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Is the new Real Driving Emission methodology really representative of people’s driving behavior?

Study case of the driving patterns of the citizens from Brussels

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Abstract

Car trips are part of everyday life for a lot of Belgians. Car fleet in Belgium represents 5.813 millions vehicle in 2019 and this transportation mode represents 74 percent of the distance travelled by Belgians in 2017.

Characterization of fuel economy and pollutants emissions has always been a challenge in order to compare ecological performances of cars. This is where standardized test cycles are making sense. These are realised in laboratory, like for WLTC or NEDC, or with random road trips following criteria like the RDE.

The RDE criteria specify conditions on speed, duration, distance, accelerations, temperatures etc. These criteria have been applied to 899 trips drove in Brussels in the frame of a master thesis last year. The aim was to find if RDE testing represents driving patterns in Brussels.

Out of the total samples of trips, all of them were too short in distance and/or duration. 30 percent were stopping too much, and 12 percent had too high or too low average speed. The conclusion was that while RDE represents driving behaviours in Brussels for acceleration and mean speed, its prescription on minimal distance is too long.

This conclusion arose a question: if RDE testing methodolology does not fit data from trips driven in Brussels, what is a typical car trip in Brussels?

The aim of this thesis is to compute a test cycle reproducing driving behaviours in Brussels. WLTP building methodology is used.

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Contents

Glossary

WLTP Worldwide Harmonised Light Vehicles Test Procedure

WLTC Worldwide Harmonised Light Vehicles Test Cycle

NEDC New European Driving Cycle

RDE Real Driving Emissions

PEMS Portable Emissions Measurement System

VED Vehicle Energy Demand

UNECE United Nations Economic Commission for Europe

GRPE Working Party on Pollution and Energy

EU European Union

NMHC Non-Methane Hydrocarbons

THC Total Hydrocarbon Pollutants

PN Peroxyacyl Nitrates

RPA Relative Positive Acceleration

Chapter 1

Introduction

Car trips are part of everyday life for a lot of Belgians. Car fleet in Belgium represents 5.813 millions vehicle in 2019 [4] and this transportation mode represents 74 percent of the distance travelled by Belgians in 2017 [10].

Characterization of fuel economy and pollutants emissions has always been a challenge in order to compare ecological performances of cars. This is where standardized test cycles are making sense. These are realised in laboratory, like for WLTC [1] or NEDC [7], or with random road trips following criteria like the RDE [3].

The NEDC test cycle has been defined in europa since 1973 [3] and represents driving patterns of this time era. The test consists in the following of a speed versus time curve on a road or, for more repeatably, on a test bench simulating mass (inertia) and resistance forces on the car.

This test cycle is however less and less representative of today's driving behaviour. The difference between real life CO_2 emissions and those measured following NEDC for the average European car is estimated in the order of 27 percent [7]. One of the reason for this difference is cycle beating techniques. They have been developed by car manufacturers to use deviation tolerances on the cycle to their advantage [6]. Also, the scandal following the discovery of defeat devices in Volkswagen diesel powered cars [8] that detected if the car was in a test cycle and adapted engine parameters urged the need for a new testing procedure.

Taking NEDC shortcomings into account, a new test cycle called WLTP had to be developed. This would create a more accurate representation of exhaust emissions and fuel economy compared to real driving situations by gathering real driving patterns and use it to create a cycle mimicking those patterns in Brussels.

In Europe, WLTP testing is accompanied with a Real Driving Emission test validating parameters measured in lab. It consists of trips drove in real life while measuring fuel consumption and pollutants rejections. Criteria of validity are prescribed in order to standardize the RDE test.

RDE criteria specify conditions on speed, duration, distance, accelerations, temperatures etc. These criteria have been applied to 899 trips drove in Brussels in the frame of a master thesis last year [9]. The aim was to find if RDE testing represents driving patterns in Brussels.

Out of the total samples of trips, all of them were too short in distance and/or duration. 30 percent were stopping too much, and 12 percent had too high or too low average speed. The conclusion was that while RDE represents driving behaviours in Brussels for acceleration and mean speed, its prescription on minimal distance is too long.

This conclusion arose a question: if RDE testing methodolology does not fit data from trips driven in Brussels, what is a typical car trip in Brussels?

The aim of this thesis is to compute a test cycle reproducing driving behaviour in Brussels. WLTP building methodology will be used and is explained in chapter 2. Also, a comparison between this new test and the old NEDC on the energetic point of view is presented. Various indicators are explained and defined in accord to scientific literature.

Chapter 3 details how data from drivers riding in Brussels has been recorded. It will also be explained how WLTP building methodology has been applied for this master thesis and how adaptations have been taken. A first version of the cycle representing Brussels driving behaviour, called target cycle, is presented.

Chapter four presents the results. Comparisons between target cycle and database are conducted. RDE criteria are applied at target cycle. Then, vehicle energy demand for the target cycle is compared to WLTC.

In chapter 5 are presented statistical tests applied on data used in this master thesis. These tests compare data harvested in 2019 versus the one recorded in 2020.

Chapter 6 presents a conclusion of this master thesis and possible follow-ups on the topic.

Chapter 2

State of the art

This section will lay the groundwork for the following chapters, both for parameters, indicators and procedures.

The WLTP, and particularly its building methodology is detailed for further use in this master thesis. This will enable us to compose a new test cycle called target cycle reproducing driving behaviour in Brussels. Then a comparison will be presented between NEDC and WLTP. This will later be used to compare energy demands of the target cycle versus WLTP.

RDE procedures, parameters and definitions are presented in order to later be applied at target cycle.

Fnally, a section defining all the parameters used is this thesis will explain how and under which conditions they are computed.

2.1 The world harmonized light-duty vehicles test procedure

The world harmonized light-duty vehicles test procedure, or WLTP, is a procedure for establishing and approving fuel consumption and pollutants rejection levels for a light duty car . It was initially released in 2015. It is used in europe, India, South Korea and Japan. In europe this procedure is defined by a UNECE regulation [17] applied in EU comission regulation (EU) 2018/1832 [1]. This regulation defines how the test procedure needs to be done, in which kind of conditions, and defines the speed versus time curve to follow.

This test cycle is conducted on a rolling bench. The car is strapped to the ground via anchor points and its wheels sit on a chassis dynamometer. Fuel consumption and pollutants rejection are measured. Moreover, CO, CO_2, NO_x, THC, PN,CH_4, $NMHC$ are measured at the exhaust of the car via gas flow meters and analyzers.

WLTP replaces NEDC testing in europe, considered not accurate enough to give good approximation of fuel consumption and exhaust gases [7]. It is complemented with a RDE test, which is a test realised on road, to complement the data obtained from WLTP procedure.

Three types of speed versus time curve exists for this procedure. These are called WLTC or Worldwide harmonized Light duty driving Test Cycle. The type of curve applied for the testing of a car depends on power to weight ratio (PWr [W/kg]):

$$PWr = \frac{P_{car}}{W_{car}} \tag{2.1}$$

with:

- P_{car} : power [kW] of the car tested.
- W_{car} : weight [Ton] of the car tested.

There are 3 classes of PWr :

- Class 1 : $PWr \leq 22$
- Class 2 : $22 < PWr \leq 34$
- Class 3 : $PWr > 34$

It is worth noting that most common cars are included in PWr class 3, as class 1 and 2 corresponds to under-powered cars or heavy passenger vehicles like buses and vans.

Fig. 2.1 represents the speed versus time curve for a class 3 car. There are 4 speed categories : low and middle represents mostly city driving while high represents extra-urban behaviour and extra high is for a speedway pattern.

