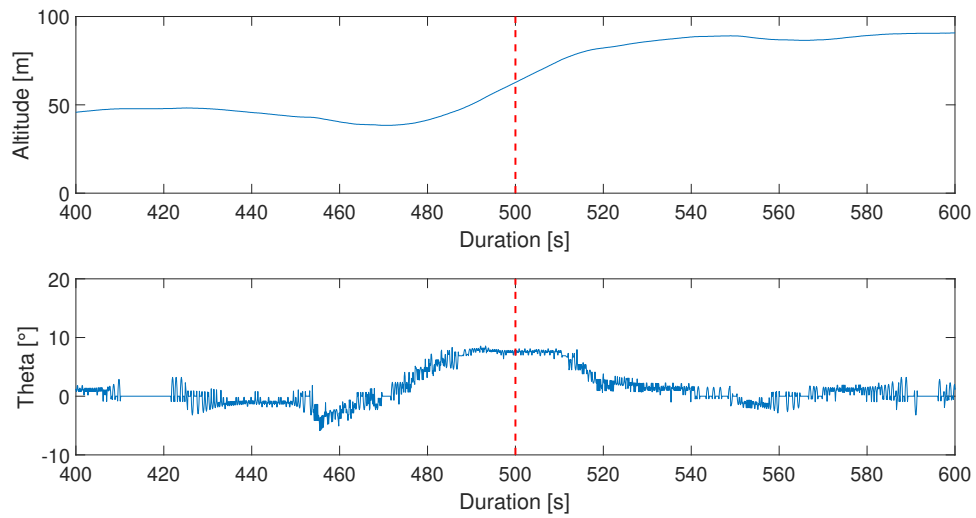


Figure 2.14: Illustration of the continuous variation of altitude and θ , which properly represents the 17 [%] ascending slope at around 500 [s].

The acceleration rectifying

FIGURE 2.15 shows that in the case of a steep road, the accelerometer connected to the OBD socket is more inclined (if $\theta > 0$) or less inclined (if $\theta < 0$).

As θ is known, the longitudinal and gravitational accelerations can be computed from the accelerometer as in the following equations:

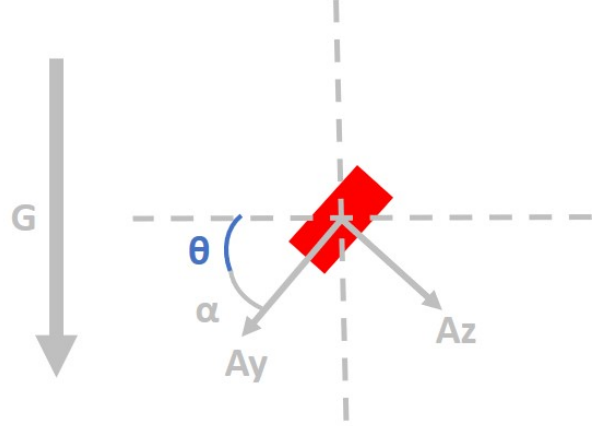


Figure 2.15: The angle θ must be taken into account during computations in the case of a steep road.

$$Ay_{rect} = Ay \cdot \cos(\alpha + \theta) - Az \cdot \sin(\alpha + \theta) [g] , \quad (2.11)$$

$$Az_{rect} = Az \cdot \cos(\alpha + \theta) + Ay \cdot \sin(\alpha + \theta) [g] , \quad (2.12)$$

with the subscript *rect* standing for *rectified*.

The accelerations in y and z directions after rectification are oscillating around 0 and 1 [g], see FIGURE 2.16. Ay_{rect} follows the acceleration coming from the OBD closely and oscillates around 0 [g]. There is not much variation for Az_{rect} , which oscillates at 1 [g] as expected due to gravitational acceleration.

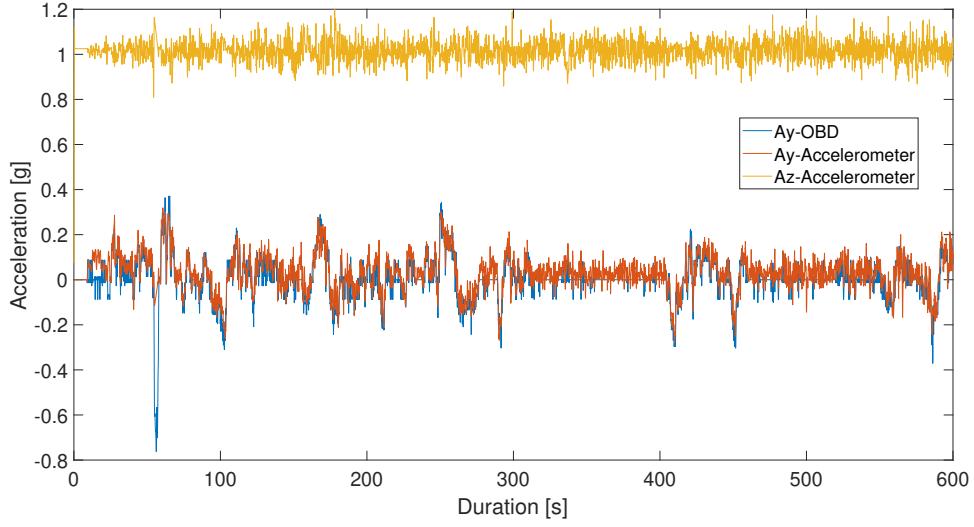


Figure 2.16: The rectified accelerations $A_{y_{rect}}$ and $A_{z_{rect}}$ oscillate around 0 and 1 [g] respectively.

However, a limitation of the acceleration computed from the accelerometer is outlined in FIGURE 2.16 at 56.2 [s]. The negative longitudinal acceleration A_y is not represented on the curve of A_y -Accelerometer, while the car was undergoing heavy braking at that time (-0.76 [g]). This highlights a limitation of the accelerometer which does not always represent the real behaviour of the car.

As explained in SECTION 2.1.2, when the acceleration exceeds a threshold, the accelerometer is outside his operating range and writes therefore inconsistent data in the file, interpreted as outliers. FIGURE 2.2 shows that there are several outliers around 50 [s], when the significant braking occurred.

2.2 Distinction between different driving cycles

Now that the tools for processing the accelerometer signals have been detailed, it is possible to derive driving behaviour from this signal. However, acceleration is not the only variable involved in driving styles, nor in the NO_x production. For example, the product $v \cdot a_{pos}$ [m^2/s] where v [m/s] is the speed and a_{pos} [m^2/s^3] the positive acceleration is widely used in the literature to estimate the consumption and pollutant emissions of vehicles ([37] [38]). Nevertheless, this criterion does not take into account all the factors that influence the torque the engine has to produce in order to move the vehicle. For this reason, the car load has been calculated as an additional parameter for determining driving behaviour or NO_x emissions.

In order to highlight specific driving behaviours, four RDE cycles were carried out by applying a conventional WLTP driving cycle under real world conditions. This section details the calculation of the car load and compares the different conducted RDE driving cycles performed.

2.2.1 Car load

The car load is calculated with the parameters of a Skoda Scala 1.6 TDI, equipped with a mechanical gearbox. This vehicle which was used, to perform the tests in this work, was released in 2019 and has been homologated with a WLTP cycle. It also complies with EURO standards. It is equipped with a SCR system using AdBlue.

The NO_x emissions are related to the car load, which can be obtained by the OBD socket. Nevertheless, this load is only calculated with the internal parameters of the engine and this car load is sometimes completely aberrant on certain cars. That is why we decided to calculate the car load under real driving conditions, by estimating the forces applying on the car and hindering its forward motion. So, the car load will be estimated from the torque that the engine has to develop in order to move the car forward.

The car load is defined as:

$$\text{Car Load} = \frac{\tau}{\tau_{max}} [\%], \quad (2.13)$$

where τ [Nm] is the torque produced by the engine at a given time and τ_{max} [Nm] the maximum torque that the engine could produce at this time.

Some assumptions have been made to determine the car load:

- Wind is negligible;
- Friction coefficient between tyre and road is equal to 0.015 [–] ([39] [40]);
- Gear box efficiency (η) is fixed at 0.95 [–];
- Air density is given by $\rho = \frac{p}{R_{spec} \cdot T}$.

with $R_{spec} = 287.1 [J/(kgK)]$ the specific gas constant for dry air. During the RDE experiment, the atmospheric pressure was 1021.1 [hPa], the temperature was 10 [°C] and the air density on this day after computation was equal to 1.25 [kg/m³].

To calculate the torque that the car must produce at each time t , the forces that are applied to the car must first be evaluated.

The first force is due to the drag of the car:

$$F_{drag} = \frac{1}{2} \cdot v^2 \cdot SC_x \cdot \rho_{air} [N] , \quad (2.14)$$

with $v [m/s]$ the speed, $SC_x [–]$ the drag coefficient multiplied by the front surface of the car and $\rho_{air} [kg/m^3]$ the air mass density. The speed of the car is given by the OBD. The SC_x of the car is equal to 0.69 [–] [41].

The second force is due to the friction between the wheel and the road:

$$F_{friction} = (m_{car} + m_{al}) \cdot g \cdot f \cdot \cos(\theta) [N] . \quad (2.15)$$

The third force occurs when the car goes up a hill and the engine has to counter the gravitational acceleration:

$$F_{slope} = (m_{car} + m_{al}) \cdot g \cdot \sin(\theta) [N] . \quad (2.16)$$

In equations 2.15 and 2.16, $m_{car} = 1340 [kg]$ is the mass of the car (curb weight) [41], $m_{al} = 105 [kg]$ the additional load in the car and $g = 9.81 [m/s^2]$ the gravitational acceleration. $f = 0.015 [–]$ is the friction coefficient between the wheel of the car and a standard road and $\theta [^\circ]$ is the angle of the road slope.

The car load must overcome these three forces in order to move forward. The force required to accelerate the vehicle must also be considered. This force will only be taken into account during positive accelerations, when the engine is loaded.

$$F = (m_{car} + m_{al}) \cdot a [N] , \quad (2.17)$$

with m_{car} and m_{al} defined above, and a the positive acceleration in $[m/s^2]$.

The power to be developed by the engine at each time can be calculated from all these forces. The power is given by:

$$P_{real} = \sum_i^4 F_i \cdot v [W] , \quad (2.18)$$

with $\sum_i^4 F_i [N]$ the sum of the four forces for $i = (1, 2, 3, 4)$ and $v [m/s]$ the speed. At any time t , this power must be equal to the engine power taking into account the transmission ratio η :

$$P_{real} = P_{engine} \cdot \eta [W] . \quad (2.19)$$

The equation for the power produced by an engine is given by:

$$P_{engine} = \tau \cdot \omega = \tau \cdot RPM \cdot \frac{2\pi}{60} [W] , \quad (2.20)$$

with RPM the engine speed in $[rpm]$ and ω in $[rad/s]$. By combining equations 2.18, 2.19 and 2.20, it is possible to obtain τ :

$$\tau = \frac{P_{engine}}{\omega} = \frac{\sum_i^4 F_i \cdot v}{\omega \cdot \eta} [Nm] . \quad (2.21)$$

The maximal torque τ_{max} is given by the characteristic curve of the engine (see FIGURE 2.17). Finally, the car load is calculated using equation 2.22. FIGURE 2.18 shows a good correlation between the calculated car load and the car load recorded by the OBD socket.

$$\text{Car Load} = \frac{\sum_i^4 F_i \cdot v}{\tau_{max} \cdot \omega \cdot \eta} [\%] . \quad (2.22)$$

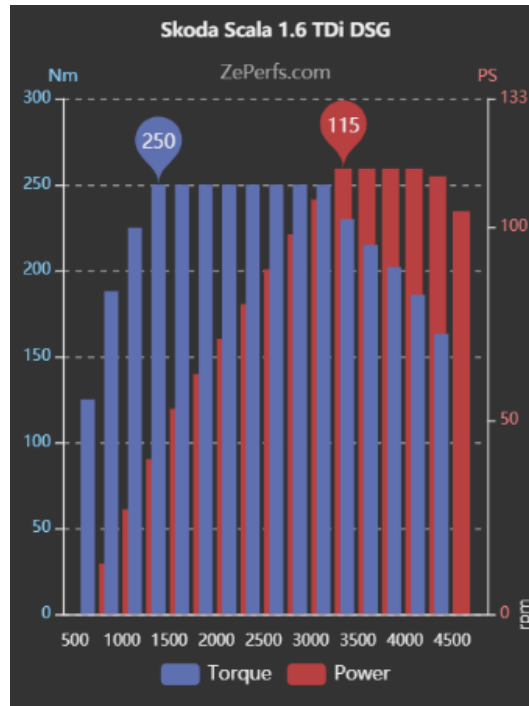


Figure 2.17: Torque - Power curve of the Skoda Scala 1.6 TDI DSG as a function of RPM [41]. Power is expressed in $[PS]$, which is the metric horsepower equal to 735.49 $[W]$.

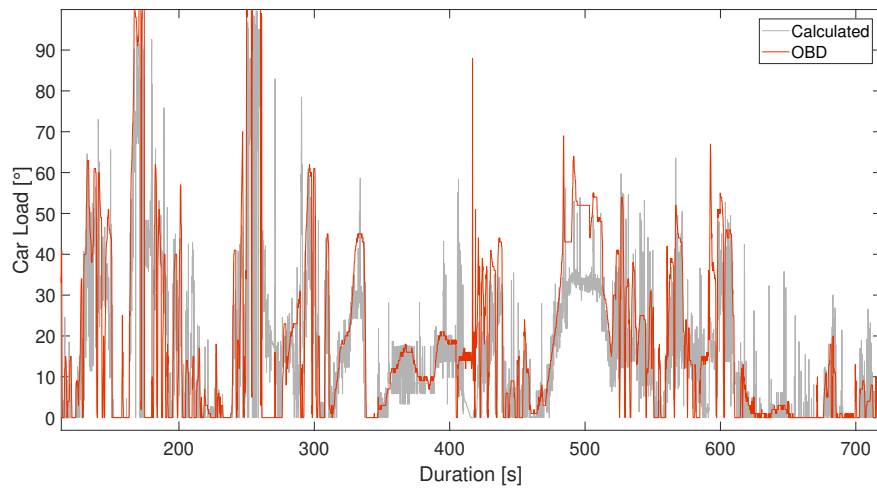


Figure 2.18: The computed car load is consistent regarding the car load recorded by the OBD socket.

2.2.2 Carrying out RDE driving cycles that comply with conventional WLTP criteria

As a reminder, the real driving emissions test RDE is complementary to the WLTP cycle. In the framework of this thesis, four RDE driving cycles were carried out under real driving conditions with different driving behaviours. Those cycles are conducted in Woluwe-Saint-Lambert (FIGURE 2.19). As in a conventional WLTP cycle, the trip is divided in four parts [22]:

- Low speed part (red) simulating an urban driving (up to 56.5 [km/h]);
- Medium speed part (yellow) simulating a suburban driving (up to 76.6 [km/h]);
- High speed part (green) simulating a driving on extra-urban roads (up to 97.4 [km/h]);
- Extra high speed part (blue) simulating a driving on highways (up to 131.3 [km/h]).

The order of the phases of the RDE cycles performed is different from the conventional WLTP cycle. Indeed the extra high speed part is the second step instead of the last one. With this order, the only parameter which can influence the data is the engine temperature. For practical reason, all the tests done for this thesis were performed with a warm engine. The engine temperature factor is therefore not taken into account.

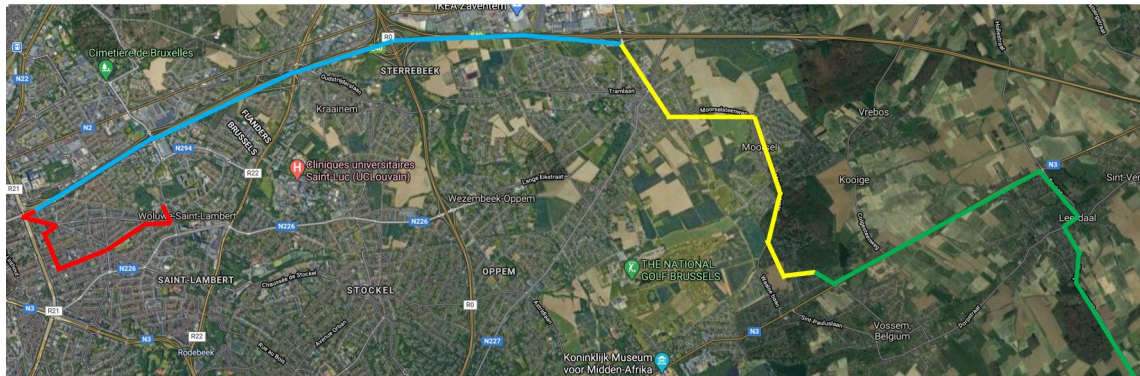


Figure 2.19: RDE trip divided into four phases in Woluwe.

The first RDE cycle performed is the reference cycle. It was carried out while driving in a normal way. The graph of speed as a function of time of this cycle shows the four phases of the cycle (see FIGURE 2.20). This graph also shows the

similarity between the reference RDE cycle and the conventional WLTP cycle (see FIGURE 1.8).

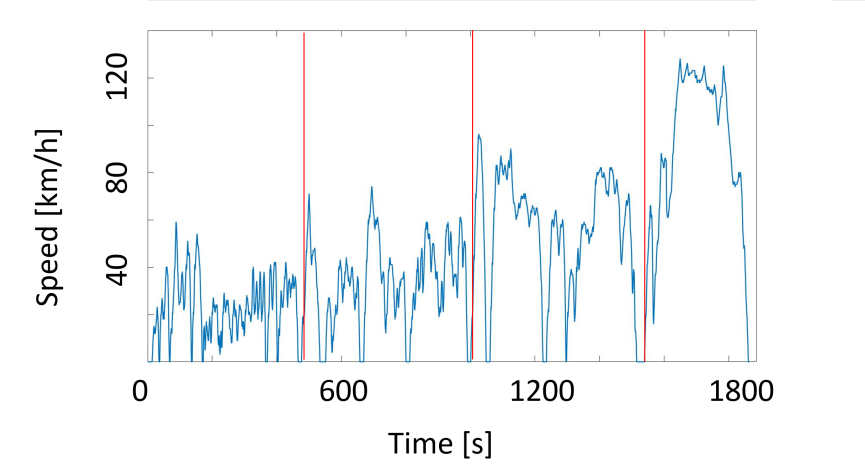


Figure 2.20: After rearrangement, the four phases of the reference RDE cycle conducted in Woluwe appear similar to those of a conventional WLTP cycle.