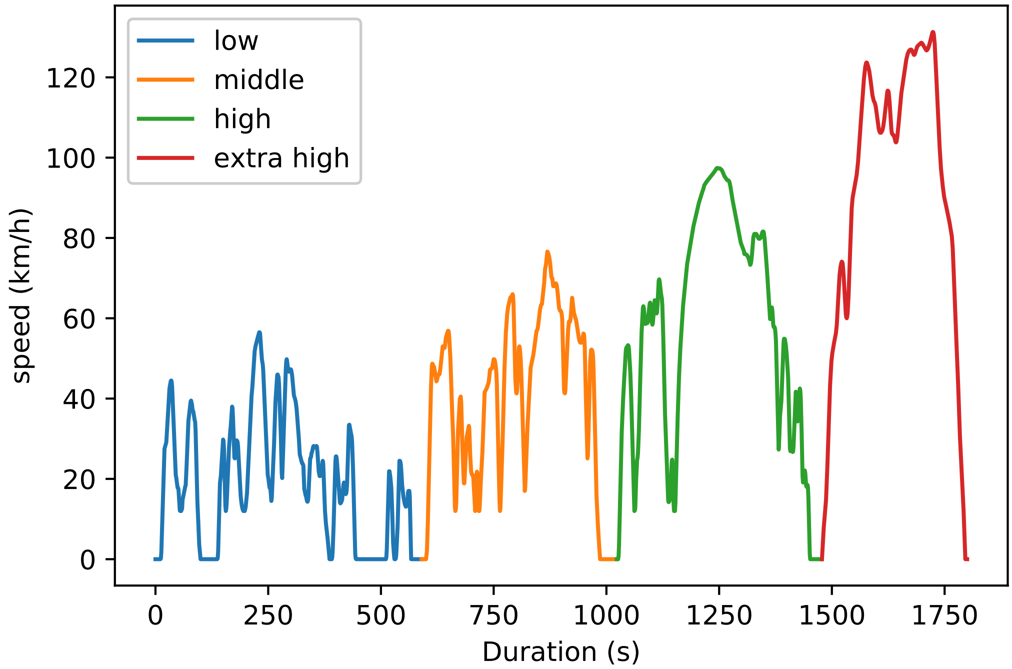

Figure 2.1: WLTC for class 3 vehicles

2.1.1 Building process

The methodology for building WLTC [16] is the basis for our computation of the target cycle representing the driving patterns in Brussels. Of course, some adaptations have been decided as, for example the region of interest is Brussels compared to the WTLC one which is worldwide.

WLTC has been developed under the the Working Party on Pollution and Energy (GRPE) and is sponsored by the European Union and Japan. USA, India and South Korea also contributed [16]. The objective is to capture real-world driving patterns into a 1800 [s] test-drive cycle.

760 000 [km] of data has been recorded into countries taking part of the building process. This data has been both recorded by dataloggers on a car and via a chasing car recording parameters of random cars in traffic.

Regional weighting factor has been used to balance data harvested by the number of total traffic hours per region.

Data has been filtered and resampled to 1 [Hz], in order to cancel noise due to high frequency oscillations and have an homogeneous data set. Two databases have been created, one for short trips and one for idling durations. Definitions of these speed signal portions are described in section 2.3.6 and 2.3.7. Exclusions criterias have been imposed to avoid outliers pollution.

These criteria are:

- idling periods with duration more than 10 [min]
- short trips with duration less than 10 [s]
- short trips with maximum speed lower than 3.6 [km/h]
- short trips with accelerations higher than 4 [m/s^2] or smaller than -4.5 [m/s^2]

The aim of this study is to find the best combination of short trips representing speed-acceleration distributions of the whole dataset of recorded dirving patterns. The result is a speed versus time curve (fig. 2.1).

More details on the methodology followed in this master thesis are explained in chapter 3 .

2.1.2 Effects on energy demands

As WTLP methodology replaces the old NEDC testing method, influence of this change on energy demand is studied in paper [11].

A panel of 31 cars in which 20 are gasoline powered and 11 diesel powered, has been studied. These cars are chosen to represent European car market in terms of size, mass, category, power and emission class. They are tested on a rolling bench while following the speed-time curve of WLTP and NEDC.

To compute Road loads to apply on the car which is tested on a rolling bench, the general equation of road load determination is applied:

$$P_i = (F_0 + F_1 * v_i + F_2 * v_i^2 + m * a_i) * v_i \tag{2.2}$$

where :

- P_i : Power required $[W]$ at time i.
- v_i : Speed $[km/h]$ at sample i.
- a_i : acceleration $[m/s^2]$ at sample i.
- F_0 : Road load coefficient $[N]$ modelling inertia and rolling resistance.
- F_1 : Road load coefficient $[N/km/h]$ modelling inertia and rolling resistance.
- F_2 : Road load coefficient $[N/(km/h)^2]$ modelling aerodynamic drag.
- m : mass of the car $[kg]$

F_0 and F_1 factors are mainly linked to rotational inertia (by ex.: wheels) and road friction of the car while F_2 is modelling aerodynamic drag. The term $m * a_i$ is the contribution of Newton's second law.

F_0, F_1 and F_2 in study [11] are given by constructors under NEDC regulations. As WLTP definitions for these parameters changes, these factors are corrected. WLTC takes corrections factors on tyre thread depth and tyre efficiency, which was assumed to be ideal under NEDC legislation. Also, during NEDC testing, the model configuration with the best aerodynamic properties was used in rolling resistance computation. WLTC specifies that the options must be taken into consideration both in the mass of the car and the aerodynamic drag modelling.

Table 2.1 illustrates differences between WLTP and NEDC road load coefficients. In this study, as road loads have been estimated based on corrections applied to NEDC coefficients, margins on these tolerances have been taken. Two scenarios are depicted for WLTP coefficients : one is noted WLTP-H and is the more penalizing while the other is noted WLTP-L and is the more favorable.

Fig. 2.3 and 2.2 represents Vehicle energy Demand (or VED) computed by integrating eq. 2.2 for phases of WLTP and NEDC test. We can note that VED is higher under WLTP compared to NEDC. Also, Extra high speed phase weights a lot on total mean of VED in both WLTP scenarios.

For gasoline powered cars, NEDC required VED of 10.9 ± 1.9 [kWh/100km], WLTP-H 15.7 ± 2.5 [kWh/100km] and WLTP-L 13.8 ± 4.3 [kWh/100km]. In the case of Diesel powered cars NEDC required 13.0 ± 4.6 [kWh/100km], WLTP-L 16.5 ± 6.3 [kWh/100km], and 18.9 ± 7.1 [kWh/100km] km for WLTP-H.

	Details	Vehicle 1 Diesel D11	Vehicle 2 Gasoline G21
Test NEDC	Test Mass [kg]	1700	1360
	$F_0[N]$	121	117
	$F_1[N/km/h]$	0.80	0.34
	$F_3[N/(km/h)^2]$	0.0265	0.0353
Test WLTP	Test Mass [kg]	1823	1570
	$F_0[N]$	121	187
	$F_1[N/km/h]$	0.8	0.52
	$F_3[N/(km/h)^2]$	0.0265	0.0381

Table 2.1: NEDC and WLTP road loads from study [11]

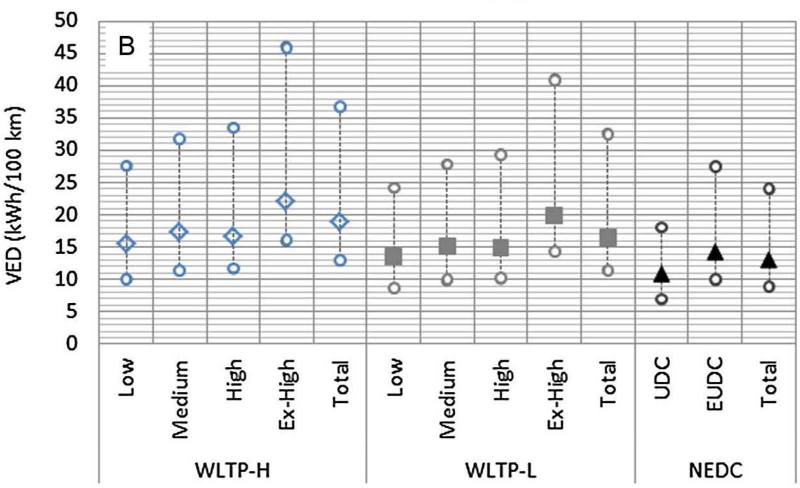

Figure 2.2: Diesel cars VED from [11]

In conclusion the new WLTP testing method is more demanding in energy per km. This is partly due to the extra high speed phase where aerodynamic drag increases proportionally to the square of speed (see eq. 2.2) and because of the more dynamic pattern depicted by a more aggressive acceleration profile of the cycle. These conclusions are confirmed by the energetic analysis of the WLTP versus NEDC on a gasoline car by the authors of WLTP methodology in [16] .

This study and the parameters of this study will be used in section 4.3 to compare on the energetic point of view the cycle representing driving behaviour in

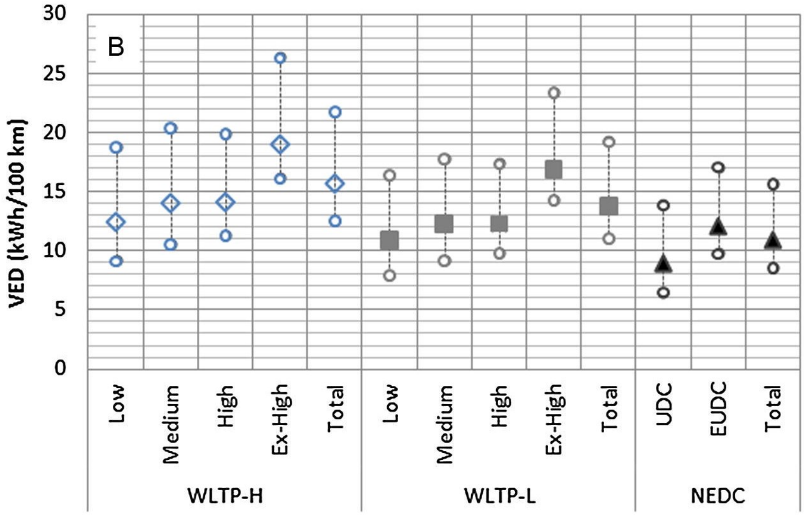

Figure 2.3: Gasoline cars VED from [11]

Brussels and the WLTC.

2.2 Real driving emissions test

Real driving emissions test, or RDE, is a procedure to measure pollutants rejection during drive-test on road and in real life. It complements measures done in-lab with WLTP and ensures that the car tested has similar pollutants level rejects for the two tests [13].

The pollutants rejections are measured thanks to a device attached to the back of the car called PEMS (see fig. 2.4).

As the RDE test is done on public roads, several criteria have been imposed to validate a trip and are explained in the following section [14].

Figure 2.4: PEMS equipement [12]

2.2.1 Trip specifications

First three types of environments are defined depending on the instantaneous spreed of the car:

- urban : $v \leq 60[km/h]$
- rural : $60[km/h] < v \leq 90[km/h]$
- motorway : $v > 90[km/h]$

Table 2.2 presents criteria for a trip to be valid in the frame of RDE test.

2.2.2 Boundary conditions

To be valid, parameters of a trip $(v * a)[95]$ defined in section 2.3.4 must be below the curve in fig. 2.5 and *RPA* defined in section 2.3.5 must be above the curve in fig. 2.5.

Boundary conditions are to be respected to have a valid trip regarding RDE definitions. These conditions are depicted in table 2.3. If data points falls within the

Trip specifics		Provision set in legal text
Total trip duration	all	between 90 and 120 [min]
distance	urban	> 16 [km]
	rural	> 16 [km]
	motorway	> 16 [km]
trip composition	urban	29% to 44% of distance
	rural	23% to 43% of distance
	motorway	23% to 43% of distance
average speed	urban	15 to 40 [km/h]
	rural	60 to 90 [km/h]
	motorway	>90 km/h (>100 km/h for at least 5 min)

Table 2.2: Distance and speed specifications for each urban, rural, and motorway part of the RDE test

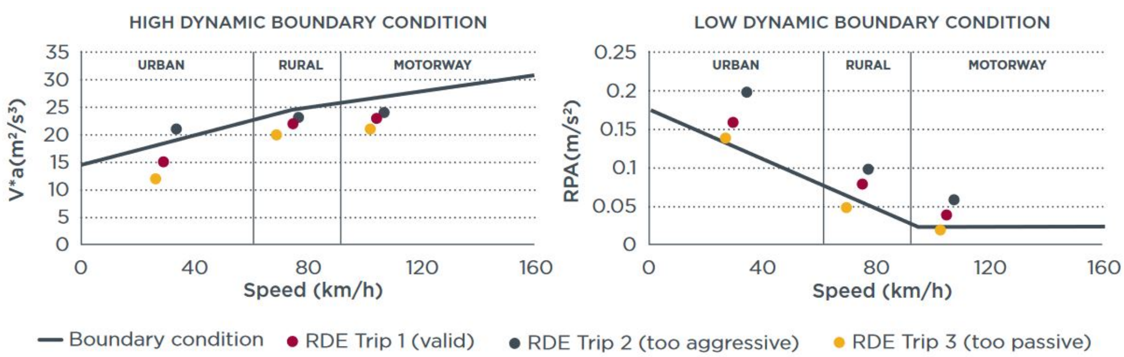

Figure 2.5: Dynamic boundary conditions with three illustrative RDE trips. [14]

extend category, the emissions measured have to be divided by a factor of 1.6 . Any data falling outside of the boundary conditions makes the whole trip invalid [14]. Conditions are specified on fig.2.5 and defines minimum *RPA* values and maximum $(v * a)$[95] values as a function of mean speed of the category. Numeric values for the two limit curves are defined as [9] :

Condition on $(v * a)[95]$:

$$\begin{cases} \overline{v} \leq 74.6[km/h] & (\text{v} \cdot a)[95] > 0.136 \cdot \overline{v} + 14.44 \\ \overline{v} > 74.6[km/h] & (\text{v} \cdot a)[95] > 0.0742 \cdot \overline{v} + 18.966 \end{cases}$$

Condition on *RPA*:

$$\begin{cases} \overline{v} \leq 94.05[km/h] & \text{RPA} < -0.0016 \cdot \overline{v} + 0.1755 \\ \overline{v} > 94.05[km/h] & \text{RPA} > 0.025 \end{cases}$$

Parameter		Provision set in legal text
Payload	all	<= 90 % of maximum vehicle weight
Altitude	Moderate	0 to 700 [m]
	Extended	Between 700 and 1300 [m]
Altitude difference		no more than 100 [m] altitude difference between start and finish
Cumulative altitude gain		1200 m/100 km
Ambient temperature	Moderate	0 to 30 [°C]
	Extended	From –7 to 0 [°C] and 30 to 35 [°C]
stop percentage		between 6 and 30 % of urban time
Maximum speed		145 [km/h] (160 [km/h] for 3% of motorway driving time)

Table 2.3: Boudary conditions of validity for RDE

2.3 Parameters and definitions

In this section the metrics and parameters used in this master thesis are described.

2.3.1 Mean velocity

mean velocity of a trip or short trip j is defined by:

$$\overline{v} = \sum_{i=1}^{N} \frac{v_i}{t_i - t_{i-1}} \tag{2.3}$$

with:

- $\overline{v}$: mean speed [km/h]
- v_i : speed of the element i [km/h]
- t_i : time of the element i [UTC]

2.3.2 Acceleration

the acceleration of element i is defined by [5]:

$$a_i = \frac{1}{3.6} \frac{v_{i+1} - v_{i-1}}{t_{i+1} - t_{i-1}} \tag{2.4}$$

with:

- a_i : acceleration of the element i $[m/s^2]$
- v_i : speed of the element i [km/h]
- t_i : time of the element i [UTC]

2.3.3 Distance

the distance is defined as:

$$x = \frac{\sum_{i=1}^{N} v_i * a_i}{3.6} \tag{2.5}$$

with:

- x : distance driven [m]
- a_i : acceleration of the element i $[m/s^2]$
- v_i : speed of the element i [km/h]

2.3.4 $(v*a)_k[95]$

The $(v*a)_k[95]$ indicator is the 95 % percentile of the distribution of speed multiplied by acceleration in a RDE speed category $(v*a)_{i,k}$.

$$(v*a)_{i,k} = \frac{v_{i,k} * a_{i,k}}{3.6} \tag{2.6}$$

with:

- a_i : acceleration of the element i $[m/s^2]$
- v_i : speed of the element i [km/h]
- $(v*a)_{i,k}$: in $[m^2/s^3]$

2.3.5 RPA

RPA or relative positive acceleration is defined by [5] :

$$RPA = \frac{\sum_{i=1}^{N} v_i * a_i^+}{x * 3.6} \tag{2.7}$$

with:

- x : distance driven [m]
- a_i^+ : positive acceleration of the element i $[m/s^2]$
- v_i : speed of the element i [km/h]

It is worth noting that only positive accelerations (a_i^+) in the trip are included in this computation.

2.3.6 IDLE portion definition

An idling portion of a trip is a portion where speed is smaller than [5 km/h] and acceleration is in the range [-0.139,+0,139] $[m/s^2]$ [16]. Fig. 2.6 presents an example of a trip divided in two short trips and two idling durations.

2.3.7 Short trip portion

A short trip is a portion that does not corresponds to an IDLE portion definition [16]. Each short trip has tree modes :

- Acceleration : $a_i \geq 0.139$ $[m/s^2]$
- Cruise : $a_i \in]-0.139, 0.139[$ $[m/s^2]$
- Deceleration : $a_i \leq -0.139$ $[m/s^2]$

Where a_i represents acceleration of sample i.