The general appearance is globally the same. Hereafter, a deeper analysis is realised to evaluate whether the RDE cycle in Woluwe is closed enough to be considered as a conventional WLTP cycle. The following TABLES 2.1 and 2.2 give a summary of the main characteristics of the conventional WLTP cycle, and those of a reference RDE cycle. Relative errors between the two cycles are given in TABLE 2.3. The main differences between these two (the conventional WLTP and the reference RDE cycle) are the average speed with and without stop in the medium part of the cycle.

Conventional WLTP cycle	Low	Medium	High	Extra high	Total
Duration [s]	589.0	433.0	455.0	323.0	1800.0
Stop duration [s]	156.0	48.0	31.0	7.0	242.0
Distance [m]	3095.0	4756.0	7162.0	8254.0	23267.0
% of stops [%]	26.5	11.1	6.8	2.2	
Maximum speed , [km/h]	56.5	76.6	97.4	131.3	
Average speed without stops , [km/h]	25.7	44.5	60.8	94.0	
Average speed with stops , [km/h]	18.9	39.4	56.5	91.7	

Table 2.1: Characteristics of a conventional WLTP cycle performed in a lab [22].

Reference RDE cycle	Low	Medium	High	Extra High	Total
Duration [s]	470.4	529.9	518.3	345.5	1864.1
Stop duration [s]	40.3	59.0	30.7	24.7	154.7
Distance [m]	3100.0	4800.0	7400.0	7600.0	22900.0
% of stops	8.6	11.1	5.9	7.1	
Maximum speed [km/h]	59.0	74.0	96.0	128.0	
Average speed without stops [km/h]	24.54	36.59	58.7	90.7	
Average speed with stops [km/h]	22.73	32.74	55.53	84.48	

Table 2.2: Characteristics of the reference RDE cycle.

Relative Error [%]	Low	Medium	High	Extra High
Duration [%]	20.1	22.4	13.9	7.0
Stop duration [%]	74.2	22.9	1.0	252.9
Maximum speed [%]	4.4	3.4	1.4	2.5
Average speed without stops [%]	4.5	17.8	3.5	3.5
Average speed with stops [%]	20.3	17.1	2.1	8.2

Table 2.3: Relative error [%] of the reference RDE cycle with respect to the conventional WLTP cycle.

The errors presented in TABLE 2.3 must be qualified. Indeed, although they sometimes represent a significant percentage, they have no fundamental impact on the overall performance of the cycle.

2.2.3 Cycle characterisation

This section explains how criteria have been determined to characterise typical driving behaviour. These criteria allow a generalisation of all types of driving styles. The first criterion is the standard deviation applied to the histogram of the acceleration obtained by the accelerometer. This allows to highlight effectively the smoothness of the driving. All histograms related to the acceleration are represented with a bin width of 0.01 [g], which was imposed in order to easily identify the trend in the distribution.

The second criterion is obtained from the product of the speed and the acceleration $v \cdot a_{pos}$ [m^2/s^3]. a_{pos} is defined as the positive acceleration greater than 0.1 [m/s^2], as written for example in the regulation of the European Union [42]. For histograms related to this second criterion, the bin width was selected at 1 [m^2/s^3].

The last criterion is the car load. The car load is worth studying in order to complete the characterisation of the driving behaviour with more properties than just speed and acceleration. As for the previous criterion, histograms are shown below with a bin width of 1 [%].

Data of the four RDE cycles presented herebelow are available in APPENDIX D.

RDE cycle - Reference behaviour

This cycle was performed in order to be as close as possible to a conventional WLTP cycle. During this cycle, the driver adopted the most ordinary driving style possible. Gear changes were made between 2200 [rpm] and 2700 [rpm] as much as possible, acceleration was smooth and there was a standard braking anticipation.

This cycle is used as a reference for the following cycle analyses. FIGURE 2.21 shows the histogram of the rectified acceleration from the accelerometer for this reference RDE cycle. The standard deviation SD is equal to 0.09 [g], which is a measure of the dispersion of a set of values, is a first means of comparison with other cycles. The mean is around 0 [g] of acceleration. This is the expected normal driving behaviour when regarding only the acceleration.

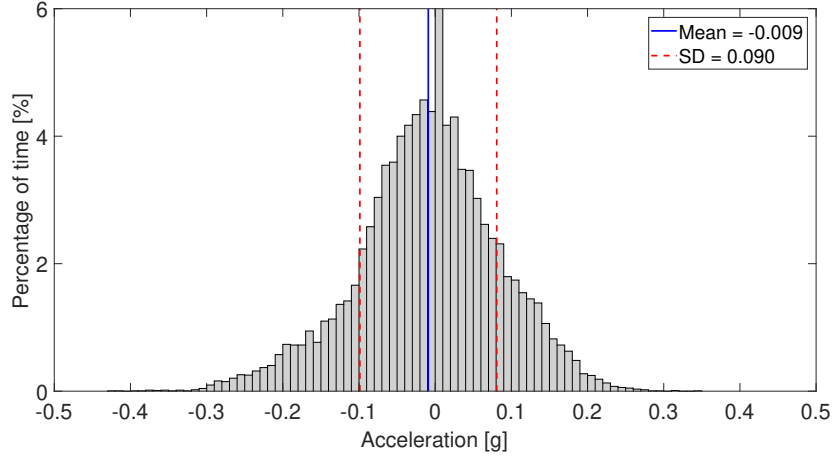


Figure 2.21: Histogram of the acceleration when driving the reference RDE cycle.

Furthermore, FIGURE 2.22 represent the histograms of the product $v \cdot a_{pos} [m^2/s^3]$ with different limits imposed. Limits at 20 and 10 [%] of time (left part of FIGURE 2.22) will allow to characterise an aggressive driving behaviour. Limits at 10 and 20 [%] of time (right part of FIGURE 2.22) are selected to highlight an economic driving behaviour.

Finally, the histogram of the car load calculated as explained in SECTION 2.2.1 is also shown in FIGURE 2.23. The limits will allow to highlight a low engine speed behaviour.

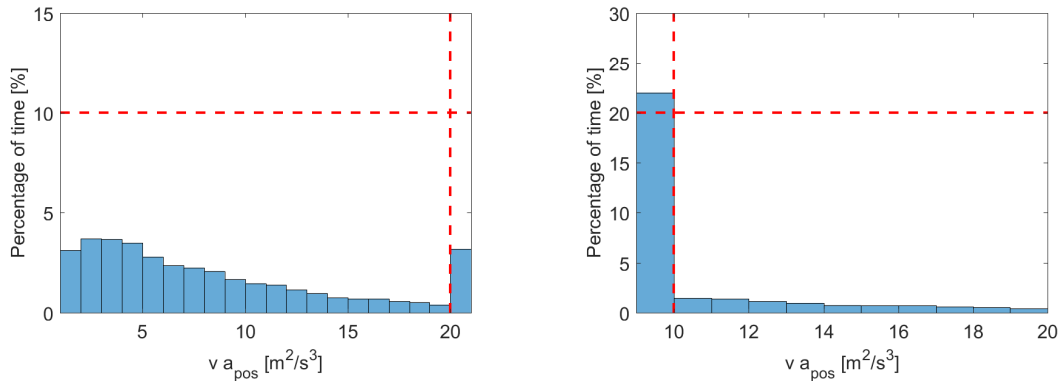


Figure 2.22: Histogram of $v \cdot a_{pos} [m^2/s^3]$ when driving the reference RDE cycle. The left graph shows limits at 20 $[m^2/s^3]$ and 10 [%] of time in red, while the right graph shows limits at 10 $[m^2/s^3]$ and 20 [%] of the time.

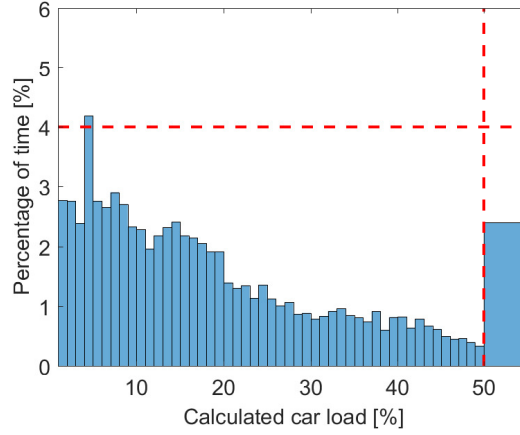


Figure 2.23: Histogram of the calculated car load [%] when driving the reference RDE cycle showing limits at 50 [%] and 4 [%] of the time in red.

Aggressive cycle

This RDE cycle has been performed with the aim of meeting the WLTP cycle criteria such as average speed, distance and maximum speed while modifying the driving style. In this cycle, the driver maximised performance while taking into account the traffic and the safety of other road users. The main differences with the conventional WLTP cycle can be seen in APPENDIX D, TABLE D.4. The only relevant difference is the maximum speed during the medium part of the cycle. As the average speeds are very similar, this difference does not invalidate the RDE cycle.

During this cycle, the driver changed gear at 3500 [rpm], with the aim of staying in the maximum torque range for the majority of the time. Braking was late, with little or no anticipation. Acceleration was strong, using as much as possible the engine potential. The car was constantly loaded, either under braking or acceleration.

FIGURE 2.24 shows the histogram of the rectified acceleration during this cycle. The standard deviation SD of 0.143 [g] is higher than the standard deviation of the reference RDE cycle. The distribution is therefore more spread out. This illustrates the fact that there were many accelerations/decelerations of different intensities during this cycle.

Regarding the product $v \cdot a_{pos}$ in FIGURE 2.25, limits were imposed in order to highlight an aggressive driving behaviour. This aggressive cycle is 14 [%] of the

time above the value of $20 \text{ [m}^2/\text{s}^3]$, while the reference cycle is only 3 [%] of the time above this value (left part of FIGURE 2.22).

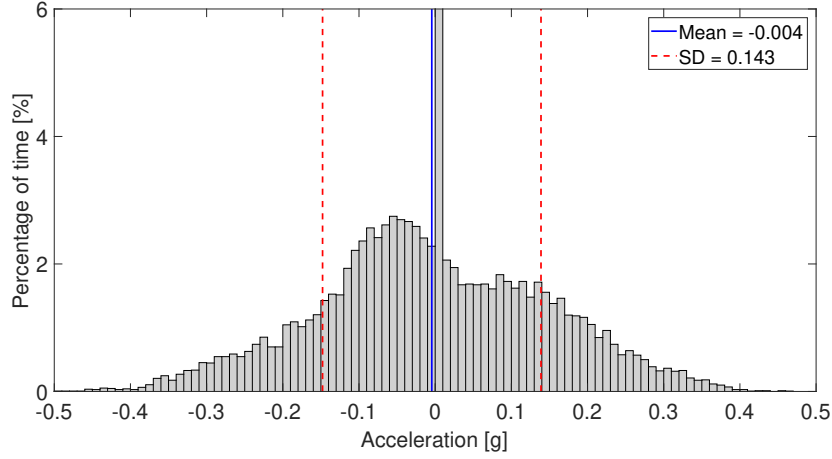


Figure 2.24: Histogram of the rectified acceleration when driving an aggressive RDE cycle.

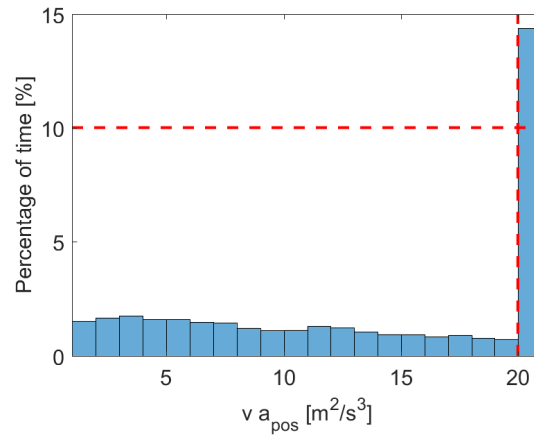


Figure 2.25: Histogram of $v \cdot a_{pos} \text{ [m}^2/\text{s}^3]$ when driving an aggressive RDE cycle.

Economic cycle

This RDE cycle has been performed with the aim of meeting the WLTP cycle criteria such as average speed, distance and maximum speed while modifying

the driving style. The aim of this cycle is to apply eco-driving tips³. The main differences with the conventional WLTP cycle are shown in APPENDIX D, TABLE D.5. In this case, the average speed in the low part of the cycle is higher than the conventional WLTP cycle. This means that this cycle could be even more economical but it can still be considered as valid regarding the WLTP criteria.

During this cycle, the driver changed gears between 2000 [rpm] and 2500 [rpm]. The accelerations were as smooth as possible and the anticipation was as high as possible.

FIGURE 2.26 shows the histogram of the rectified acceleration during this cycle. The standard deviation SD of 0.075 [g] is smaller than the standard deviation of the reference RDE cycle (FIGURE 2.21). The distribution is therefore less spread out. Indeed, the narrow distribution is concentrated around the mean value of 0.004 [g]. This illustrates the fact that there were very little accelerations/decelerations during this cycle. Limits are shown in FIGURE 2.27 illustrating the histogram of the product $v \cdot a_{pos}$. This economic cycle is 27 [%] of the time below the value of 10 [m^2/s^3].

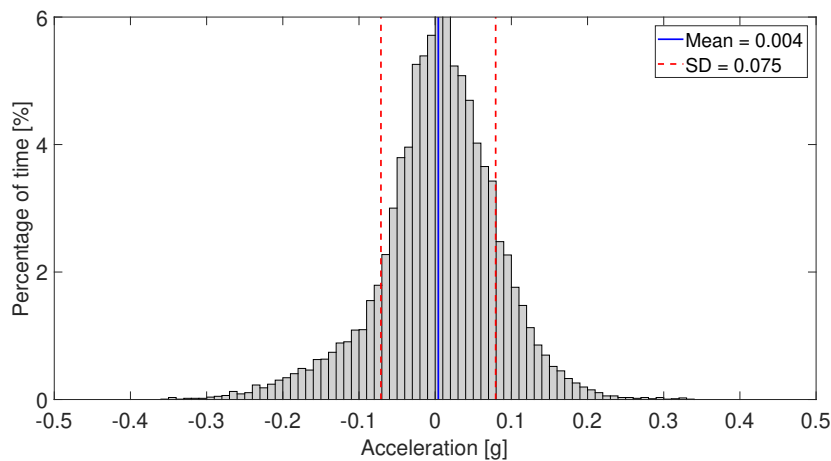


Figure 2.26: Histogram of the rectified acceleration when driving an economic RDE cycle.

³For example, the cycle was carried out without air conditioning and with the windows closed in order to be as aerodynamic as possible.

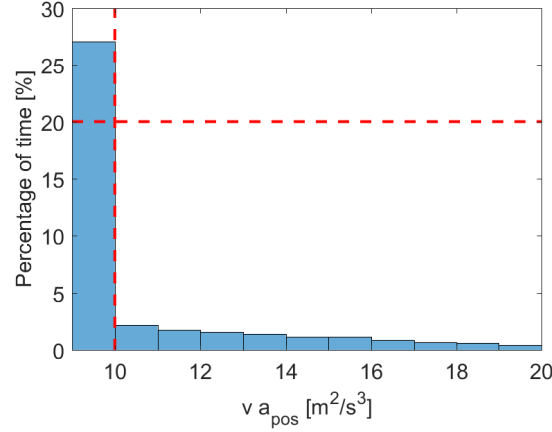


Figure 2.27: Histogram of $v \cdot a_{pos}$ [m^2/s^3] when driving an economic RDE cycle.

Low engine speed cycle

This RDE cycle has been performed with the aim of meeting the WLTP cycle criteria such as average speed, distance and maximum speed while modifying the driving style. The objective was to point a low engine speed driving style which could appear as normal from an external point of view. The main differences with the conventional WLTP cycle can be seen in APPENDIX D, TABLE D.6. The average speed of this cycle is globally under the average speed required by the conventional WLTP cycle. This means that if the cycle had been conducted more closely to the WLTP cycle criteria, the engine would have been under more load which would have led to a higher NO_x production.

During this cycle, the driver deliberately adopted a non-optimal driving style. Engine speeds were set at 1500 [rpm] whenever possible. The engine was fully loaded during acceleration at very low engine speeds. The driver anticipated in a normal way and the braking was done as in the reference cycle.

The histogram in FIGURE 2.28 has a similar distribution to the histogram of the reference cycle (FIGURE 2.21) with a standard deviation SD of 0.088 [g]. However, regarding the calculated car load (FIGURE 2.29), values are above 50 [%] of car load 5.15 [%] of the time, compared to 2.86 [%] in the reference RDE cycle (FIGURE 2.23).

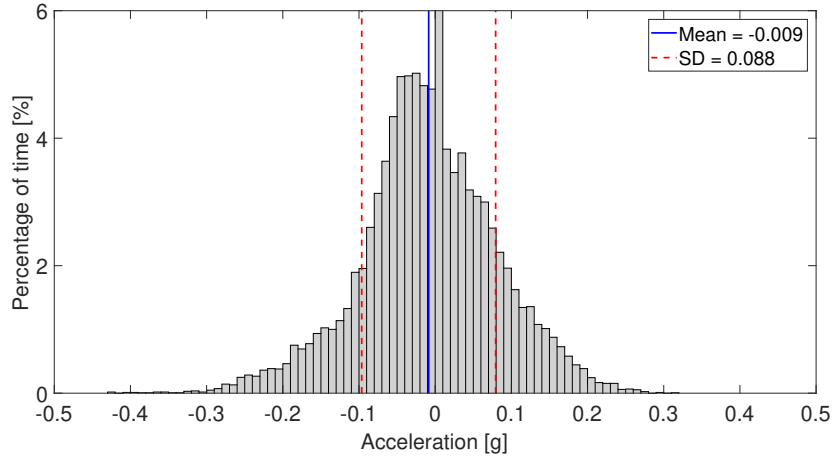


Figure 2.28: Histogram of the rectified acceleration when driving a low engine speed RDE cycle.

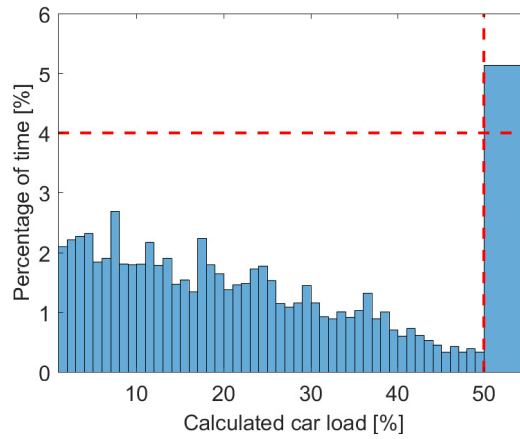


Figure 2.29: Histogram of the calculated car load [%] when driving a low engine speed RDE cycle.