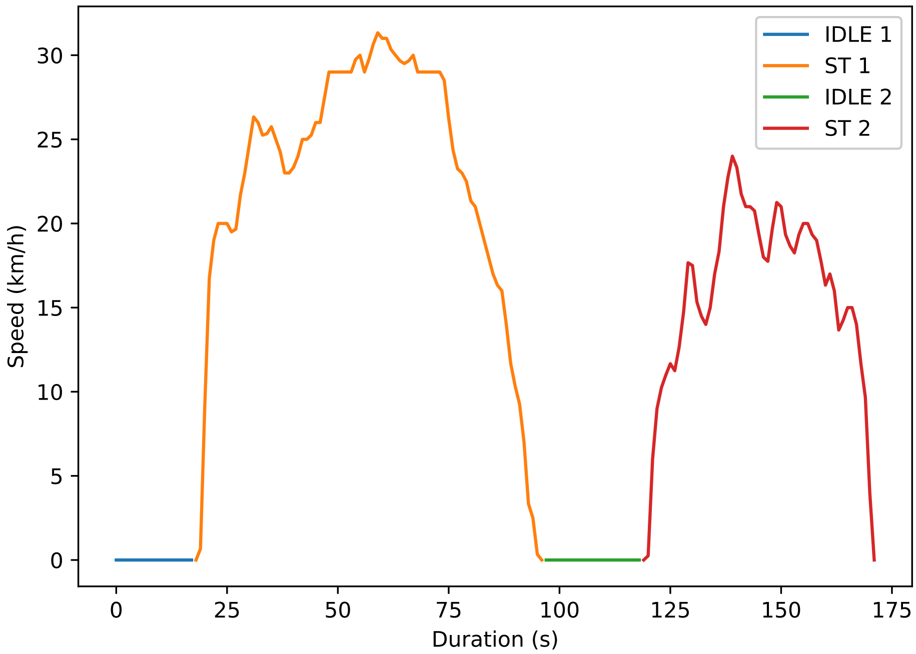

Figure 2.6: A trip divided in short trip and IDLE portions

Chapter 3

Methodology

3.1 Overview

To obtain a target cycle representing the driving characteristics of drivers at Brussels, the methodology followed by the group of experts in charge of developing of the WLTP test cycle [16] has been applied. This methodology consists of four big steps (see fig. 3.1):

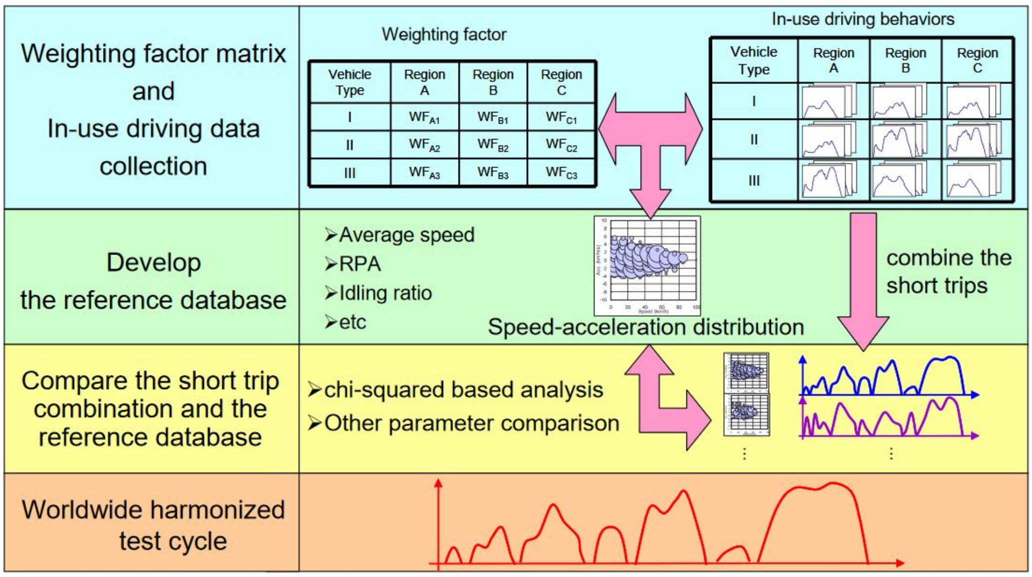

Figure 3.1: Methodology used for the building of the WLTP test [5]

The first step is to collect data from in real life driving, and especially in Brussels, which is the region of focus here.

With all this data recorded, the second step has been launched and consists in computations of parameters for characterization of the database like RPA, average speed, Sspeed-acceleration distribution, short trip and idling durations etc. These parameters gives accuracy objectives to attain with the target cycle.

With the objectives known for the target cycle, we performed an analysis between combinations of candidate short trips. This comparison retains the combination of short trips that presents the least discrepancy with valid data saved in Brussels.

The last step is about refining the speed versus time graph obtained thanks to the previous steps. This is all about having credible parameters to be able to reproduce this target cycle in laboratory.

In the following section the methodology to find the target cycle representing driving behaviour in Brussels is explained. This reasoning is based on the one applied by the group of experts in charge of the WLTC development [16]. Some adaptation have been done and will also be explained.

3.2 Data collection

Data of driving patterns in Brussels has been recorded via dataloggers saving position, speed and several parameters from studied cars. 57 drivers took part to the data harvesting process. 51 have been recorded from February to April 2019 in the frame of a master thesis on RDE cycle by Camille Lambert [9]. The six remaining have been recorded from March to June 2020 in the context of a coronavirus pandemic. The six drivers recorded in 2020 totalised 3 months of records while the 51 others had a recording duration of about 2 weeks per driver. The disparity between these recording durations are due to the fact that confinement and restrictions on displacement prevented getting dataloggers back according to schedule. Out of 2257 trips used in this master thesis, 1398 have been recorded in 2020 while the remaining 859 comes from Camille's database dating from 2019

3.2.1 Data Collecting devices

For this master thesis, data was collected via devices developed by the team of Pr. Contino. They record various driving parameters of the car during trips. There are two types of data loggers used.

3.2.1.1 Datalogger V1.0

The V1.0 data logger, used for data recording in a previous master thesis wrote by Camille Lambert [9]. It consists of an Arduino board centralizing and saving data coming from 3 sources: an accelerometer, a GPS chip and the OBD socket of the car studied. the device is powered by a battery and the battery is powered by a 12V socket from the car. The OBD (On-Board Diagnostic) socket is a standardized interface for all constructors. It allows to get informations about the current state of the car via a CAN protocol. The Arduino board sends a request for a parameter and the car sends back the associated value. All the data is stored in a micro SD card under a .CSV format.

Table 3.1 shows the 12 parameters saved by the V1.0 device:

The target recording period $T_{sampling}$ is 0.300 [s] or 3.333 [Hz] for every parameter except for the engine coolant temperature which is recorded every 10 samples. The reason for the 0.300 [s] period is that we cannot go any lower without loosing data in the transfer between the ECU of the car and the datalogger via the OBD socket. In fact, the first request of parameters to the ECU would not be saved by the datalogger before having to send the next request. So the parameter limiting the recording frequency is the time to save informations on the SD card by the Arduino.

The datalogger V1.0 has some limitations discovered by the team related to Camille's thesis.

The first big limitation of the V1.0 is the bulkiness of the device and the number of cables around it. It is difficult to install in some (small) cars and, because of the cables, the driver is always reminded that he is recorded, which could change his driving style.

Parameter	Source	Units
Date	GPS	UTC
Latitude	GPS	decimal form
Longitude	GPS	decimal form
GPS speed	GPS	mknot
Altitude	GPS	cm
Acceleration x	accelerometer	counts
Acceleration y	accelerometer	counts
Acceleration z	accelerometer	counts
Engine load	OBD	%
Engine rotationnal speed	OBD	RPM
OBD speed	OBD	km/h
Engine coolant temperature	OBD	°C

Table 3.1: Parameters saved by V1.0 datalogger

The second one is the loss of GPS signal. The GPS chip is in the same box as the battery, the accelerometer and the Arduino board. Because of the bulkiness of the assembly, it is sometimes placed under the passenger seat or behind the driver seat. This leads to bad GPS signal reception.

3.2.1.2 Datalogger V2.0

A second datalogger model (see annex 7.1) has been developed, also by the research team of Pr. Contino, taking into account limitations of the V1.0. To have a more reasonably-sized device, a development kit For OBD transfert build by Longan-Labs was used. This kit includes a box containing the arduino board and an OBD2 socket. It is also battery-free thanks to its powering via 12V pins on the OBD socket. For the GPS signal problem, a deported GPS chip has been used and connected to the dispositive. It allows to place GPS chip in a good spot for signal reception. Finally, an accelerometer-gyrometer has been added to the dispositive.

Table 3.2 shows the 15 parameters saved by the V2.0 device.

Parameter	Source	Units
Date	GPS	UTC
Latitude	GPS	decimal form
Longitude	GPS	decimal form
Altitude	GPS	cm
GPS speed	GPS	mknot
OBD speed	OBD	km/h
Engine load	OBD	%
Engine coolant temperature	OBD	°C
Engine rotationnal speed	OBD	RPM
Acceleration x	accelerometer-gyrometer	g
Acceleration y	accelerometer-gyrometer	g
Acceleration z	accelerometer-gyrometer	g
Gyro count x	accelerometer-gyrometer	dps
Gyro count y	accelerometer-gyrometer	dps
Gyro count z	accelerometer-gyrometer	dps

Table 3.2: Parameters saved by V2.0 datalogger

3.3 Data handling, filtering and resampling

To create a cycle of speed versus time representing the driving style of Brussels drivers following the process used to build the WLTC, we only need data on speed versus time and position versus time to base our computations. This signal has to be at 1 Hz as it is in the WLTC building process [16]. This assumption is a compromise between accuracy of the measurement and computing time for the analyzing part in order to find the best representative driving behaviour of Brussels driving style. It also allows to reduce noise induced by high frequency sampling.

To store and retrieve data effectively, SQL databases were used. All the raw data in .CSV from data loggers is harvested and transferred to an SQL database. The computations are made using Python language. sqlalchemy [1] and sqlite3 [2] libraries

[1]https://www.sqlalchemy.org
[2]https://sqlite.org/index.html

are used to extract and update data from the trips database.

3.3.1 Data filtering and resampling

The main challenge here is to account for signal fail which happens when the data recorder receives no data from sensors.The conditions to detect signal fails in the case of the two data recorders protocol is depicted in table 3.3.

Signal	Condition signal fail
Position	[Latitude,Longitude] = [0,0]
GPS speed	[Latitude,Longitude,GPS speed] = [0,0,0]
OBD2 speed	OBD2 speed = 0 and GPS speed $\geq$ 10 [km/h]

Table 3.3: Conditions for signal failure detection

Here is an overview of the strategy used to filter the raw data coming from dataloggers to a clean database with 1 [Hz] sampling:

- Speed signal loss compensation
- Geographical position signal loss compensation
- Resampling
- Gerographically filter data

These filters and the resampler are used in sequential order as described in fig. 3.2

3.3.2 Speed signal loss compensation

Two speed signals are available from data recorded on a car : one coming from the odometer via the OBD2 port of the car and the other from the GPS chip. As we have 3.34% of GPS speed signal fail vs. 0.09% for OBD2 speed signal fail in our raw database, we chose to use the speed coming from the odometer since it is less likely to fail and has a lower noise level than the one coming from the GPS chip.

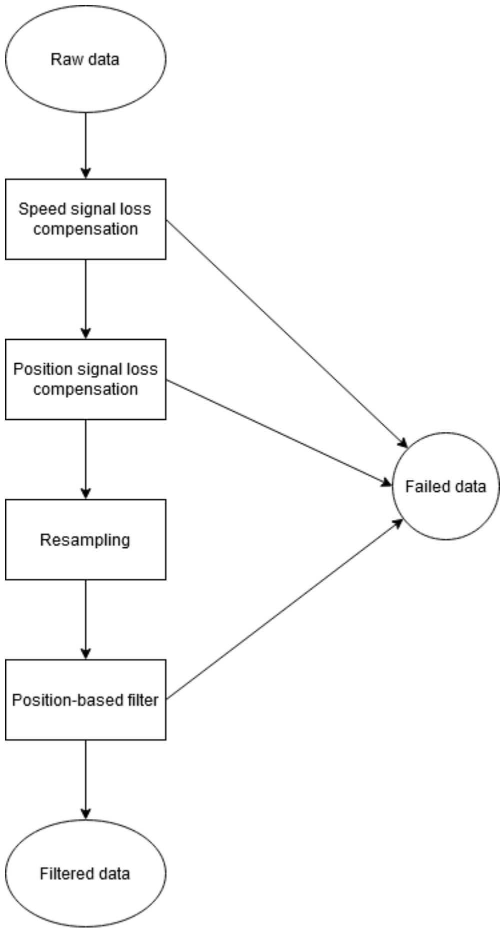

Figure 3.2: Data Filtering and re sampling strategy

To overcome OBD2 speed signal fail, the strategy here is to detect it and if needed replace it with the GPS speed. There were 40 samples where GPS and OBD2 speed signals have both failed. These samples are here simply removed from the database because they represent 40 out of 9 866 757 samples and will not influence the following steps of data filtering.

3.3.3 Position signal loss compensation

In the application of this thesis, we need to know the geographical position of the car studied in order to determine if it rides in or out of Brussels. The problem is that, sometimes, the GPS signal is lost due to datalogger problems or bad GPS signal reception (like in tunnels).

We linearly interpolate missing position data for the next step being resampling. The linear interpolation has the advantage of being less computationally demanding while having well defined up and down limits, which adds robustness to our algorithm.

A case where we cannot interpolate between GPS positions is when the GPS signal has completely failed over the whole trip. This is the case in 216 trips. These are rejected.

3.3.4 Resampling

With the clean and interpolated data on the speed and position of the car, we resample it from $T_{sampling,rawdata}$ to $T_{sampling,data} = 1[s]$ using a python filtering method applying the moving average principle. We must note that $T_{sampling,rawdata}$ is not always consistent (see fig. 3.3). This inconsistency is due to two factors :

- The first one is that we have data coming from two types of recording devices with 2 different sampling periods (one at 0.1 [s] and the other at 0.3 [s]).
- Secondly, theoretical sampling periods are not always possible due to delays during communication between recording devices and OBD2 and/or GPS chip.

Hence the moving average technique is suited to this problematic as it does not need signals sampled at constant frequency.

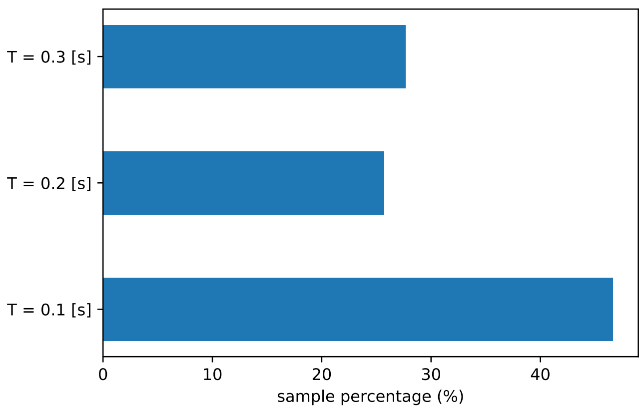

Figure 3.3: Raw data sampling

3.3.5 Gerographically filter data

For this filter, we apply a condition that at least 95 percent of the positions of a trip are contained in a region determined by the circle in fig 3.4. This is done measuring the distance between the center of the circle and and every position during the trip.

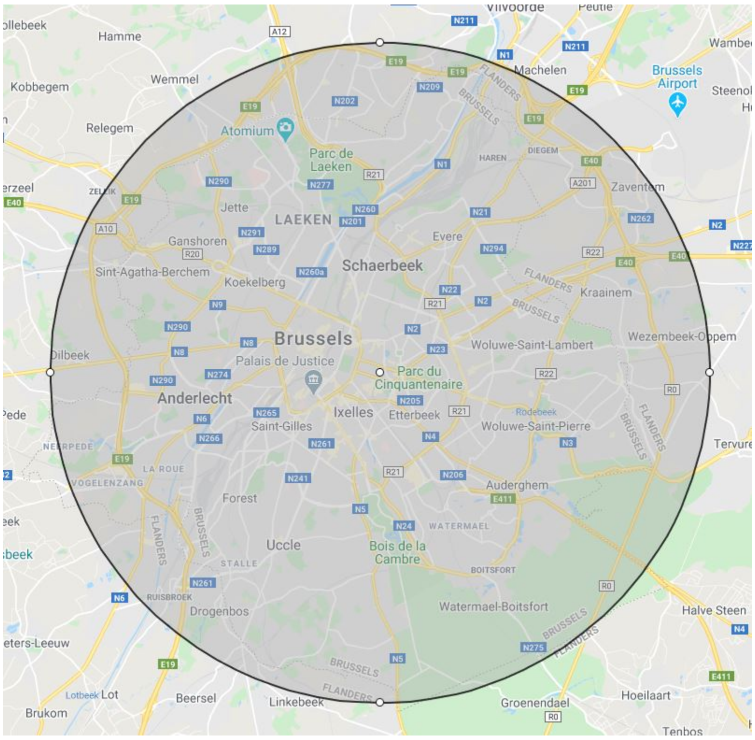

Figure 3.4: Definition of Brussels limits

The circle contains all of Brussels territory plus nearly all the length of R0 (the ring) in order to represent the most of road characteristics. Its center coordinates are $50.842303°N, 4.376230°E$ and its radius is equal to 8522.20 [m].