2.3 Driving behaviour identification

After analysing the four specific driving cycles, a comparison between those has been realised and a tool to characterise all types of driving cycles has been developed. This tool is based on data from the datalogger processed in different steps.

The first point of comparison between the four cycles is the acceleration histogram represented in FIGURE 2.30. The distribution of the acceleration between the low engine speed cycle and the reference cycle are similar, with a standard deviation

of 0.088 and 0.09 [g] respectively. However, the average speed of the low engine speed cycle is on average slower than the speed of the reference cycle, which means that the most of the acceleration in the low engine speed cycle was achieved at low speeds. In the aggressive cycle, a wider acceleration distribution is observed.

The second point to note is the high concentration of acceleration around 0 [g], whatever the cycle. This is due to moments of low acceleration/deceleration or constant speeds, or when the car is stationary. Furthermore, it can also be explained by the fact that the accelerometer almost never measures zero acceleration, which may be due to engine vibration or a lack of hardware accuracy.

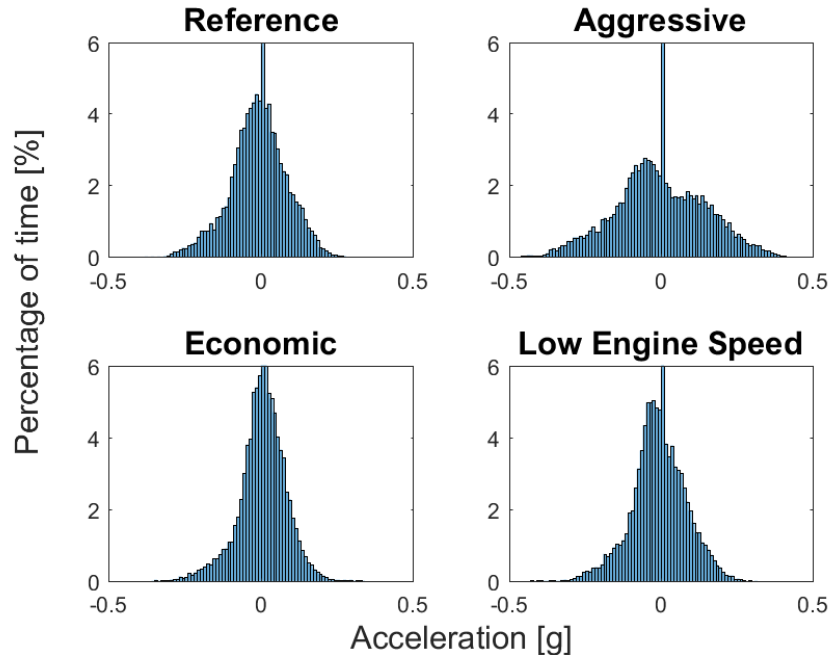


Figure 2.30: Histograms of the rectified accelerations from the accelerometer for the four specific RDE cycles described above.

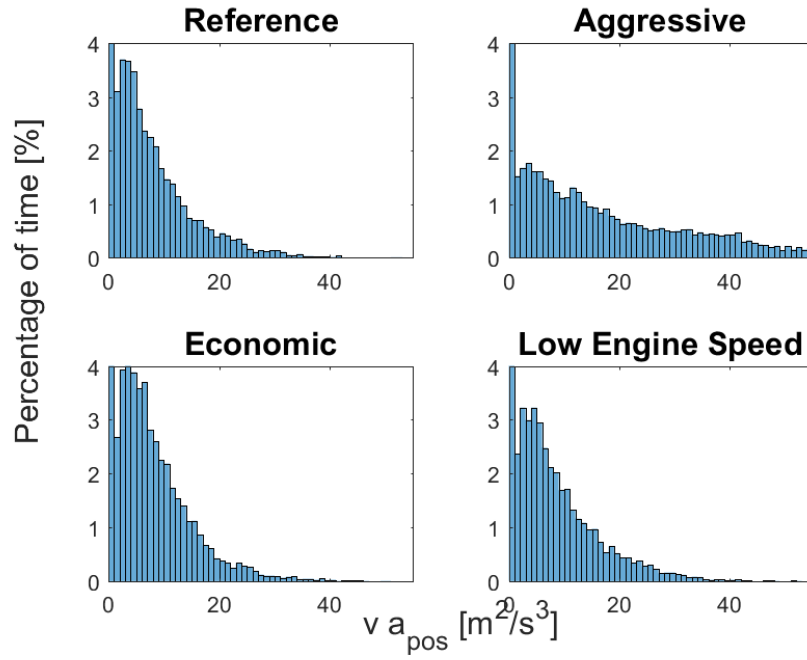


Figure 2.31: Histograms of $v \cdot a_{pos}$ [m²/s³] for the four specific RDE cycles described above.

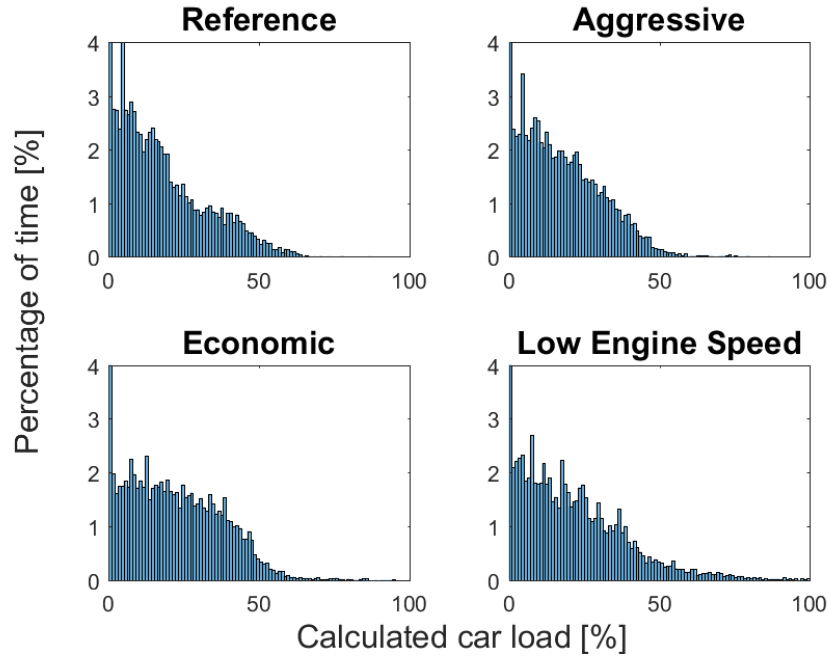


Figure 2.32: Histograms of the calculated car load [%] for the four specific RDE cycles described above.

Regarding the histograms of $v \cdot a_{pos}$ in FIGURE 2.31, that of aggressive driving is as expected more spread out than the others. Furthermore, product $v \cdot a_{pos}$ in the economic driving cycle is more concentrated near zero, meaning that the accelerations are smooth, even in high speed driving. FIGURE 2.32 shows the histograms of the calculated car load for the four specific cycles described above.

All these parameters allow the creation of a decision tree to classify the driving behaviour of a RDE cycle (see FIGURE 2.33).

The first decision level of the tree concerns the standard deviation of the acceleration. This parameter is sufficient to distinguish the less aggressive cycles from the others. If the standard deviation is above 0.08 [g], the driving cycle is considered as potentially aggressive (right part of the decision tree).

The second decision level of the tree considers the $v \cdot a_{pos}$ parameter. For the left part of the tree, the criterion is based on the percentage of time under 10 [m^2/s^3]. This percentage is fixed at 20 [%] (see FIGURE 2.27). If this condition is met, the driving behaviour will be directed into the potential economic part.

The right part of the tree is related to potentially more aggressive driving behaviours. In this case, the threshold of the $v \cdot a_{pos}$ product is set at 10 [%] of the time above 20 [m^2/s^3] (see FIGURE 2.25).

The last level of the tree refers to the car load criterion. As for the previous level, the selection is based on a percentage of time above a threshold value. The cycle is considered as a low engine speed cycle if for more than 4 [%] of the time the car load is greater than 50 [%]. In all other cases, the driving behaviour will be determined according to the position at the bottom of the decision tree.

This tree was made with a limited number of cycles. Some of the criteria boundaries were defined on the basis of few cycles and probably need to be modified. The purpose of this tree is to try with a limited number of cycles to categorise all types of driving behaviours. That is why an ordinary cycle with a standard deviation of less than 0.08 can be found further down the tree and why no criteria are discriminating.

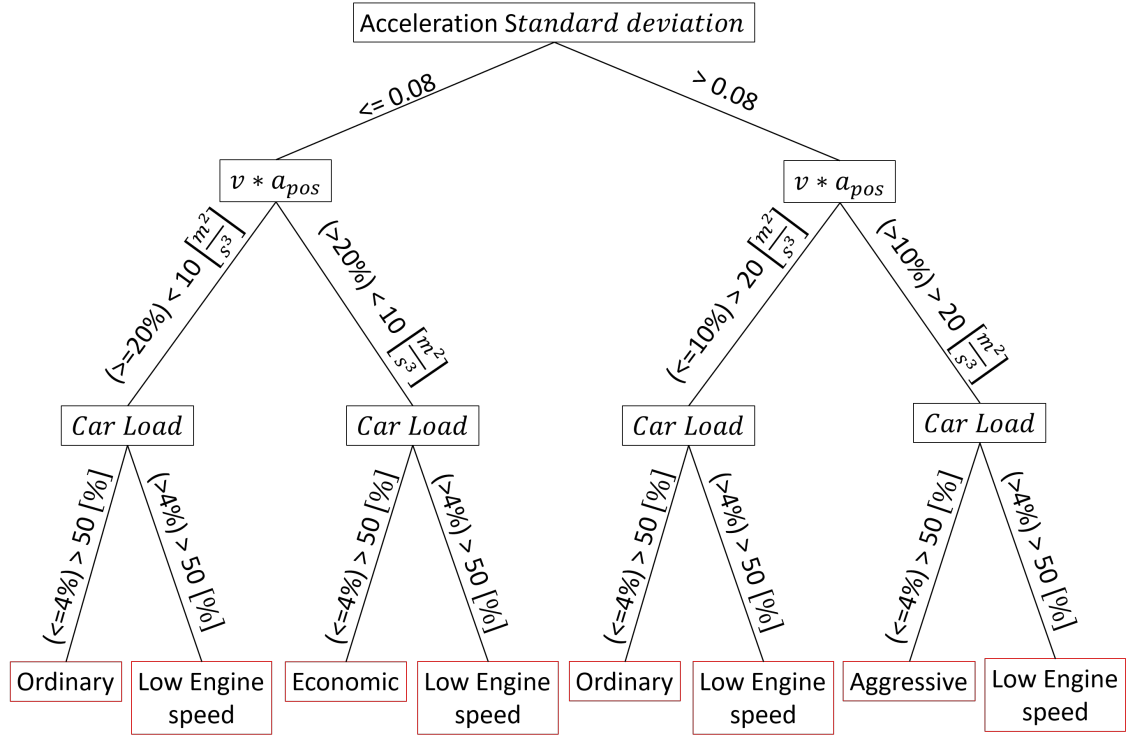


Figure 2.33: Decision tree for the characterisation of driving behaviours.

Finally, four new cycles were carried out (to distinguish the two measurements campaigns, the cycles of the second series of tests will be named "B-cycles"). These B-cycles had two objectives:

- To validate or invalidate the logic tree;
- To study the influence of the driving behaviours on the NO_x production (see CHAPTER 3).

As for the previous series of tests, the B-cycles were conducted in order to highlight the driving behaviours described before: ordinary (conducted as the reference cycle in a normal way), aggressive, economic and low engine speed. The B-cycles are detailed in APPENDIX D.

The analyses of the B-cycles behaviours with the help of the logic tree confirmed the identification of the four behaviours. However, the decision tree presents some limitations:

- The criteria were determined on the basis of one cycle of each type. A refinement of the criteria with more data seems necessary. To give more

weight to the tree, more cycles of the same type should be realised. A subsequent statistical analysis could help to define more coherent limits.

- The ordinary cycle, the economic cycle and the low engine speed cycle have similar characteristics. At the $v \cdot a_{pos}$ level, the criterion set by the logic tree to determine whether a cycle is economic or not are met for both ordinary and low engine speed drivers. This parameter probably needs to be refined to allow a clearer separation between the driving behaviours. On the contrary, the aggressive cycle is easily identified, whatever the criteria. This suggests that there are other driving behaviours than the four defined in this thesis.
- Cycles were performed with the aim of highlighting a behaviour. The driving type was deliberately stereotyped. For example, during the low engine speed behaviour cycle, the gear change was made under 1500 [rpm] throughout the 27 minutes of driving. This seems unlikely in ordinary conditions. This driving cycle was conducted in order to detect an additional NO_x emission in low gear driving conditions.

Chapter 3

Influence of the driving behaviour on the NO_x emissions

This chapter analyses the NO_x production of the different B-cycles performed in the previous section in order to study the relation between driving style and NO_x production. It consists of three parts. The first part presents the device used to measure the gas concentrations in the exhaust under real driving conditions. The second part explains how to convert the $[ppm]$ to $[g/km]$ of NO_x for comparison with the NO_x emissions limits defined in the EURO standards (FIGURE 1.5). The last part concludes with an analysis of the relation between NO_x emissions and driving behaviour over the four performed cycles.

3.1 NO_x Measurement Device - Testo 350 XL

An exhaust gas analyser is used to measure the NO_x emissions during the RDE cycles. The *Testo 350 XL* device allows to take measurements of a wide range of different industrial emissions [43]. The Testo is equipped with several sensors allowing, among other things, to continuously measure the NO_x concentrations in the exhaust gases of a car. A computer can be connected to the analyser box through an USB wire, thereby replacing the function of the control unit. This enables direct feedback during driving to check the consistency of the measurements. The analyser box (FIGURE 3.1) is equipped with all the elements needed to correctly measure exhaust gases: sensors, filters, pumps and a thermoelectric (Peltier) chiller for removing the moisture [43]. A probe is used to collect the exhaust gases.

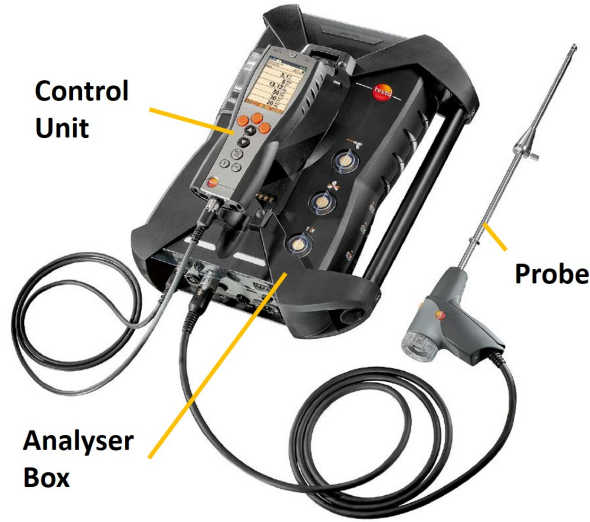


Figure 3.1: The exhaust gas analyser is a portable device divided in two parts: the control unit and the analyser box. It is also equipped with a probe to measure exhaust gas emissions [43].

TABLE 3.1 shows some of the gases measurable with the Testo and their response times. Although these appear to be high, they are maximum response times and throughout our experiments, the Testo was often very responsive to gas measurements, regardless of the measured gas. The NO and NO₂ sensors have an accuracy of ± 5 [ppm]¹.

Measured parameters	Units	Response Time
O ₂	[%]	< 20 [s]
NO	[ppm]	< 30 [s]
NO ₂	[ppm]	< 40 [s]
CO ₂	[%]	< 10 [s]
CO	[ppm]	< 40 [s]

Table 3.1: Main gases measured with the Testo.

¹More information about the Testo can be found in the user guide [43].

3.2 Conversion from $[ppm]$ to $[g/km]$

The Testo gives the concentrations of NO_x in the exhaust gases in parts-per-million ($ppm = 10^{-6}$), while these concentrations are expressed in $[g/km]$ in the EURO standards. It must be pointed out that the measured concentrations are given in $[ppm]$ by volume, written $[ppm_v]$ in what follows. The mass concentrations are written $[ppm_m]$.

By making the assumption that only the NO and NO_2 are taken into account, the amount of NO_x in the exhaust gases expressed in $[g/km]$ is computed as follows:

$$NO_x = \frac{\dot{m}_{NO_x}}{v} = \frac{\dot{m}_{NO} + \dot{m}_{NO_2}}{v} \left[\frac{g_{NO_x}}{km} \right], \quad (3.1)$$

with $\dot{m}_{NO}$ $[g/s]$ and $\dot{m}_{NO_2}$ $[g/s]$ the mass flow rates of NO and NO_2 and v $[km/s]$ the speed of the car from the OBD socket. However, given that:

$$\dot{m}_{NO_x} = (ppm_{m,NO_x} \cdot 10^{-6}) \cdot \dot{m}_{gas} \left[\frac{g_{NO_x}}{s} \right], \quad (3.2)$$

with $ppm_{m,NO_x} = ppm_{m,NO} + ppm_{m,NO_2}$ $[\mu g_{NO_x}/g_{gas}]$ the mass fraction of NO_x in the exhaust gases and $\dot{m}_{gas}$ $[g/s]$ the mass flow rate of the exhaust gases. The amount of NO_x from equation 3.1 can be rewritten as²:

$$NO_x = \frac{((ppm_{m,NO} + ppm_{m,NO_2}) \cdot 10^{-6}) \cdot \dot{m}_{gas}}{v} \left[\frac{g_{NO_x}}{km} \right]. \quad (3.3)$$

Therefore the mass fractions $ppm_{m,NO}$, ppm_{m,NO_2} and $\dot{m}_{gas}$ the mass flow rate of the exhaust gases have to be determined to get the NO_x emitted in $[g/km]$.

3.2.1 Determination of the mass fractions $ppm_{m,NO}$ and ppm_{m,NO_2}

Starting from the law of perfect gases:

$$p \cdot V = n \cdot R \cdot T [J]. \quad (3.4)$$

In order to facilitate the reading, the determination of the mass fraction is detailed herebelow for NO. The same calculation applies in the case of NO_2 .

²Speeds below 1 $[km/h]$ are not taken into account to avoid the increase of NO_x emissions at low speeds.

The volume concentration $ppm_{v,NO}$ can be written as:

$$ppm_{v,NO} \cdot 10^{-6} = \frac{V_{NO}}{V_{gas}} = \frac{n_{NO} \cdot R \cdot T_{NO} \cdot p_{gas}}{n_{gas} \cdot R \cdot T_{gas} \cdot p_{NO}} [-] , \quad (3.5)$$

where $R = 8.314 [J/(kgK)]$ is the universal gas constant and for $i = (NO, gas)$: $T_i [K]$, $p_i [Pa]$, $n_i [mol]$ and $V_i [m^3]$ are the temperature, pressure, number of moles and occupied volumes of the exhaust elements i . Knowing that $T_{NO} = T_{gas} = T_{exhaust} [K]$ and $p_{NO} = p_{gas} = p_{exhaust} [Pa]$, these equations can be simplified to obtain the following:

$$ppm_{v,NO} \cdot 10^{-6} = \frac{n_{NO}}{n_{gas}} [-] . \quad (3.6)$$

Furthermore, knowing that $m = n \cdot M [kg]$ with $M [kg/mol]$ the molar mass, the mass fraction $ppm_{m,NO}$ can be expressed as:

$$ppm_{m,NO} \cdot 10^{-6} = \frac{m_{NO}}{m_{gas}} = \frac{n_{NO}}{n_{gas}} \cdot \frac{M_{NO}}{M_{gas}} [-] . \quad (3.7)$$

By injecting equation 3.6 into equation 3.7, the following equation is obtained:

$$ppm_{m,NO} = ppm_{v,NO} \cdot \frac{M_{NO}}{M_{gas}} [-] . \quad (3.8)$$

Some assumptions are made at this point:

- Exhaust gases are considered as dry combustion products, meaning the water H_2O has been removed from the exhaust gases. $[gas]$ will denote the molar fractions of the dry combustion products.
- Considering that the NO_x , CO and H_2 are present in low concentrations (expressed in $[ppm_v]$), the exhaust gases are supposed to be mainly composed of O_2 , CO_2 and N_2 .
- The molar masses of the exhaust gases are: $M_{O_2} = 32 [g/mol]$, $M_{CO_2} = 44 [g/mol]$, $M_{N_2} = 28 [g/mol]$.
- The molar masses of the NO_x are: $M_{NO} = 30 [g/mol]$ and $M_{NO_2} = 46 [g/mol]$.

The assumptions imply that:

$$[O_2] + [CO_2] + [N_2] = 1 [-] , \quad (3.9)$$

and

$$M_{gas} = M_{O_2}[O_2] + M_{CO_2}[CO_2] + M_{N_2}[N_2] [g/mol] . \quad (3.10)$$

When injecting equation 3.9 in equation 3.10, the molar mass of the exhaust gases is obtained:

$$M_{gas} = (M_{O_2} - M_{N_2})[O_2] + (M_{CO_2} - M_{N_2})[CO_2] + M_{N_2} \text{ [g/mol]} . \quad (3.11)$$

So, equation 3.8 becomes:

$$ppm_{m,NO} = ppm_{v,NO} \cdot \frac{M_{NO}}{(M_{O_2} - M_{N_2})[O_2] + (M_{CO_2} - M_{N_2})[CO_2] + M_{N_2}} [-] . \quad (3.12)$$

After replacing the molar masses by their values, the equation becomes:

$$ppm_{m,NO} = ppm_{v,NO} \cdot \frac{30}{4[O_2] + 16[CO_2] + 28} [-] , \quad (3.13)$$

The mass fraction ppm_{m,NO_2} is obtained in the same way with the following equation:

$$ppm_{m,NO_2} = ppm_{v,NO_2} \cdot \frac{46}{4[O_2] + 16[CO_2] + 28} [-] . \quad (3.14)$$

3.2.2 Determination of the mass flow rate of the exhaust gases $\dot{m}_{gas}$

By applying the law of conservation of mass to the engine, it follows that:

$$\dot{m}_{gas} = \dot{m}_a + \dot{m}_f \left[\frac{g}{s} \right] , \quad (3.15)$$

with $\dot{m}_a$ [g/s] the mass flow rate of the air entering the engine and $\dot{m}_f$ [g/s] the mass flow rate of fuel used for the combustion inside the cylinders.

The mass flow rate of air $\dot{m}_a$ is acquired directly via the measurement device reading information from the OBD socket. However, the mass flow rate of fuel $\dot{m}_f$ must be evaluated from other measurable parameters: the excess-air coefficient λ and the mass flow rate of air $\dot{m}_a$.

The air-fuel ratio must be introduced since λ depends on it. It is the ratio between the mass of air and the mass of fuel reacting during combustion:

$$AF = \frac{m_a}{m_f} [-] . \quad (3.16)$$

When there is a complete and stoichiometric combustion, the air-fuel ratio is called AF_{st} . The excess-air coefficient is defined as:

$$\lambda = \frac{AF}{AF_{st}} [-] . \quad (3.17)$$

Using both equations 3.16 and 3.17 and by converting the masses into mass flow rates, the mass flow rate of fuel can be obtained:

$$\dot{m}_f = \frac{\dot{m}_a}{\lambda \cdot AF_{st}} \left[\frac{g}{s} \right] . \quad (3.18)$$

Knowing that AF_{st} is a fixed value depending on the fuel used, only λ remains to be measured in order to calculate the mass flow rate of the exhaust gases $\dot{m}_{gas}$.

However, in practice it is very complicated to measure the λ on cars. The following conditions must be met in order to obtain it:

- The car needs to have an OBD socket.
- The car must be equipped with a wide-band λ sensor.
- Finally, the manufacturer must allow access to this probe.

Many different attempts have been made during this thesis to get or approximate λ . These are described in APPENDIX E.

Assumption: $\dot{m}_f$ can be approximated

For diesel engines the air-fuel ratio stoichiometric AF_{st} equals approximately 14.5 [-] [44]. As a reminder, diesel engines work in lean conditions (equivalence ratio $\Phi < 1$), it implies that $\lambda = 1/\Phi > 1$. This means that AF_{actual} (when the engine is running) is higher than AF_{st} . The amount of air sent into the cylinder compared to the amount of fuel is very large. In other words, the amount of fuel is negligible compared to the amount of air.

To illustrate this, a comparison can be done on the range of AF_{actual} . The equivalence ratio is supposed to vary from $\Phi = 0.3$ [-] and $\Phi = 0.6$ [-] in diesel engines and if these values are taken using equation 3.17 (with $AF_{st} = 14.5$), AF_{actual} equals 48.3 [-] and 24.2 [-] respectively. Furthermore, these values consider only atmospheric engines. In turbocharged diesel engines, the AF_{actual} at idle may exceed 160 [-] [45]. The equivalence ratio Φ was set at 0.5, this means that $\lambda = 2$ [-].

Using equation 3.18 and 3.15, the mass flow rate of gas ($\dot{m}_{gas}$) is thus equal to:

$$\dot{m}_{gas} = \dot{m}_a \left(1 + \frac{1}{\lambda \cdot AF_{st}} \right) \approx \dot{m}_a \cdot 1.0345 \left[\frac{g}{s} \right] . \quad (3.19)$$

3.3 Relation between the driving behaviour and the NO_x emissions

The production of NO_x is a complex phenomenon, as seen in SECTION 1.1. Various parameters are involved, such as temperature, residence time of the fuel in the cylinder and whether or not the exhaust gases are recirculated through the EGR valve. This section goes through an analysis of the NO_x production for each driving behaviour, an identification of the most interesting behaviours and finally the EURO standards compliance of the average NO_x production over a RDE cycle.

3.3.1 NO_x emissions under different driving behaviours

The first analysed behaviour is the aggressive one. The NO_x production in this cycle is continuously below 2.5 [g/km], with many production peaks (FIGURE 3.2). There are also periods of very low production when the car is stationary. The product $v \cdot a_{pos}$ oscillate on average between 0 and 60 [m²/s³] throughout the cycle, regardless of the cycle phase. This means that in the *low* part, there were high accelerations for low speeds, while in the *extra high* part, there were lower accelerations for high speeds. This could be expected in view of the driving behaviour, which aimed to exploit the engine performance as much as possible.

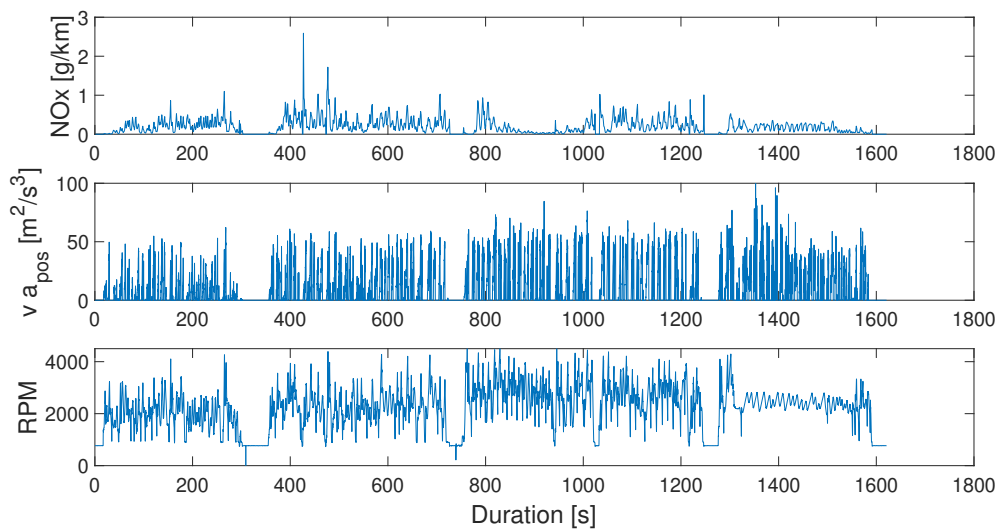


Figure 3.2: Evolution over time of the NO_x emissions in [g/km], $v \cdot a_{pos}$ [m²/s³] and the engine speed [rpm] for the aggressive driving cycle.

In the last part of the cycle (the *extra-high* part carried out on the motorway), the NO_x production is globally lower and varies less than during the other three parts. In this phase, the variation of engine speed is less important. A parallelism can be drawn between engine speed variation and NO_x production. On the other hand, no clear trend emerges between the NO_x emissions and $v \cdot a_{pos}$ in the different phases of this RDE test, neither for this aggressive behaviour nor for the others.

The second analysed behaviour is the economic one. NO_x production over this cycle varies little. Indeed, apart from two peaks just before 800 and 1100 [s], the NO_x emissions of this cycle stay below 0.016 [g/km] (FIGURE 3.3), whatever the car load. Looking at the engine speed, it varies between 1000 and 2100 [rpm] excepted at 300, before 800 and after 1000 [s] where it drops to 0 [rpm]. The engine was thus switched off just before these peaks. The corresponding NO_x peaks are therefore probably due to the engine restart. It seems that the first restart of the engine did not produce additional NO_x . This could be linked to the fact that the car was stopped for a very short time.

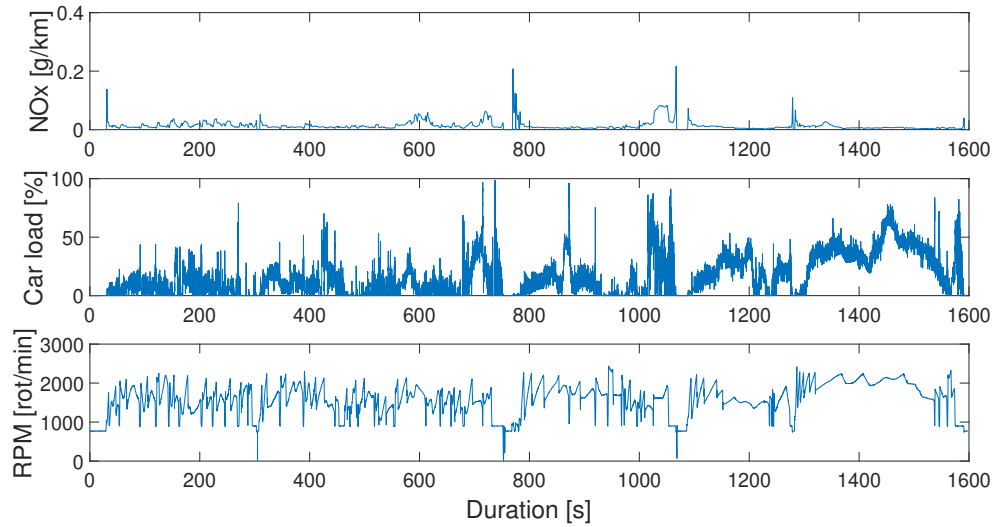


Figure 3.3: Evolution over time of the NO_x emissions in [g/km] for the economic cycle. Values on the y-axis were set to highlight the low NO_x production level.

The third analysed behaviour is the low engine speed one. The NO_x production in this cycle is below 0.5 [g/km] in the *low* and the *extra-high* part of the cycle. For the *medium* and the *high* part, the emissions are lower than for the two others, below 0.03 [g/km] (FIGURE 3.4). As in the other tests, the influence of car load does not appear clearly.

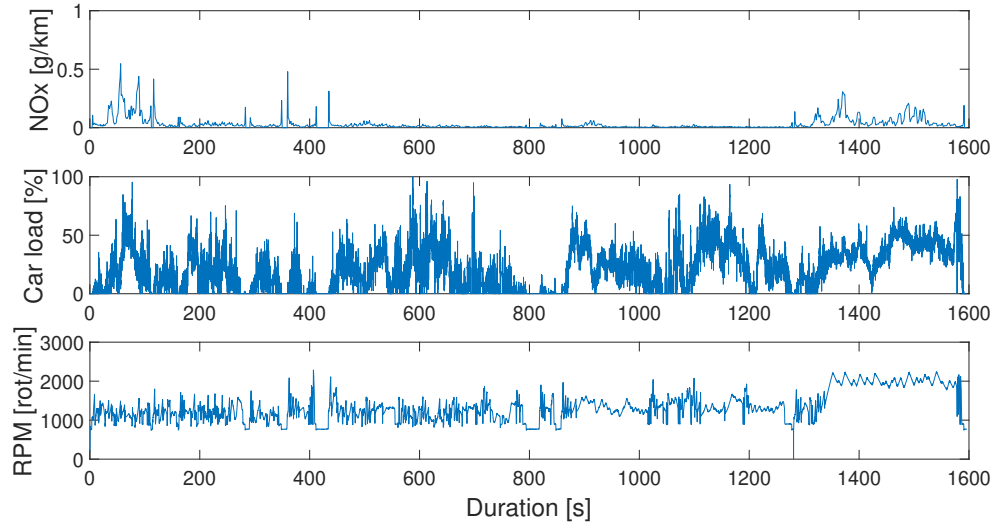


Figure 3.4: Evolution over time of the NO_x emissions in [g/km] , the calculated car load [%] and the engine speed [rpm] for the low engine speed cycle.

A more detailed analysis of the engine speed shows that the NO_x production increases above 2000 $[\text{rpm}]$. This is particularly visible in the *extra high* part of the cycle (see FIGURE 3.5) where the revolutions per minutes are slightly above 2000 $[\text{rpm}]$ for several hundred seconds. This leads to NO_x production between 0.05 and 0.3 $[\text{g}/\text{km}]$. These NO_x emission values are ten times higher than during the periods below 2000 $[\text{rpm}]$. This higher NO_x emission level could be due to the EGR valve closing above 2000 $[\text{rpm}]$, which would increase the NO_x level. It is worth noting that above 2000 $[\text{rpm}]$, NO_x production and car load follow the same trend.

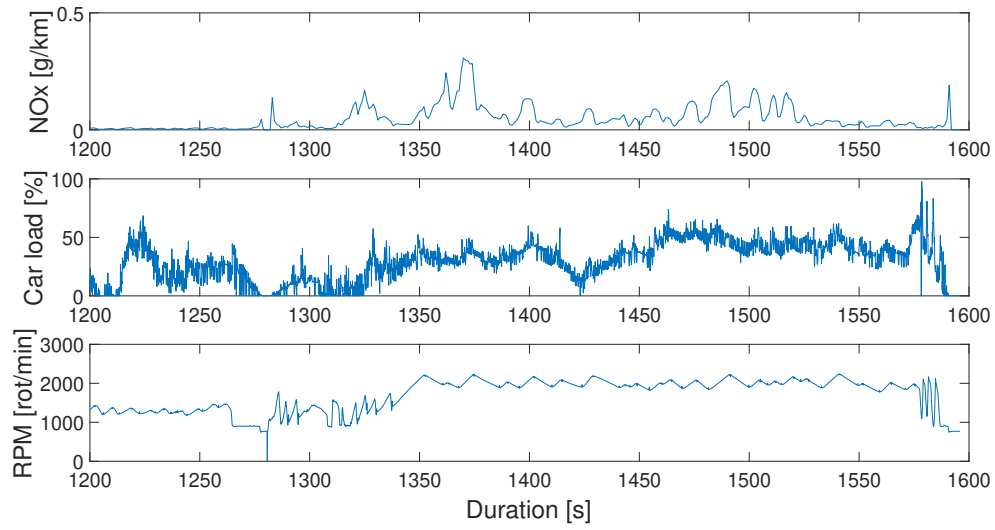


Figure 3.5: Evolution between 1200 and 1600 $[\text{s}]$ of the NO_x emissions in $[\text{g}/\text{km}]$, the calculated car load $[\%]$ and the engine speed $[\text{rpm}]$ for the low engine speed cycle.

Regarding the ordinary RDE test, the NO_x production in this cycle is below 0.6 [g/km] (see FIGURE 3.6). It is more complicated in this case to derive a relationship using the engine speed, as it varies significantly throughout the cycle between 1000 and 3000 [rpm] . It is also difficult to establish a link between NO_x production and car load.