3.3.6 Conclusion

This filtering and resampling step took raw data at various sampling periods. Interpolation and resampling methods were applied to have a clean database. Then, exclusion criteria where applied in order to remove unnecessary data.

Out of 2257 trips in the raw database, 733 were removed. 216 of them had no GPS signal and thus were not valid and 517 had more than 5 percent of datapoints detected as outside of Brussels.

3.4 Data analysis

3.4.1 Short Trip Database constitution

At this stage, we divide trips into short trips following rules explained in section 2.3.7.

To prevent excessive noise due to stop and go traffic, short trips with a duration of less than ten seconds or with a maximum speed of less than 3.6 [km/h] are excluded from the short trips database. This assumption is the same as the one used in WLTC building process [16]. Every short trip is labelled by a speed category. Criteria for speed category labelling are described in table 3.6.

Category	Max speed of the short trip (km/h)
Low	60
Middle	80
High	110
Extra - high	> 110

Table 3.4: Speed criteria for short trip labelling

Next, the repartition of short trips by speed category is described in fig. 3.5. We see that most measurements for short trips lie in the "Low" column which implies that a lot of the driving in Brussels is done at low speed (less than 60 [km/h], which is plausible because it is city driving).

Speed category	Low	Middle	High	ExHigh
N ST percentage %	88.8	6.1	3.4	1.7

Table 3.5: Distribution of short trips by speed category

This distribution of short trips in speed categories (see tab. 3.5) is however not satisfying for our further computations in order to find a cycle representing driving patterns in Brussels.

Firstly, this distribution will induce a big number of comparisons in the optimum-finding algorithm. This is because of comparisons between low-speed short trip candidates with short durations and on a long time relatively to the other

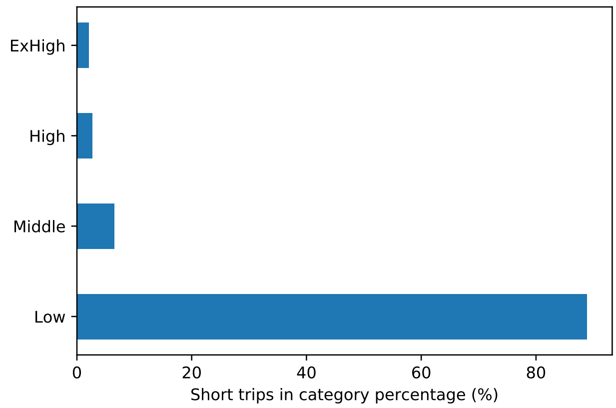

Figure 3.5: Distribution of short trips by speed category

categories in order to find the right combination for the low speed part of the cycle. As it already took to the authors of the WLTC cycle 24 hours of computational time and about 10^7 iterations [16], a better definition with an equal distribution of number of short trips in speed categories would help.

Secondly, to find the right speed categories definition, the authors of the WLTC performed a comparative analysis [16]. They tried different combinations of speed limits to have an homogeneous distribution of short trips. Three types of analysis have been performed:

- The first one compares the speed-acceleration distributions of each region in function of the limits for speed categories. The aim is to impose speed categories that result in homogenous speed-acceleration distributions. In the case of this master thesis, as we only study one region being Brussels as defined in section 3.3.5, this analysis is not possible.

- The second one is a comparison of parameters (mean speed, RPA, acceleration portion etc.) to find speed patterns that correspond to every world region. It is not applicable in the case where only Brussels is concerned in this master thesis.

- The third method is based on choosing thresholds between speed categories by looking at the maximum speed for short trips distribution. The aim is to have a rather even distribution of short trips between categories. We use this method in this master thesis.

We computed the maximum speed distribution for short trips (see fig. 3.6) and tested several combination of speed ranges to label short trip categories. We end up choosing these speeds as thresholds : [25,40,80] [km/h]. These are a good fit as the distribution of short trips per categoriy is rather equal in frequency (see tab. 3.6), except for the Extra high speed phase. We chose to separate high and extra high speed phase to keep accuracy of the target test cycle regarding reality, moreover if we merged the two categories we would end up with a short trip category defined by maximum speed from 40 [km/h] to 140 [km/h]. This big range is not acceptable as it would include in the same category trips on the speedway with others driven in town. Finally, the short trip database duly computed is saved in a database with

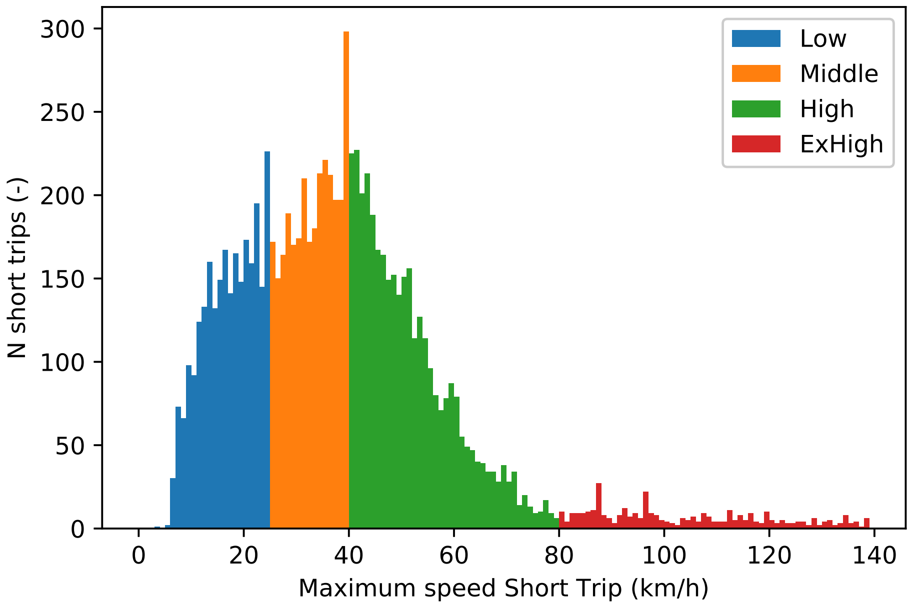

Figure 3.6: Maximum speed of short trips distribution

Speed category	Low	Middle	High	ExHigh
N ST percentage %	37.9	30.4	27.0	4.7

Table 3.6: New distribution of short trips by speed category

two tables : one containing speed and position for every short trip and the other one containing parameters (like mean speed, max speed and RPA among others) for every short trip.

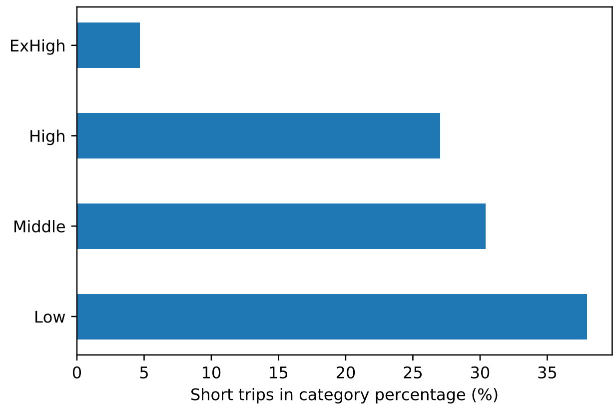

Figure 3.7: New distribution of short trips by speed category

3.4.2 IDLE Database constitution

To describe an IDLE section we only need 2 characteristics : its duration and the speed type of short trips that follows temporally the IDLE section as Every IDLE section is linked to a short trip as described in section 3.4.1 and fig. 2.6. Idling periods of more than 10 [min] are deleted to avoid outliers weighting too much in the analysis following reasoning in [16]. All of this data is saved in the IDLE database.

3.4.3 Phases duration determination for the cycle

In this section is presented how the phases durations for the cycle are computed.

Firstly, we have to impose the duration of the target cycle. The mean trip duration in our database is 766 [s] with standard deviation equal to 1747 [s]. With this wide range of durations in mind, we impose a total duration of the target cycle to be 1800 [s]. This is an accepted compromise between statistical represantativeness and feasibility in the laboratory [16]. Later comparisons with target cycle and WLTC will also be easier with the same duration.

The length of each speed phase is computed via a division of the total duration of the category by the total duration of the data as described in eq. 3.1 and applied in [16].

$$D_{phase,i} = \frac{D_{total,i}}{D_{total}} \tag{3.1}$$

where :

- $D_{phase,i}$: Duration of the speed phase i in the target cycle [s].
- $D_{total,i}$: Total duration of short trips and IDLE of speed category i [s].
- D_{total} : Total duration of valid data [s].