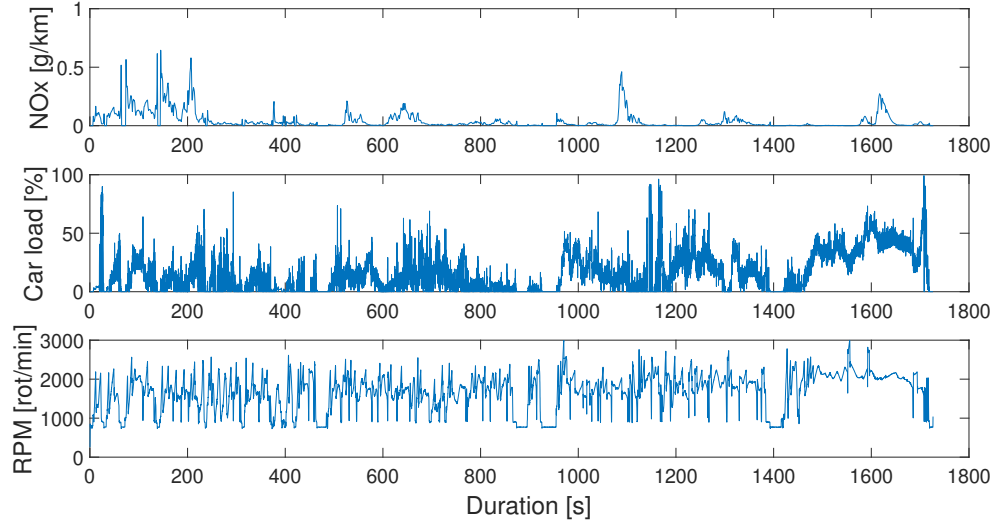


Figure 3.6: Evolution over time of the NO_x emissions in [g/km] and the calculated car load [%] for ordinary driving cycle.

3.3.2 Comparison of the NO_x emissions under the four driving behaviours

As a reminder, the Testo outputs the volume concentrations of NO and NO_2 expressed in [ppm] , which when added together for each RDE test gives the result shown in FIGURE 3.7.

The $\text{[ppm}_v\text{]}$ of NO_x are then converted to [g/km] for each RDE test by applying the calculations described in SECTION 3.2. The results are given in FIGURE 3.8, with the same y-axis limits for the purpose of comparison. The NO_x peaks sometimes exceed 1 [g/km] for the aggressive cycle.

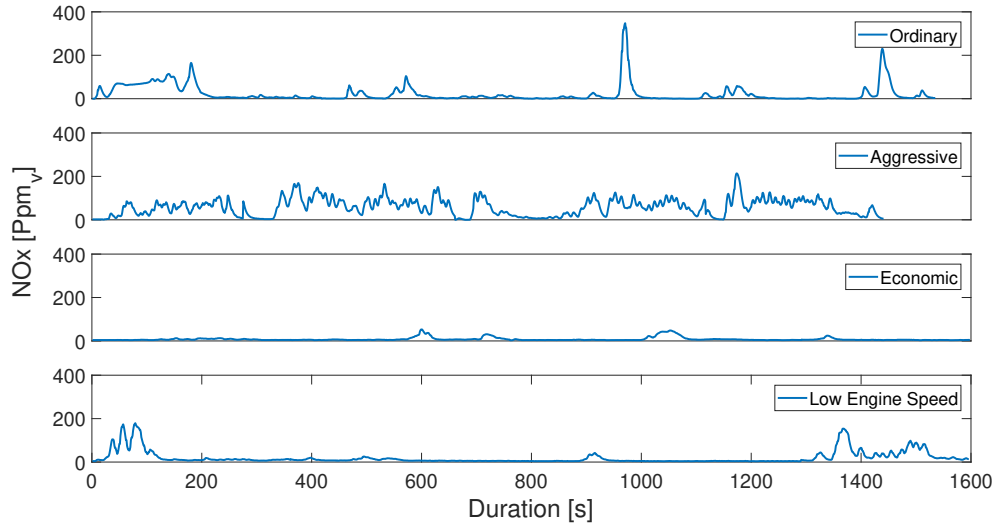


Figure 3.7: Evolution over time of the NO_x emissions in $[ppm_v]$ of the four different RDE cycles performed. This is the raw data from the Testo.

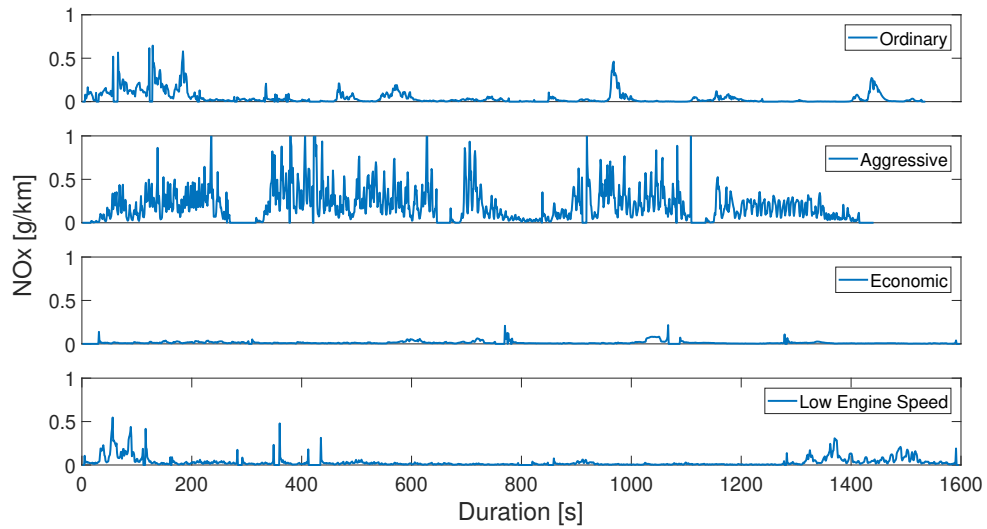


Figure 3.8: Evolution over time of the NO_x emissions in $[g/km]$ of the four different RDE tests. From top to bottom, the mean values in $[g/km]$ are respectively: 0.0412, 0.195, 0.0132, 0.0315.

The NO_x produced for each RDE test are commented hereafter.

- Compared to the other cycles, the economic cycle emits almost no NO_x, regardless of the phase of the test. Economical driving as described in SECTION 2.2.3 (with a lot of anticipating and changing gear at the optimal moment), is therefore recommended for a lower NO_x emission.
- The aggressive test is the most NO_x emitting compared to the other tests. Indeed, on average, the NO_x emission level is more than four times higher. An aggressive driving behaviour has therefore a direct impact on the NO_x production. The more aggressive the driving, the higher the NO_x production.
- Unexpectedly for the low engine speed behaviour, the NO_x production is quite low, of the same order of magnitude as the ordinary cycle. The conducted experiments thus show that driving at low engine speed (in non-optimal conditions) has no negative influence on NO_x production. Regarding the NO_x emissions, this type of driving was not a bad driving behaviour.
- It should be noted that all four cycles were performed with a warm engine. However, NO_x production is observed during the first 200 seconds for both the ordinary and the low engine speed cycle. One assumption is made to explain this phenomenon: a pause was made (about 20 [min]) before starting these two cycles and the SCR had time to cool down in between. It is important to note here that the SCR temperature was not monitored and is different from the engine block temperature as the SCR is positioned in the exhaust line. All tests started with an engine block temperature of 90 [°C]. The fact that the SCR could cool down quickly was not anticipated. The production of NO_x at the beginning of these cycles is therefore perhaps due to the heating time of the SCR. Once it is warm, the production of NO_x is globally lower.

3.3.3 EURO standards compliance

A comparison of NO_x emissions with the European Emission Standards is proposed. The EURO 6 standard was introduced in 2014 (FIGURE 1.5). EURO 6 limits the NO_x emissions at 0.080 [g/km] for light passenger and commercial vehicles. TABLE 3.2 provides a summary of the NO_x emissions for each RDE test performed in this study. In three out of four tests, the average obtained value is below the limit value of the EURO 6. Those three tests are thus compliant with this European standard. If the car is driven economically, it emits on average one eighth of the authorised limit.

The car is WLTP homologated and emits half the permitted EURO limit during an ordinary RDE test. This allows to say that the car complies well with the EURO 6 and that the WLTP cycle is representative of real driving conditions in the majority of cases.

However, although the car is homologated and emits on average two times less than the limit set for ordinary driving, the quantity of NO_x emitted can still be higher than the European standard (more than two times higher than 0.080 [g/km] in this case).

	Ordinary cycle	Aggressive cycle	Economic cycle	Low engine speed cycle
NO_x average value $[\text{g/km}]$	0.0412	0.195	0.0132	0.0315
Absolute difference $[\text{g/km}]$	-0.0388	0.115	-0.0668	-0.0485
Relative difference %	48.5	143.75	83.5	60.625

Table 3.2: Obtained mean values of the NO_x emissions in $[\text{g/km}]$ for the four RDE tests performed. A comparison with the limit value of $0.080 \text{ [g}_{\text{NO}_x}/\text{km}]$ through the calculation of the absolute and relative differences reveals that three tests (green values in the Table) are compliant with the EURO 6 standard.

Finally, a comparison in terms of NO_x emissions between the 2019 Skoda Scala used for the RDE tests presented above and an older car (Audi A1 from 2014) is presented in APPENDIX B. Two similar RDE tests were carried out with a similar driving style. In addition, both cars have similar engines. An important difference between both cars is that the Skoda is equipped with a SCR, while the Audi is not. This analysis illustrates the technological progress made in NO_x prevention over 9 years.

Conclusion

In recent years, vehicle homologation conditions have evolved, in particular the cycle to simulate the driving conditions of a vehicle. The old cycle used by manufacturers until 2017 to certify vehicles was completely obsolete. A new cycle (WLTP) has been developed, in order to overcome the defects of the previous cycle.

The aim of this thesis is to verify whether the NO_x emissions in real-life conditions depend on the driving behaviour and comply with the European Emission Standards. In order to answer this research question, several RDE tests were carried out. The purpose of those tests was to simulate a WLTP cycle on road.

The first step of this work was the characterisation of different driving behaviours. To achieve this, a decision tree was developed using a datalogger. The second step involved RDE cycles in which the production of NO_x was measured. The driving behaviour of these tests were identified by the decision tree. The final step was to determine whether the driving style influences the production of NO_x .

Only a part of the available information with the OBD socket was used to evaluate the driving behaviour. However, OBD socket could provide multiple information as the gear ratio, the position of the EGR valve or the rotation speed of the turbo which could be interesting to correlate with the driving style. This thesis has laid a foundation that can be exploited in future research. Two main paths can be explored. The first is to analyse a lot of data on a limited number of cars. For this purpose, the development of the Arduino mega by adding a GPS chip and an appropriate accelerometer is necessary. The second path is to collect a limited number of data on a lot of cars by using the datalogger. However, changing the accelerometer seems essential for qualitative data collection. Dataloggers would allow the collection of large amounts of data in order to define more driving behaviours and to generalise the results.

Several conclusions could be drawn. Firstly, the WLTP cycle is well representative of reality. A trip has been defined taking up the four parts of a WLTP cycle in

Woluwe. No major difficulty was encountered to realise RDE cycles by respecting the main criteria of a conventional WLTP. Secondly, the car which was used for the tests respects in three out of four driving styles the maximum allowed NO_x production. Thirdly, the driving style has an important influence on NO_x production. Indeed, an aggressive behaviour can emit 14 times more than an economic one in terms of NO_x. The NO_x production could exceed the limit value of 0.080 [g/km] while aggressive driving.

In conclusion, the WLTP cycle is representative of real driving conditions. The cars which were homologated since the implementation of this cycle comply with the EURO standard in real driving conditions. Finally, the driving behaviour has a strong influence on NO_x emissions.

Appendix A

Experimental setups

Two different experimental set-ups were used to carry out the experiments. In both cases, the Testo 350 XL was placed in the trunk. The probe of the Testo is also in the trunk and a flexible hose is placed over it (see FIGURE A.1).

In the first case, the hose is placed directly in the exhaust before passing through the trunk to reach the probe. The trunk is not completely closed to avoid the hose being pinched.



Figure A.1: Position of the Testo and its probe in the trunk.



Figure A.2: Hose directly put in the exhaust.

Once the trunk is closed, a check on the freedom of the exhaust to flow through the pipe is carried out by switching on the engine and putting the pipe against one's hand to feel if the exhaust gases are flowing through the pipe. The main problem with this setup is that the pipe will reach its glass transition temperature with the heat of the exhaust gases and deform. In the first case, the exhaust pipe is horizontal, the deformation of the pipe does not affect the collection of the gases (see FIGURE A.2). If the tailpipe is directed towards the ground, as is the case in the second experiment (see FIGURE A.3), the pipe will deform and exit the exhaust. In the second experiment, a 1.2 [cm] diameter copper pipe was custom bent to fit into the exhaust.



Figure A.3: Copper pipe attached to the exhaust.



Figure A.4: Copper pipe attached to the framework of the car. All the

It is attached with wire to the exhaust brackets and taped to the bodywork (see FIGURE A.4). This copper piece allows the exhaust gases to be cooled at the hottest point and prevents the hose from overheating. After the copper part, the hose runs along the bodywork (see FIGURE A.5) and enters the passenger compartment through the left rear window. This prevents the hose from being pinched and deformed.¹ The main problem with this technique is the increased heat exchange surface between the exhaust gases and the outside air. This outside air is potentially colder than the air inside of the car, which can cause problems with the flow of exhaust gases through the pipe. This poor gas circulation leads to completely invalid results.

In conclusion, the best solution is a combination of the two setups. A first part in copper to avoid overheating of the pipe and pass the pipe directly into the trunk.

¹Watch out, police stopped the car because pedestrian thought this was attempted suicide. They told us to put a sign with the message "Test anti-pollution en cours" to avoid misunderstanding from people.



Figure A.5: Side of the car with the hose

Reducing the size of the hose as much as possible also avoids condensation in the hose which could have changed the gas flow. The difference of the NO_x production between the two experimental setups for the same driving behaviour and the same route is showed in FIGURE A.6 and FIGURE A.7.

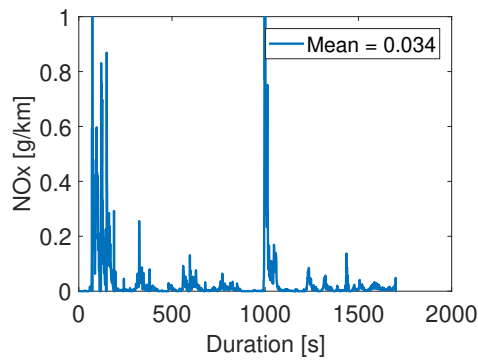


Figure A.6: Evolution over time of the NO_x emissions in $[g/km]$ for the aggressive cycle made with the hose put in the wrong way.

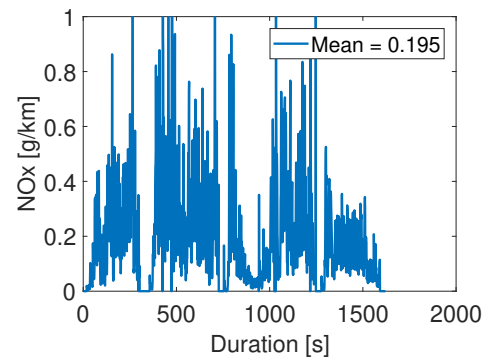


Figure A.7: Evolution over time of the NO_x emissions in $[g/km]$ for the aggressive cycle made with the hose put in the right way.

Appendix B

Comparison of the NO_x production with an Audi A1 from 2014

As mentioned earlier, a RDE cycle has been performed with an older car than the Skoda Scala used in the various tests. The purpose of this analysis was to highlight the difference in NO_x production between an older and a newer car.

This appendix resumes the main differences between the 2019 **Skoda Scala** SCR-equipped and a 2014 **Audi A1** non equipped of a SCR in terms of NO_x emissions. The engine of the Audi is the *1.6 R4 16v TDI CR 55-85kW (EA189)* and it has been designed in 2010, while the engine of the Skoda is the *1.6 R4 16v TDI CR 55-88kW (EA288)* and it has been designed in 2019.

This test with the Audi was also an opportunity to test the decision tree developed in SECTION 2.3 a second time. The driving behaviour desired by the driver (normal driving) was indeed obtained after running through the criteria tree. The analysis of the accelerometer data can be seen in FIGURES B.2, B.3, B.4 and B.5.

Several points should be noted to better understand this comparison:

- The WLTP cycle performed with the Audi A1 is the same as the one performed with the Skoda Scala in Woluwe, see SECTION 2.2.2
- The driving style was similar, the objective was to have an objective comparison in a normal, ordinary driving. The decision tree effectively recognised this driving style.
- The engine of both cars is similar. Indeed, it is the 1.6 TDI engine of the

Volkswagen Group. The difference between the two is that one was designed in 2010 and the other in 2019.

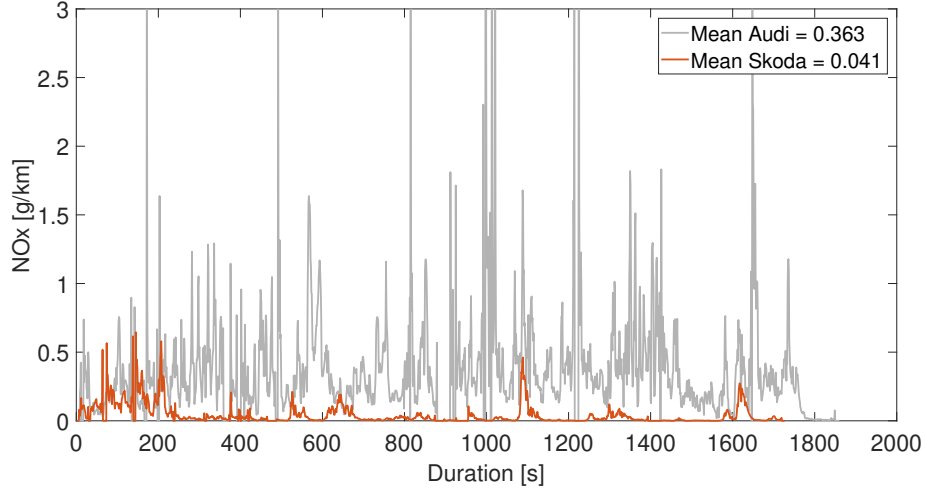


Figure B.1: Comparison of the NO_x emissions between an Audi A1 made in 2014 and a Skoda Skala made in 2019 on a normal RDE cycle. The Skoda emits on average 0.041 $[g/km]$, while the Audi emits on average 0.363 $[g/km]$.

FIGURE B.1 shows the difference between the NO_x emitted by the Audi and those emitted by the Skoda. The difference is noticeable visually, but especially when comparing the averages. Indeed, on the same route with the same driver and the same driving style, an older diesel car (2014) without SCR emits on average about 9 times more NO_x than a new WLTP approved car from 2019 equipped with a SCR.