To compute the number of short trips $N_{ST,i}$ per speed phase with eq. 3.2

$$N_{ST,i} = \frac{P_i - \bar{I}_i}{\overline{ST_i} + \bar{I}_i} \tag{3.2}$$

$N_{ST,i}$ was rounded to the nearest integer and where:

- P_i : Duration of the speed phase i in the target cycle [s].
- $\bar{I}_i$: Average idling duration for speed phase i [s].
- $\overline{ST_i}$: Average short trip duration for speed phase i [s].

Idling portions $N_{IDLE,i}$ per speed phase are determined by eq. 3.3:

$$N_{IDLE,i} = N_{ST,i} + 1 \tag{3.3}$$

Results for the target cycle are presented in table 3.7:

Speed Phase	$D_{phase,i}$ [s]	$\bar{I}_i$ [s]	$\overline{ST_i}$ [s]	$N_{ST,i}$ [-]	$N_{IDLE,i}$ [-]
Low	136.95	14.97	23.12	4	5
Middle	457.07	35.07	74.63	4	5
High	831.38	17.59	108.92	7	8
ExHigh	374.58	16.55	395.76	1	2
Total	1800	N/A	N/A	16	20

Table 3.7: Speed phases durations

The reader must acknowledge that the number of short trips for high and extra high speed phases are rounded up in order to have at least one short trip per speed category.

Each short trip duration is determined by dividing the y axis of the cumulative frequency graph of each speed category by the number of short trips needed in this category. The value of the duration of the short trip is equal to the mean value of all samples in the box (see fig. 3.8). In fig 3.8, we get 2 and 20 seconds as mean for each box. The Boxes heights are equal to 50 and 100 % of the cumulative frequency. The same reasoning is applied to get short trips durations. All the histograms of short trip durations and idling durations are presented in appendix 7.3 and 7.2 .

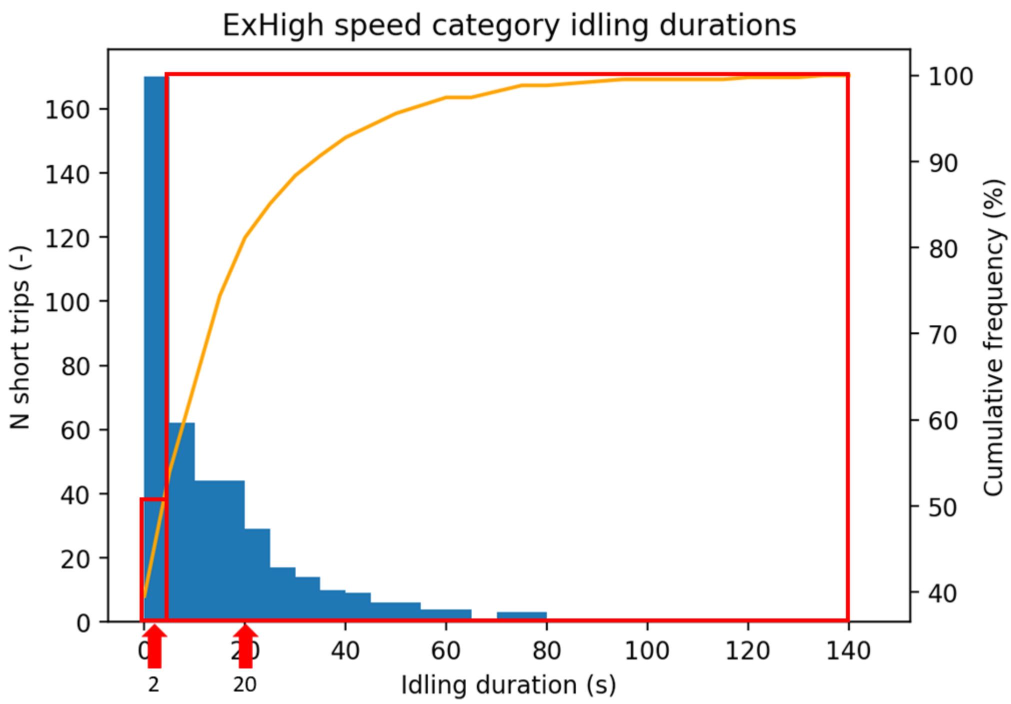

Figure 3.8: Histogram and cumulative frequency for idling durations of extra high speed phase

In appendix 7.4 the results of this analysis. The total duration of the target cycle is obtained by taking the sum over all the durations (short trips and idling).

3.4.4 Combinatory analysis

In this section the strategy to find the best combination of short trips to represent driving patterns in Brussels is explained. This best combination has to be representative of the trips database.

3.4.4.1 Candidates

A database containing all short trips coming from the short trips database and corresponding to a duration and speed category of appendix 7.4 has been constructed. These short trips are called candidates.

At least one candidate has been found for every short trip durations in table 7.1 except for Middle speed phase short trip number 4 (Middle ST4) and for Extra High speed phase number 1 (ExHig ST1). A separate analysis has been conducted in order to find a suitable speed curve for these short trips and is explained in section 3.4.4.3.

Due to the fact that we have to analyse a lot of short trips of short duration, a condition on the mean speed of the candidate has been imposed as following:

$$\overline{v}_{ST,i} \in]\mu - \sigma, \mu + \sigma[\tag{3.4}$$

With:

- $\overline{v}_{ST,i,j}$: mean for short trip from speed category i short trip j.
- μ : mean of $\overline{v}_{ST,i}$ distribution for this short trip duration.
- σ : Standard deviation of $\overline{v}_{ST,i}$ distribution for this short trip duration.

This condition is here to reduce the number of candidates and hence the number of possible combinations possible to analyze. The reduction of possible combinations is needed as on the computer [3] running the code for combination analysis, 10^6 iterations takes approximately 12 h. Thanks to this reduction of possible candidates, the number of iterations is in the order of 10^6, opposed to $6 * 10^6$ before imposing conditions on the mean speed.

[3] desktop computer - Intel i5 4690K processor

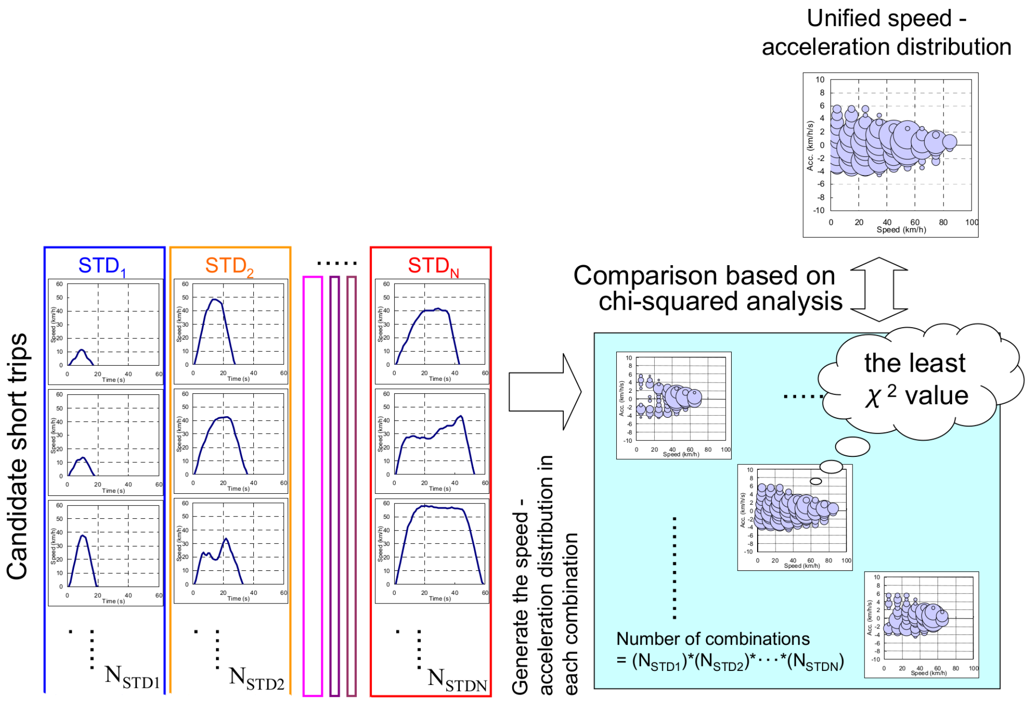

Figure 3.9: Speed - acceleration distribution for candidates combinations from [19]

3.4.4.2 Candidates combination analysis

An analysis has been conducted for every speed category candidate combination to find the one that represents the whole speed category data the best(see fig. 3.9). Then, the same type of speed - acceleration graph was computed for every short trips combinations.