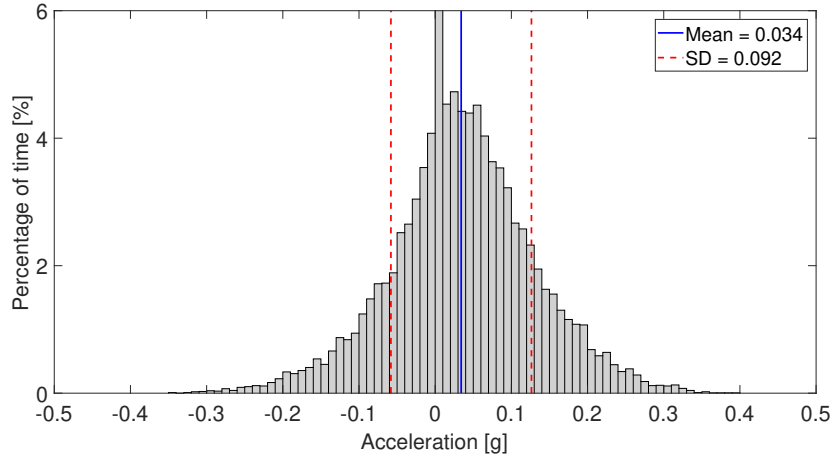


Figure B.2: Histogram of the rectified acceleration when driving a normal RDE cycle with the Audi A1.

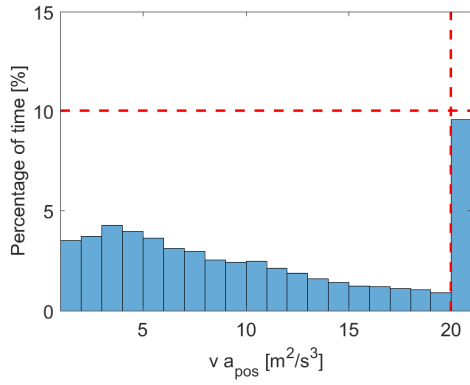


Figure B.3: Histogram of $v \cdot a_{pos} [m^2/s^3]$ when driving a normal RDE cycle with the Audi A1.

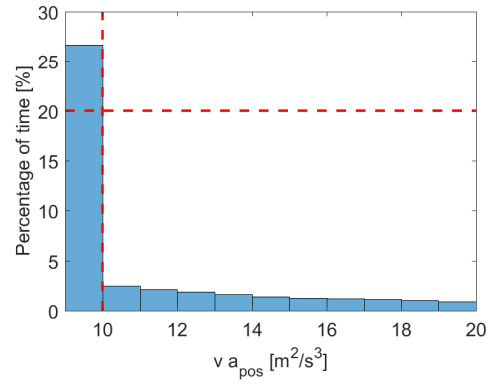


Figure B.4: Histogram of $v \cdot a_{pos} [m^2/s^3]$ when driving a normal RDE cycle with the Audi A1.

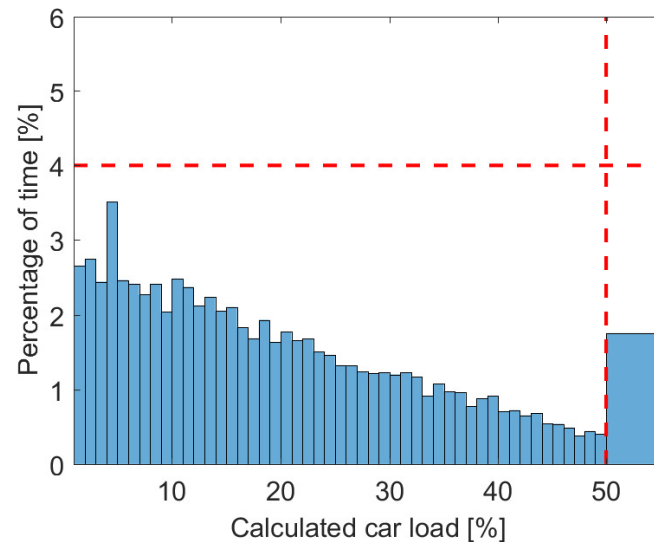


Figure B.5: Histogram of the calculated car load [%] when driving a normal RDE cycle with the Audi A1.

Appendix C

Accelerometer: complementary information

Thanks to the accelerometer we were able to deduce driving behaviour. We tried to push this analysis well beyond the vehicle's acceleration.

More precisely, we have tried to determine the following parameters with varying degrees of success using the accelerometer. To do a deeper analysis, we filmed all our journeys (see FIGURE C.4). Note that some parameters were determined but not used in this thesis:

- Gear shifts. During a gear shift, there is a sudden decrease in acceleration during the time of the shift. The speed of the gear change on a car equipped with a manual gearbox would add a criterion for determining the driver's driving behaviour. It can be seen in FIGURE C.1 this gear change. This gear change was particularly aggressive, that is why it is possible to see it. However, most of the time, the gear change is not visible with the accelerometer.
- Road quality. This will influence fuel consumption and pollutant production. In addition, very poor quality roads such as cobbled roads generate a very noisy signal that needs to be recognised to avoid misinterpretation. Finally, the presence of speed breaks generates accelerometer signal bursts that can be assimilated to sudden braking or acceleration. Being able to recognise any road features would help refine the signal received from the accelerometer and make the interpretation of the latter more accurate.
- Driver cornering behaviour. For this purpose, we carried out an analysis of the acceleration along the X axis. It was possible to recognise the passage through roundabouts or the aggressiveness of the driver in bends. This X-acceleration analysis did not add any value to the analysis of driver behaviour.

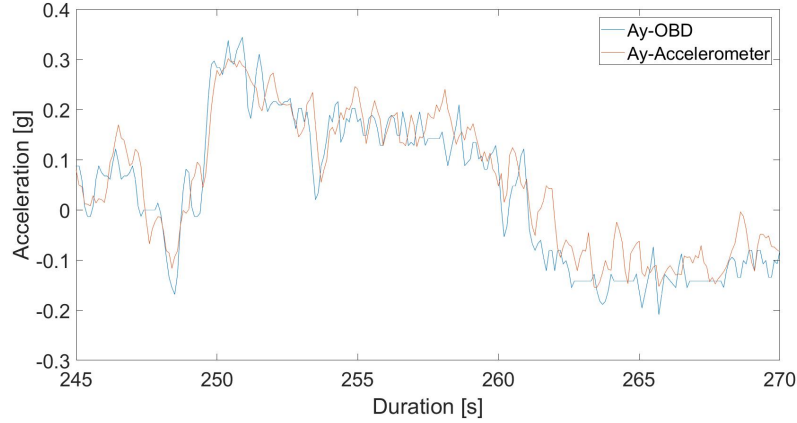


Figure C.1: Comparison between the acceleration obtain with the derivative of the speed and the acceleration obtain with the datalogger. At 254 seconds, we can observe the gear change.

- Emergency situations. One parameter that seemed interesting to analyse was the behaviour of the accelerometer in extreme situations. We therefore tried to characterise heavy braking. This is impossible with the accelerometer of the dataloggers (FIGURE C.2).

The reason why these parameters could not be determined is mainly due to the low quality of the accelerometer. Indeed, the accelerometer sends back a very noisy signal that needs to be filtered to deduce behaviours. Filtering the signal results in a loss of information, but the datalogger is not accurate enough to afford not to filter it. Secondly, this datalogger is not suitable for the purpose for which it is intended. Its measurement range is limited to 1 [g] in each of the 3 dimensions. This means that if the OBD socket is perfectly horizontal or vertical (this is the case for 2 out of 8 cars tested), the datalogger considers all the data according to Z or Y as outliers, causing many problems in the calculation of rectifying and acceleration. It was the case for the Skoda Scala, see FIGURE C.3, which obliged us to buy an extension cable for the OBD plug and to stick the accelerometer to the dashboard. Sticking the accelerometer to the dashboard allows to divide the gravitational acceleration according to the X side and the Z side of the datalogger. this avoids the appearance of outliers.

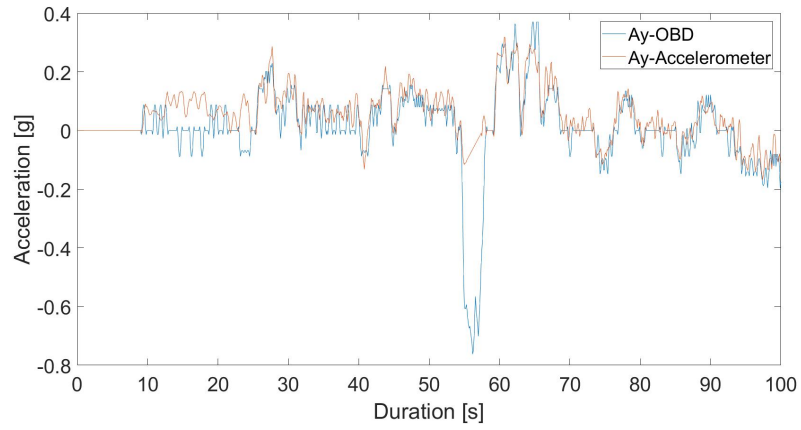


Figure C.2: Comparison between the acceleration obtain with the derivative of the speed and the acceleration obtain with the datalogger. At 53 seconds, we can observe the emergency braking. The accelerometer consider it as an outlier.



Figure C.3: Position of the datalogger in the Skoda Scala.



Figure C.4: Position of the GoPro and example of images filmed by it.

Appendix D

Complementary information about the different cycles

Complementary information about the first campaign of test: four RDE tests performed with different driving behaviours

WLTP Aggressive driving	Low	Medium	High	Extra High	Total
Duration [s]	454.4	443.8	505.4	299.0	1702.6
Stop duration [s]	76.7	65.6	57.3	6.7	206.3
Distance [m]	3100.0	4800.0	7400.0	7600.0	22900.0
% of stops	16.9	14.8	11.3	2.2	
Maximum speed [km/h]	61.0	88.0	102.0	130.0	
Average speed without stops [km/h]	27.55	45.71	64.21	99.6	
Average speed with stops [km/h]	23.44	39.09	57.15	97.73 ,	

Table D.1: **Agressive** RDE cycle

WLTP ECO	Low	Medium	High	Extra High	Total
Duration [s]	364.8	425.9	468.7	318.5	1577.9
Stop duration [s]	60.4	25.0	27.5	8.1	121.0
Distance [m]	3100.0	4800.0	7400.0	7600.0	22900.0
% of stops	16.6	5.9	5.9	2.5	
Maximum speed [km/h]	57.0	70.0	96.0	127.0	
Average speed without stops [km/h]	32.87	43.14	60.77	93.81	
Average speed with stops [km/h]	27.65	40.67	57.37	91.72	

Table D.2: **Eco** RDE cycle

WLTP Low engine speed Driver	Low	Medium	High	Extra High	Total
Duration [s]	341.2	457.8	537.4	350.4	1686.8
Stop duration [s]	19.8	28.6	63.2	7.5	119.1
Distance [m]	3100.0	4800.0	7400.0	7600.0	22900.0
% of stops	5.8	6.2	11.8	2.1	
Maximum speed [km/h]	58.0	77.0	97.0	128.0	
Average speed without stops [km/h]	29.22	39.73	55.77	77.61	
Average speed with stops [km/h]	28.05	37.52	50.14	76.24	

Table D.3: **Low engine speed** RDE cycle

Relative Error [%] Agressive Cycle	Low	Medium	High	Extra High
Duration [%]	22.9	2.5	11.1	7.4
Stop duration [%]	50.8	36.7	84.8	4.3
Maximum speed [%]	8	14.9	4.7	1
Average speed without stops [%]	7.2	2.7	5.6	6
Average speed with stops [%]	24.0	1.0	0.8	6.2

Table D.4: Relative Error [%] for the **agressive** RDE cycle.

Relative Error [%] Eco Cycle	Low	Medium	High	Extra High
Duration [%]	38.1	1.6	3	1.4
Stop duration [%]	61.3	47.9	11.3	15.7
Maximum speed [%]	0.9	8.6	1.4	3.3
Average speed without stops [%]	27.9	3.1	0.0	0.2
Average speed with stops [%]	46.3	3.0	1.2	0.3

Table D.5: Relative Error [%] for the **eco** RDE cycle.

Relative Error [%] Low engine speed cycle	Low	Medium	High	Extra High
Duration [%]	42.1	5.7	18.1	8.5
Stop duration [%]	87.3	40.4	103.9	7.1
Maximum speed [%]	2.7	0.5	0.4	2.5
Average speed without stops [%]	13.7	10.7	8.3	17.4
Average speed with stops [%]	48.4	5	11.6	17.1

Table D.6: Relative Error [%] for the **low speed engine** RDE cycle.

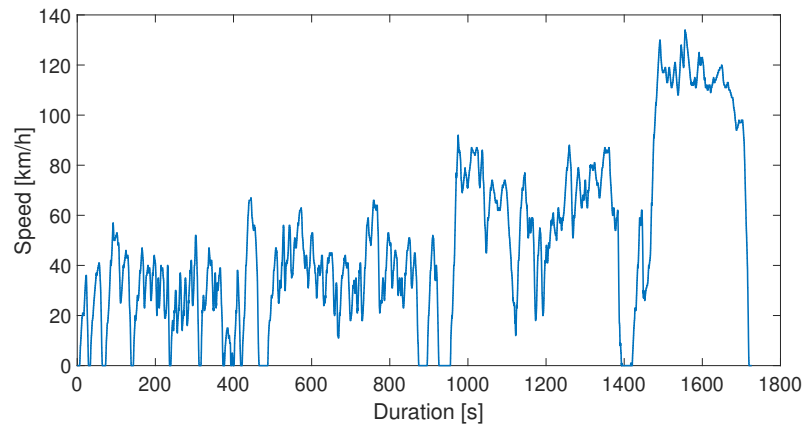


Figure D.1: Graph of the speed when driving an **ordinary** RDE cycle.

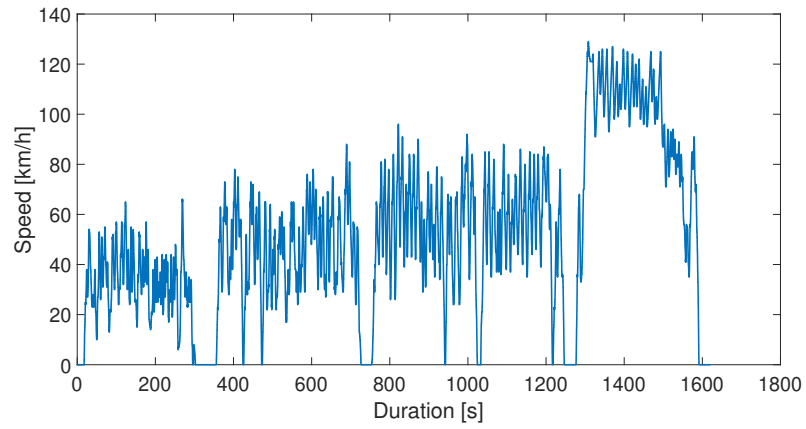


Figure D.2: Graph of the speed when driving an **aggressive** RDE cycle.

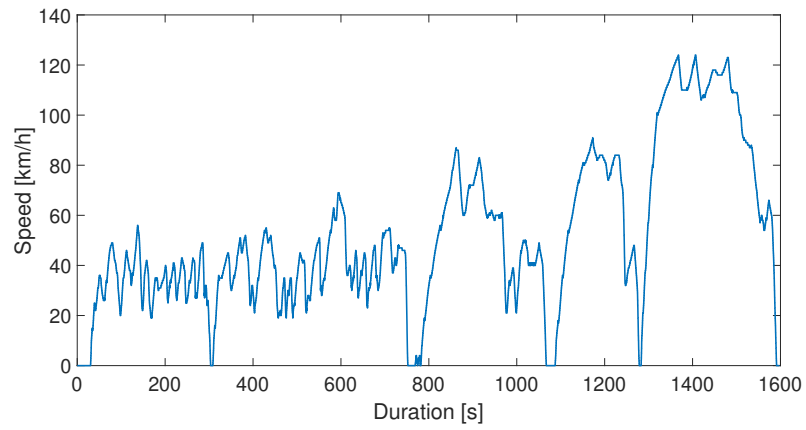


Figure D.3: Graph of the speed when when an **economic** RDE cycle.

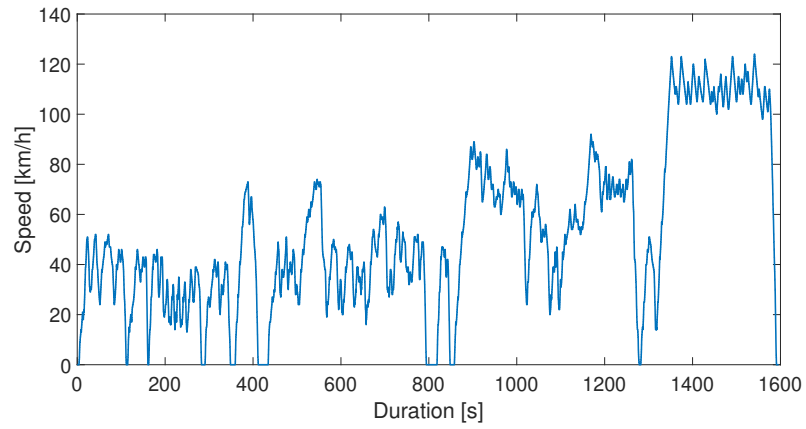


Figure D.4: Graph of the speed when driving a **low engine speed** RDE cycle.

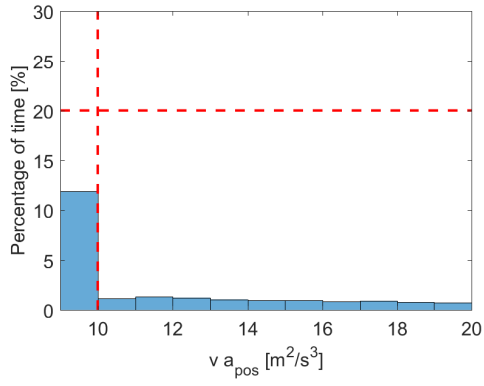


Figure D.5: Histogram of $v \cdot a_{pos} [m^2/s^3]$ when driving an **aggressive** RDE cycle.

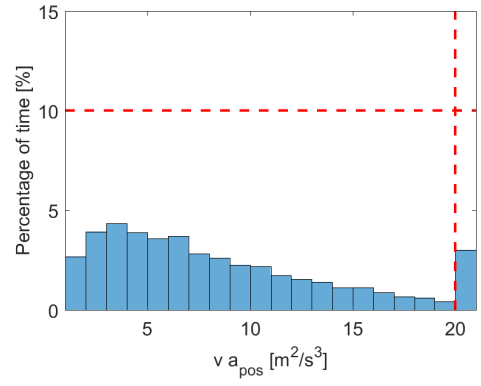


Figure D.6: Histogram of $v \cdot a_{pos} [m^2/s^3]$ when driving an **economic** RDE cycle.

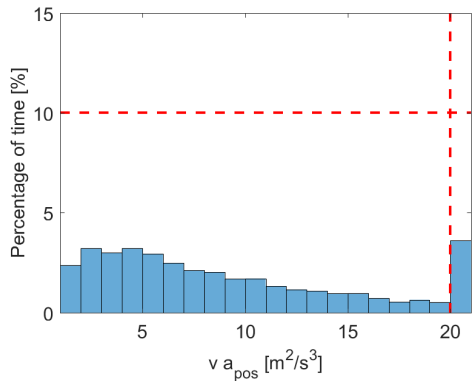
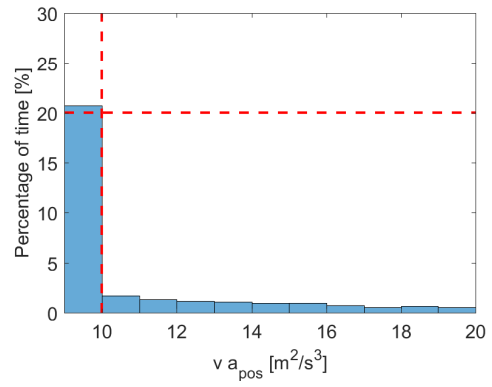


Figure D.7: Histogram of $v \cdot a_{pos} [m^2/s^3]$ when driving a **low engine speed** RDE cycle.



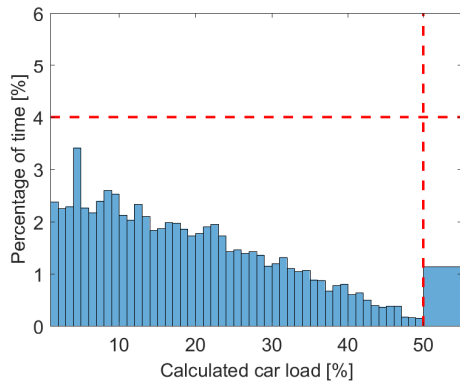


Figure D.8: Histogram of the calculated car load [%] when driving an **aggressive** RDE cycle.

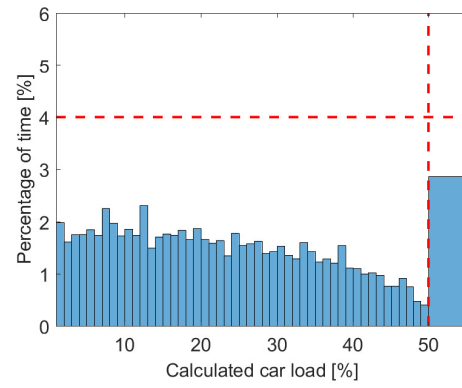


Figure D.9: Histogram of the calculated car load [%] when driving an **economic** RDE cycle.

Complementary information about the second campaign of test: four WLTP B-cycles performed with different driving behaviours

WLTP Ordinary B	Low	Medium	High	Extra High	Total
Duration [s]	376.1	577.3	439.4	332.9	1725.7
Stop duration [s]	41.9	87.3	2.4	35.0	166.0
Distance [m]	3100	4800	7400	7600	22900
% of stops	11.1	15.1	0.5	10.5	
Maximum speed [km/h]	57.0	67.0	92.0	134.0	
Average speed without stops [km/h]	29.71	36.73	62.36	97.05	
Average speed with stops [km/h]	26.86	31.54	62.13	87.36	

Table D.7: **Ordinary** B-cycle.

WLTP Agressive driving B	Low	Medium	High	Extra High	Total
Duration [s]	308.9	429.8	508.9	372.7	1620.3
Stop duration [s]	27.5	64.9	31.4	58.6	182.4
Distance [m]	3100	4800	7400	7600	22900
% of stops	8.9	15.1	6.2	15.7	
Maximum speed [km/h]	66.0	88.0	96.0	129.0	
Average speed without stops [km/h]	32.92	46.37	55.83	94.48	
Average speed with stops [km/h]	30.17	39.54	52.76	79.75	

Table D.8: **Agressive** B-cycle

WLTP Eco B	Low	Medium	High	Extra High	Total
Duration [s]	305.0	449.6	527.4	315.1	1597.1
Stop duration [s]	33.0	7.1	47.9	7.8	95.8
Distance [m]	3100	4800	7400	7600	22900
% of stops	10.8	1.6	9.1	2.5	
Maximum speed [km/h]	56.0	69.0	91.0	124	
Average speed without stops [km/h]	33.91	39.81	55.41	94.94	
Average speed with stops [km/h]	30.36	39.26	51.13	92.8	

Table D.9: **Economic B-cycle**

WLTP low engine speed Driver B	Low	Medium	High	Extra High	Total
Duration [s]	358.4	457.5	464.3	315.0	1595.2
Stop duration [s]	30.7	46.9	16.3	7.3	101.2
Distance [m]	3100	4800	7400	7600	22900
% of stops	8.6	10.3	3.5	2.3	
Maximum speed [km/h]	52.0	74.0	92.0	124	
Average speed without stops [km/h]	31.18	42.03	59.85	94.47	
Average speed with stops [km/h]	28.83	37.84	58.01	92.62	

Table D.10: **Low speed engine B-cycle**

Relative Error [%] Ordinary Cycle	Low	Medium	High	Extra High
Duration [%]	36.1	33.3	3.4	3.1
Stop duration [%]	73.1	81.9	92.3	400
Maximum speed [%]	0.9	12.5	5.5	2.1
Average speed without stops [%]	15.6	17.5	2.6	3.2
Average speed with stops [%]	42.0	20.2	9.6	5.0

Table D.11: Relative Error [%] for the **ordinary** B-cycle

Relative Error [%] Aggressive Cycle	Low	Medium	High	Extra High
Duration [%]	46.7	0.7	11.8	15.4
Stop duration [%]	82.4	35.2	1.3	737.1
Maximum speed [%]	16.8	14.9	1.4	1.8
Average speed without stops [%]	28.1	4.2	8.2	0.5
Average speed with stops [%]	59.6	0.1	6.9	13.3

Table D.12: Relative Error [%] for the **aggressive** B-cycle

Relative Error [%] Eco Cycle	Low	Medium	High	Extra High
Duration [%]	48.2	3.8	15.9	2.4
Stop duration [%]	78.8	85.2	54.5	11.4
Maximum speed [%]	0.9	9.9	6.6	5.6
Average speed without stops [%]	31.9	10.5	8.9	1.0
Average speed with stops [%]	60.6	0.6	9.8	0.9

Table D.13: Relative Error [%] for the **Economic** B-cycle

Relative Error [%] Low engine speed Cycle	Low	Medium	High	Extra High
Duration [%]	39.2	5.7	2.0	2.5
Stop duration [%]	80.3	2.3	47.4	4.3
Maximum speed [%]	8.0	3.4	5.5	5.6
Average speed without stops [%]	21.3	5.6	1.6	0.6
Average speed with stops [%]	52.5	4.2	2.3	0.7

Table D.14: Relative Error [%] for the **low engine speed** B-cycle

Histograms of B-cycles

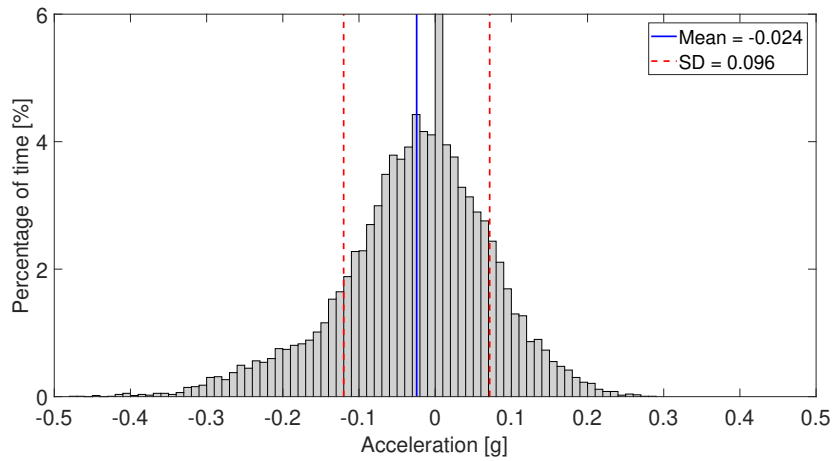


Figure D.10: Histogram of the rectified acceleration when driving an ordinary RDE cycle.

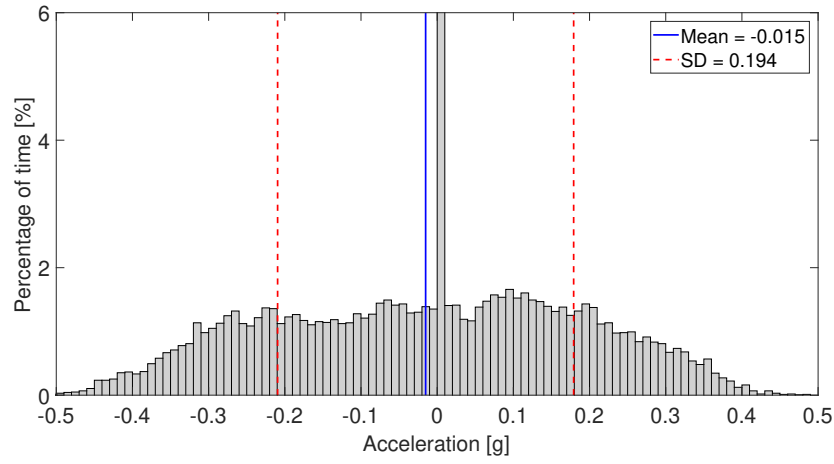


Figure D.11: Histogram of the rectified acceleration when driving an aggressive RDE cycle.

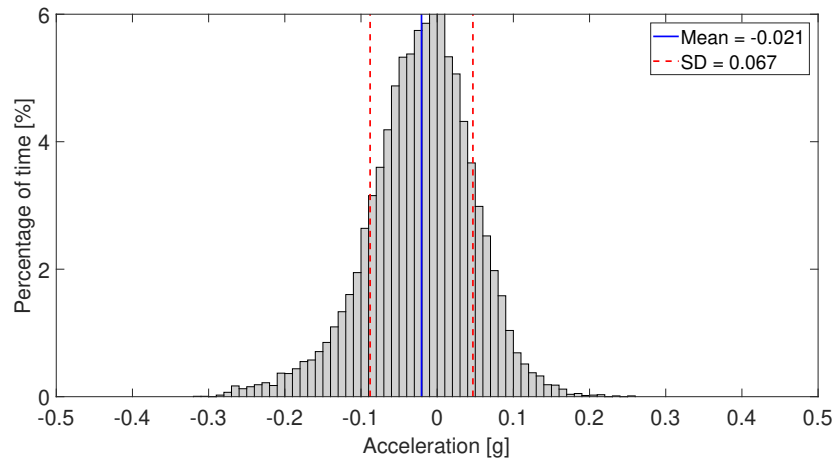


Figure D.12: Histogram of the rectified acceleration when driving an economic RDE cycle.

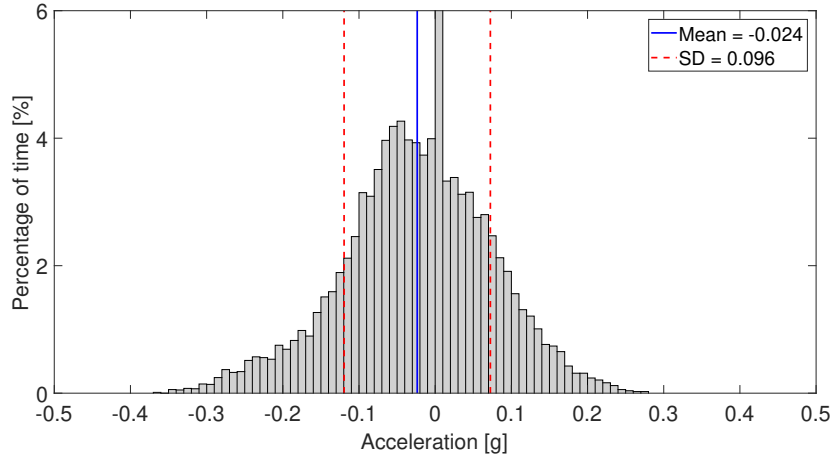


Figure D.13: Histogram of the rectified acceleration when driving a low engine speed RDE cycle.

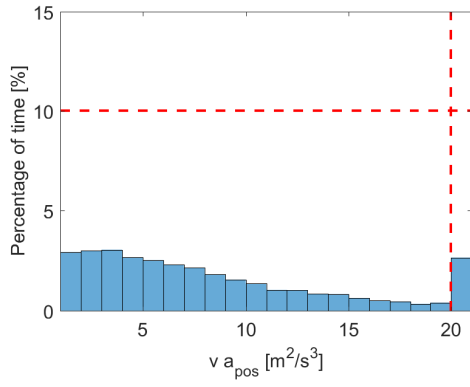


Figure D.14: Histogram of $v \cdot a_{pos}$ [m^2/s^3] when driving a RDE cycle normally.

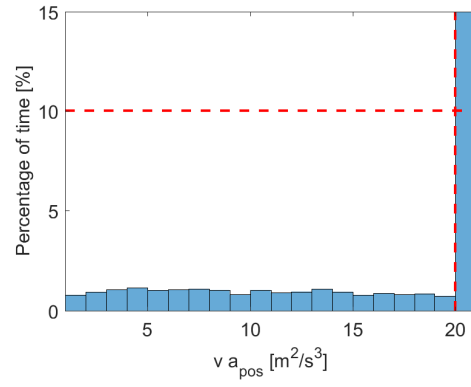


Figure D.15: Histogram of $v \cdot a_{pos}$ [m^2/s^3] when driving a RDE cycle aggressively.

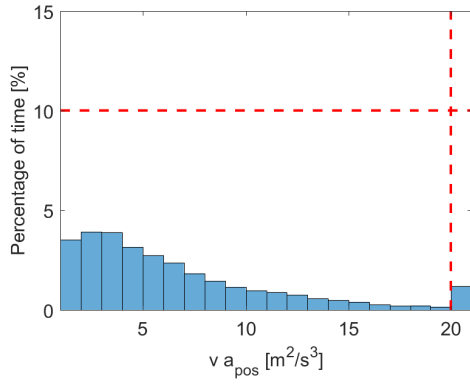


Figure D.16: Histogram of $v \cdot a_{pos}$ [m^2/s^3] when driving an economic RDE cycle.

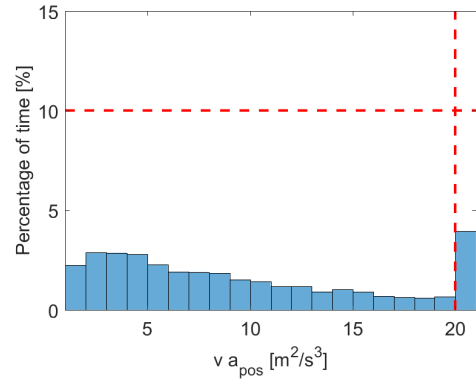


Figure D.17: Histogram of $v \cdot a_{pos}$ [m^2/s^3] when driving a low engine speed RDE cycle.

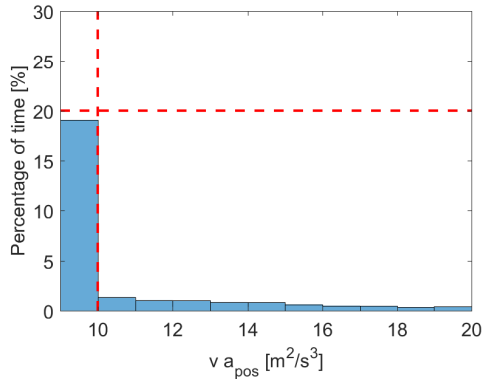


Figure D.18: Histogram of $v \cdot a_{pos}$ [m^2/s^3] when driving a RDE cycle normally.

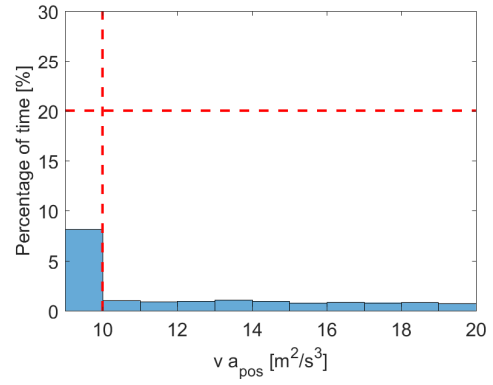


Figure D.19: Histogram of $v \cdot a_{pos}$ [m^2/s^3] when driving a RDE cycle aggressively.

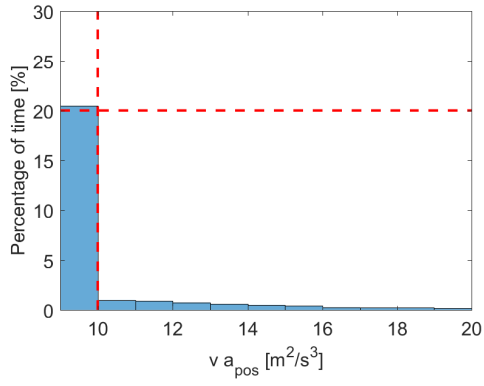


Figure D.20: Histogram of $v \cdot a_{pos}$ [m^2/s^3] when driving an economic RDE cycle.

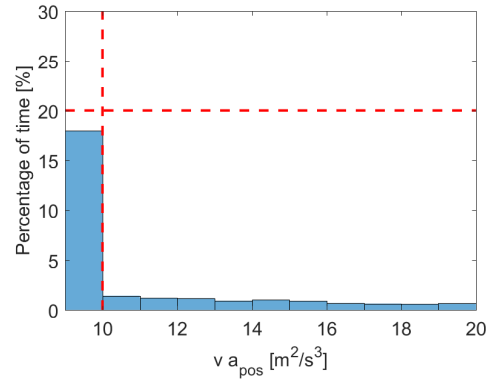


Figure D.21: Histogram of $v \cdot a_{pos}$ [m^2/s^3] when driving a low engine speed RDE cycle.

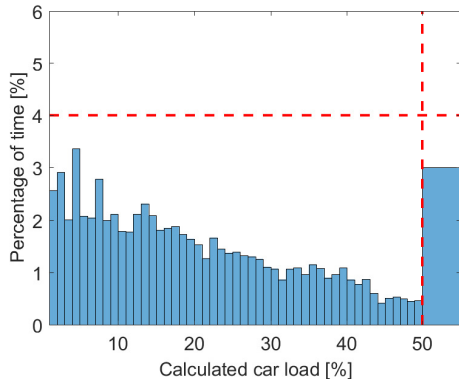


Figure D.22: Histogram of the calculated car load [%] when driving a RDE cycle normally.

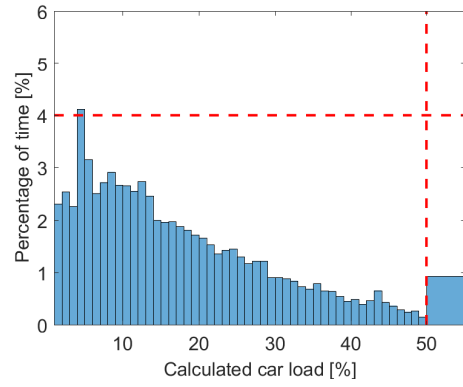


Figure D.23: Histogram of the calculated car load [%] when driving a RDE cycle aggressively.

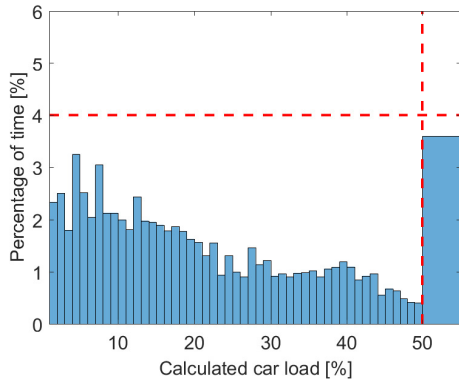


Figure D.24: Histogram of the calculated car load [%] when driving an economic RDE cycle.

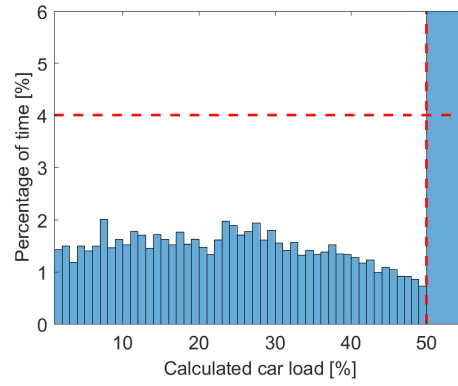


Figure D.25: Histogram of the calculated car load [%] when driving a low engine speed RDE cycle.

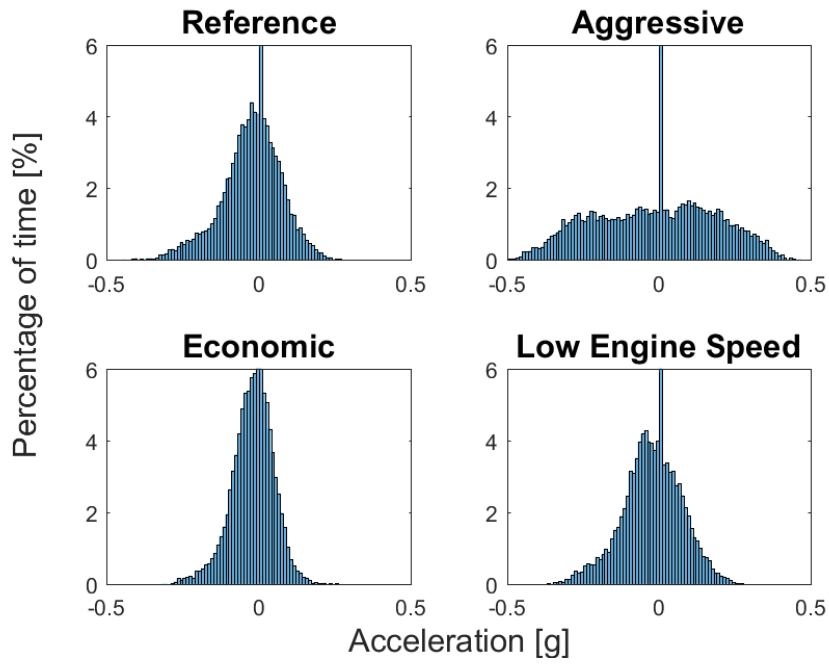


Figure D.26: Histograms of the rectified accelerations from the accelerometer for the four cycle where the NO_x production where measured.

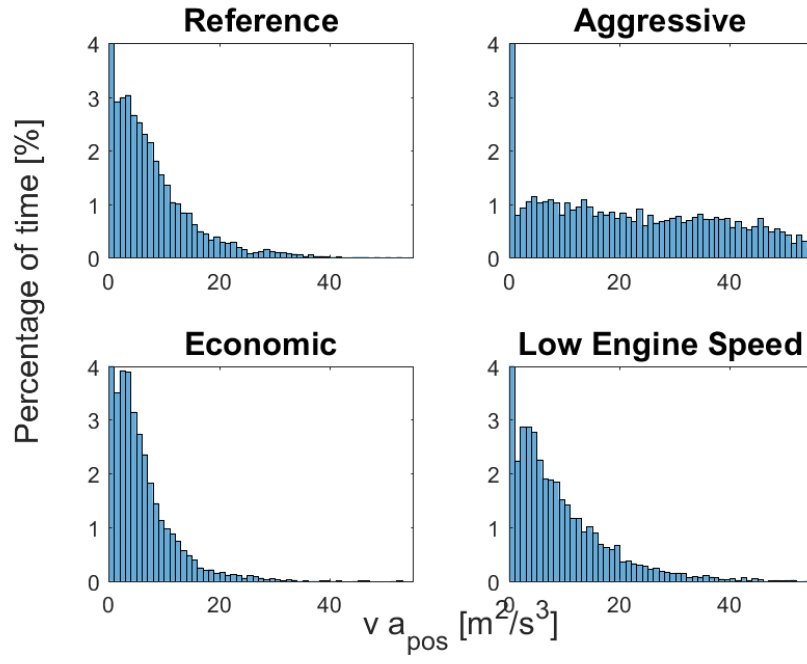


Figure D.27: Histograms of the calculated $v \cdot a_{pos}$ [m²/s³] for the four cycle where the NO_x production where measured.

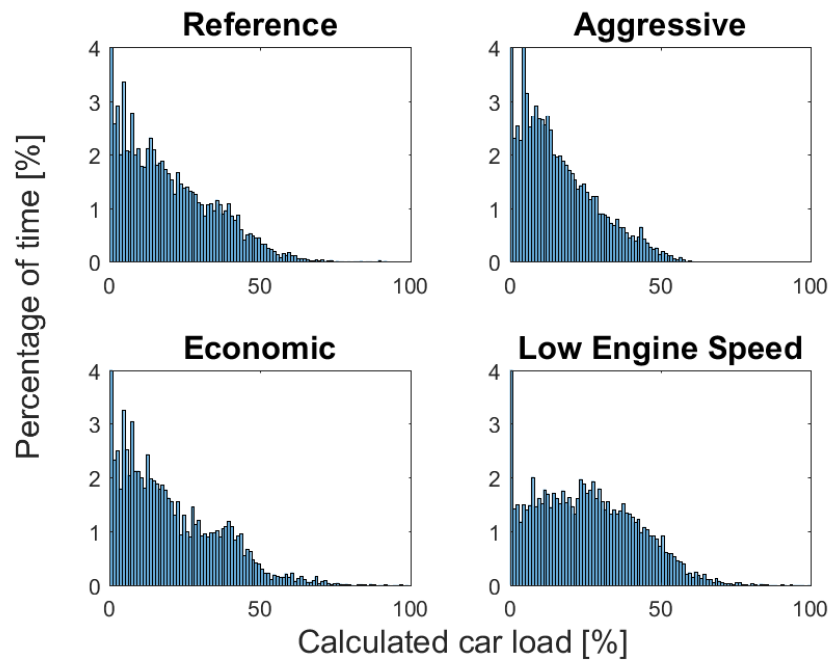


Figure D.28: Histograms of the calculated car load [%] for the four cycle where the NO_x production where measured.

Appendix E

Finding the excess-air coefficient λ

Determination of λ from Arduino

In order to obtain λ , multiple solutions have been explored. The first one, was to use the datalogger developed by the team of Prof. Contino. This datalogger works with an Arduino environment allowing a relatively simple handling. However, the possible modifications are limited and prevents us from obtaining the data necessary to obtain λ . The two main problems are :

- 98% of the memory of the Arduino is used, which means that any addition of lines of code must be compensated by a removal of other lines. In practice, it is therefore only possible to take 4 different information of data from the OBD socket at the same time, knowing that 3 of these 4 information of data are essential to determine the driver's behaviour.
- The datalogger only has access to a limited part of the information available on the OBD socket. Unfortunately, the code was developed by Ms. Liu (who is unfortunately no longer at UCLouvain) and it is difficult to modify it to access more different data.

We were therefore unable to extract sufficient data to infer λ with the Datalogger.

As this solution was not possible due to the problems mentioned above, we tried to obtain λ using an Arduino Mega. The advantage of the latter is that it is much more powerful than the datalogger and has a much larger memory. It is more adapted than the datalogger for our use. Indeed, the datalogger was developed with a view to being placed on a large number of cars without disturbing the driver. In our case, we were monitoring all the parameters during our experiments and the

larger space occupied by the Arduino Mega assembly was not a problem. With the latter we had access to all the parameters made available by the manufacturers and we could read many more parameters at the same time. The list of parameters is available on this page https://en.wikipedia.org/wiki/OBD-II_PIDs. The only problem with this setup is that the manufacturers only make a certain amount of information available and that this available information varies from manufacturer to manufacturer.

We have created several codes to facilitate the use of the Arduino and the taking of data via the OBD socket. To use the Arduino Mega to its full potential, you must :

- upload the "PID_Detector" code to the Arduino Mega. This code will return a code of numbers and letters on the Arduino PC console.
- Copy the code displayed on the console and paste it into the MatLab function "PID_Convertor". This function will return a list of all the parameters made available by the car. This saves a lot of time and avoids trial and errors.
- Go to the page "https://en.wikipedia.org/wiki/OBD-II_PIDs", take the addresses corresponding to the data you want to monitor
- Write down the addresses of the desired data in line 27 of the Arduino code "LR_All" and modify the name corresponding to line 29. The data will be written on an SD card. Be careful, these data must be post processed, they are written in hexadecimal format and need to be converted.
- Change the date and time on line 143 of the Arduino code "LR_All" (optional)
- Put clean SD card in the reader
- Connect the OBD plug to the car
- Upload the code to the Arduino (data collection will start at the end of the upload).
- Unplug the Arduino
- Read the .txt file on the SD card with a computer. The file has not been closed correctly, if the Arduino is reconnected it will not be able to write to the SD card.
- Post process the data using the MatLab code: "str_hex_2_dec"

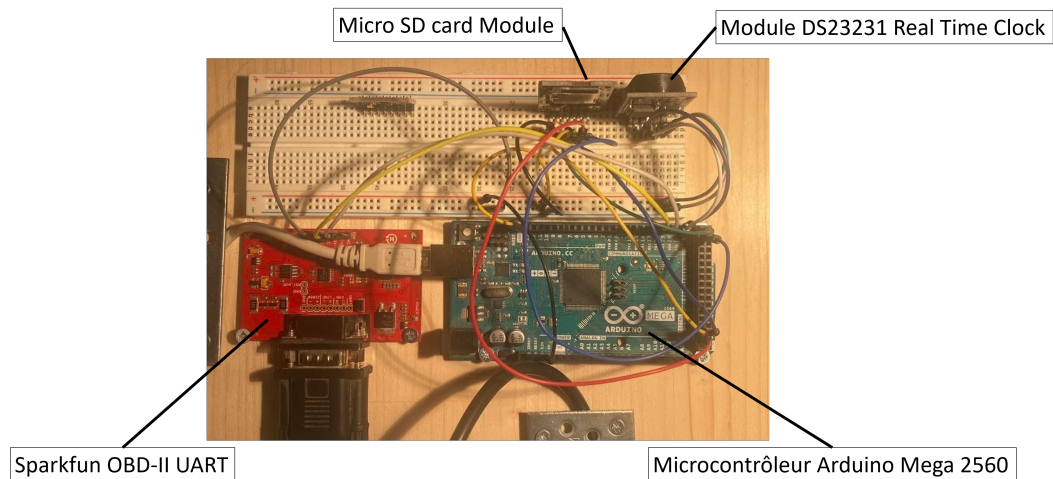


Figure E.1: Arduino Mega setup

Another way of obtaining the exhaust mass flow was to bubble. This consists of calculating the mass flow rate using a pipe and a basin of water. A pipe is attached to the exhaust outlet and dipped into a basin of water. A bucket of known volume is taken and filled with water and returned. Place the hose at the base of the bucket, switch on the engine and calculate the time it takes for the bucket to empty. The volume per unit time is then obtained and the exhaust mass flow rate can be deduced. The problem is that the mass flow rate can only be calculated for constant, point-in-time speeds. It is not possible to calculate the mass flow precisely along a route with permanent speed variations, so this solution was discarded. 2 pictures of the assembly are shown below.

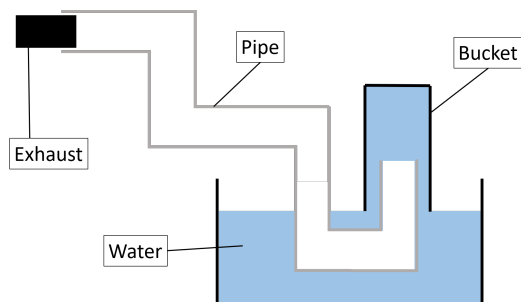


Figure E.2: Experiment at time 0

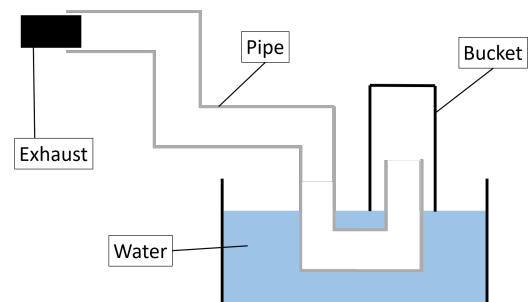
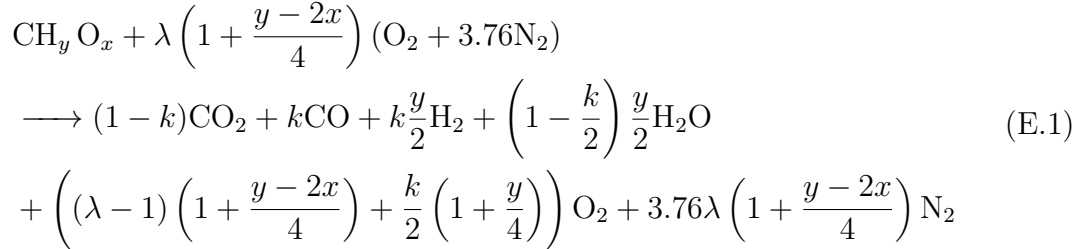


Figure E.3: Experiment at time t

Determination of λ from Testo

An other attempt was made to obtain λ only using the exhaust gas analyser.

A generic fuel CH_yO_x has the following stoichiometry of combustion¹:



with $\lambda [-]$ the excess-air coefficient and $k [-]$ the coefficient of unburned species. In equation E.1, the quantity $4.76\left(1 + \frac{y-2x}{4}\right)$ is the stoichiometric air-fuel ratio AF_{st} . The coefficient of unburned species is defined as:

$$k = \frac{[\text{CO}]}{[\text{CO}] + [\text{CO}_2]} [-] \quad (\text{E.2})$$

The excess-air coefficient is defined as:

$$\lambda = \frac{[\text{O}_2] - \frac{1}{2}\left(1 + \frac{y}{4}\right)[\text{CO}]}{\left(1 + \frac{y-2x}{4}\right)([\text{CO}_2] + [\text{CO}])} + 1 [-] \quad (\text{E.3})$$

Knowing that $[\text{O}_2]$, $[\text{CO}_2]$ and $[\text{CO}]$ are measured continuously with the Testo, λ can theoretically be found. However, the λ found via this method is biased. Indeed, it oscillates between 2 and 50, which is completely aberrant and therefore invalidates this method for finding λ .

¹From the course MECA2160 - Combustion and Fuels.

Appendix F

Tables of the evolution of the EURO

Diesel	Date	CO	NMHC	NO _x	HC + NO _x	PM	PN
Euro 1	July 1992	2.72	–	–	0.97	0.14	–
Euro 2	January 1996	1.0	–	–	0.7	0.08	–
Euro 3	January 2000	0.64	–	0.50	0.56	0.05	–
Euro 4	January 2005	0.50	–	0.25	0.30	0.025	–
Euro 5a	September 2009	0.50	–	0.180	0.230	0.005	–
Euro 5b	September 2011	0.50	–	0.180	0.230	0.005	6.0×10^{11}
Euro 6	September 2014	0.50	–	0.080	0.170	0.005	6.0×10^{11}

Figure F.1: Emission limits [g/km] of the successively introduced Euro emission standards for **diesel** passenger vehicles

Petrol	Date	CO	NMHC	NO _x	HC + NO _x	PM	PN
Euro 1	July 1992	2.72	–	–	0.97	–	–
Euro 2	January 1996	2.2	–	–	0.5	–	–
Euro 3	January 2000	2.3	–	0.15	–	–	–
Euro 4	January 2005	1.0	–	0.08	–	–	–
Euro 5	September 2009	1.0	0.068	0.060	–	0.005	–
Euro 6	September 2014	1.0	0.068	0.060	–	0.005	6.0×10^{11}

Figure F.2: Emission limits [g/km] of the successively introduced Euro emission standards for **gasoline** passenger vehicles

Appendix G

Link to the Github

Here is a link to obtain further information about the codes and data obtained in the various experiments: https://github.com/lacave-guillaume/Master_Thesis_GLacave_GCorbisier.git.

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École polytechnique de Louvain

Rue Archimède, 1 bte L6.11.01, 1348 Louvain-la-Neuve, Belgique | www.uclouvain.be/epl