Firstly, a speed - acceleration distribution has been computed for each speed category. Then a comparison was conducted between this distribution and the distribution of the combination of candidates (see fig. 3.11). Pearson's chi-square test for goodness of fit is used here [2]. The goal is to find the short trip candidates combinations that minimizes the chi-square value computed between these two distributions. It is computed for our distribution speed - acceleration as :

$$\chi^2 = \sum\sum \frac{(O_{i,j} - E_{i,j})^2}{E_{i,j}} \tag{3.5}$$

with:

- $O_{i,j}$: Observed frequency, here the number of data points from the candidate combination in the interval of speed - acceleration i,j.

- $E_{i,j}$: Expected frequency, normalized to the number of data points in the candidate combination, here the number of data points from the speed category database in the interval of speed - acceleration i,j.

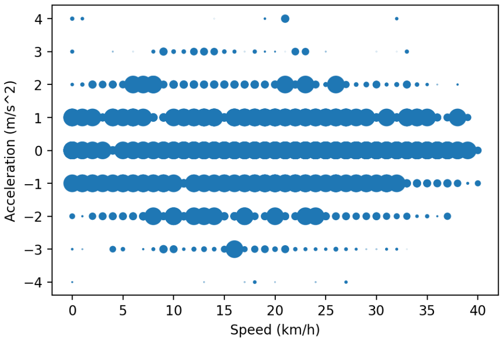

Figure 3.10: Speed - acceleration distribution scatter plot for middle speed category

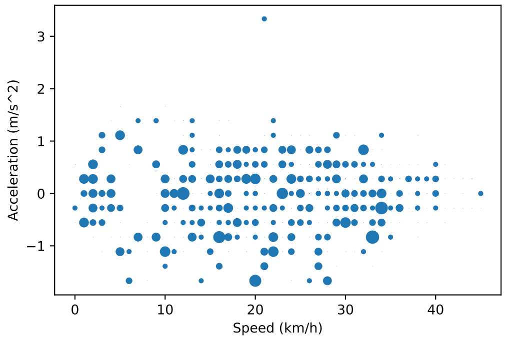

Figure 3.11: Speed - acceleration distribution scatter plot for a middle speed candidate combination

3.4.4.3 Remaining High and extra High trips

The two remaining Short trips to find are the 179 [s] middle and 353 [s] extra high short trips. As they do not have candidates from short trips database corresponding to their speed class and duration, a separate analysis has been conducted to find the best suitable speed curve.

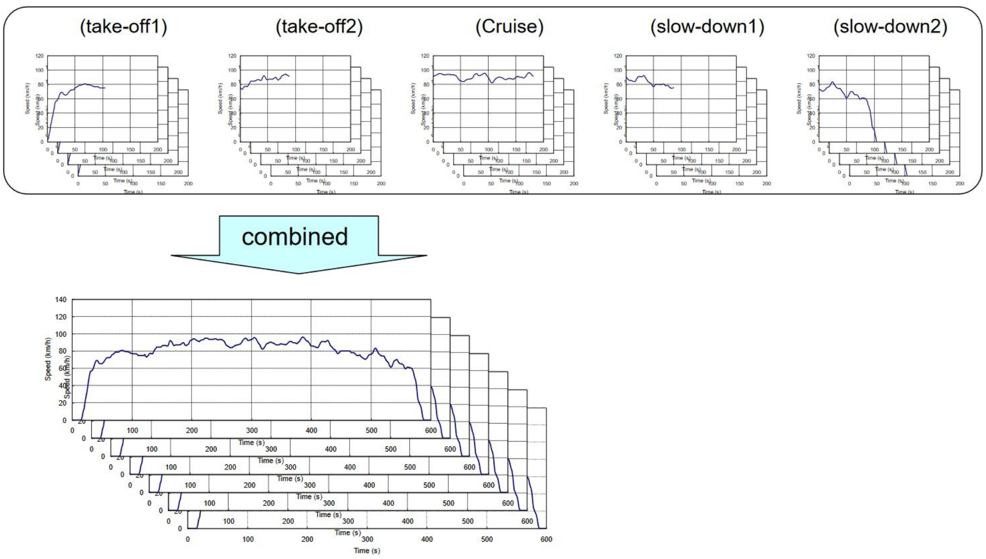

Figure 3.12: Methodology from [5]

Every short trip of the category is analysed separately to find, if applicable, take-off, cruise or slow-down patterns as shown in fig 3.12. We impose three conditions to recognize patterns:

- a speed at the beginning of the pattern.
- a speed at the end of the pattern.
- a duration.

Durations for take off 1, take off 2, slow down 1 and slow down 2 are arbitrarily set to 30 [s] . Then, the duration for cruise is equal to the short trip duration minus all the 4 durations already set.

We set the speed boundary between take off 1 and 2 to be the 33% percentile of the category speed distribution (see eq. 3.6). The same speed is used to set the boundary between slow down 1 and 2. The speed of the boundary between take off 2 and cruise phase is set to be the speed equal to the 66 % percentile of the speed distribution from the speed category (see eq. 3.7).

$$v_{boundary,1-2} = v_{boundary,2-1} = P_{33} \tag{3.6}$$

$$v_{boundary,cruise} = P_{66} \tag{3.7}$$

With P_x : the xth percentile of the speed distribution from the speed category.

The same combinatory analysis based on chi-square as above is conducted to find the best combination between the candidates here.

3.5 Target cycle correction

3.5.1 Target cycle V1.0

All the procedures applied above give the target cycle, i.e. the one that minimizes the chi-square value by comparison with all the valid data coming from the data-loggers. In fig. 3.13 the raw version (V1.0) is presented. The order of short trips in speed categories is random except for the first short trip and idling period. These two are chosen to match idling duration and short mean speed from database. These characteristics are presented in table 3.8.

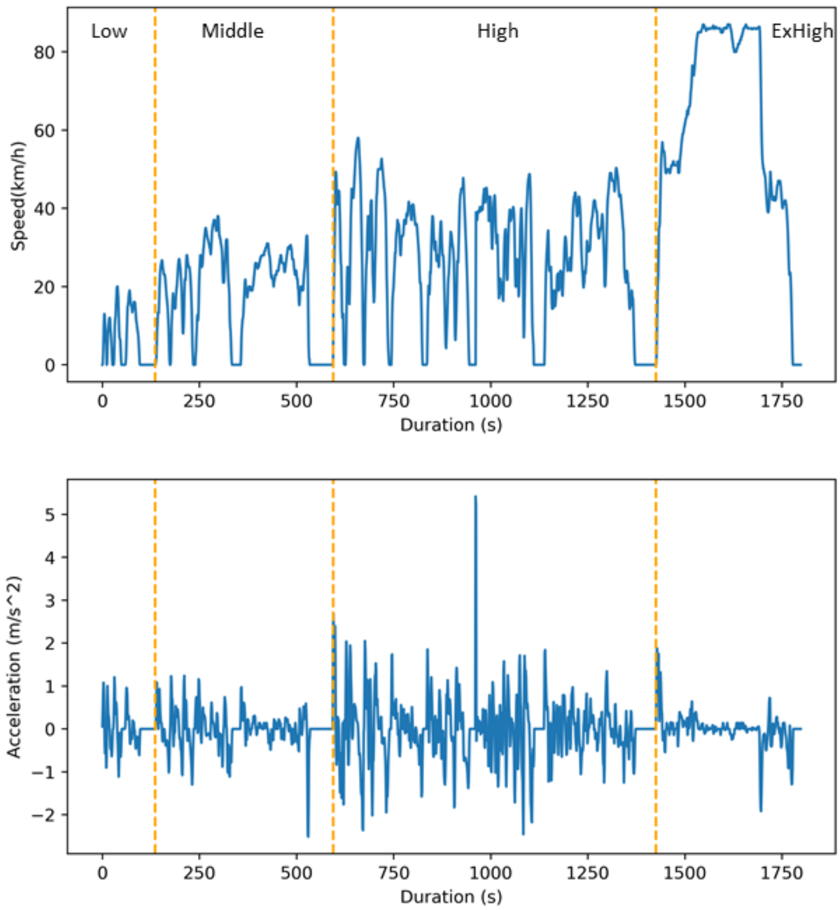

Figure 3.13: Target cycle V1.0

Type	Real-life duration [s]	cycle duration [s]
idling	22.45	15
short trip	32.26	29

Table 3.8: First short trip and idling duration characteristics

The V1.0 of the target cycle present one problem:

On the speed vs. time fig. 3.13 we have acceleration spikes at +5.5 and -2.7 [m/s^2] which are unacceptable for a test cycle. Acceleration has to stay above -1.475 [m/s^2] for avoidance of wheel lock under braking [5]. The upper acceleration threshold is also set to 1.475 [m/s^2].

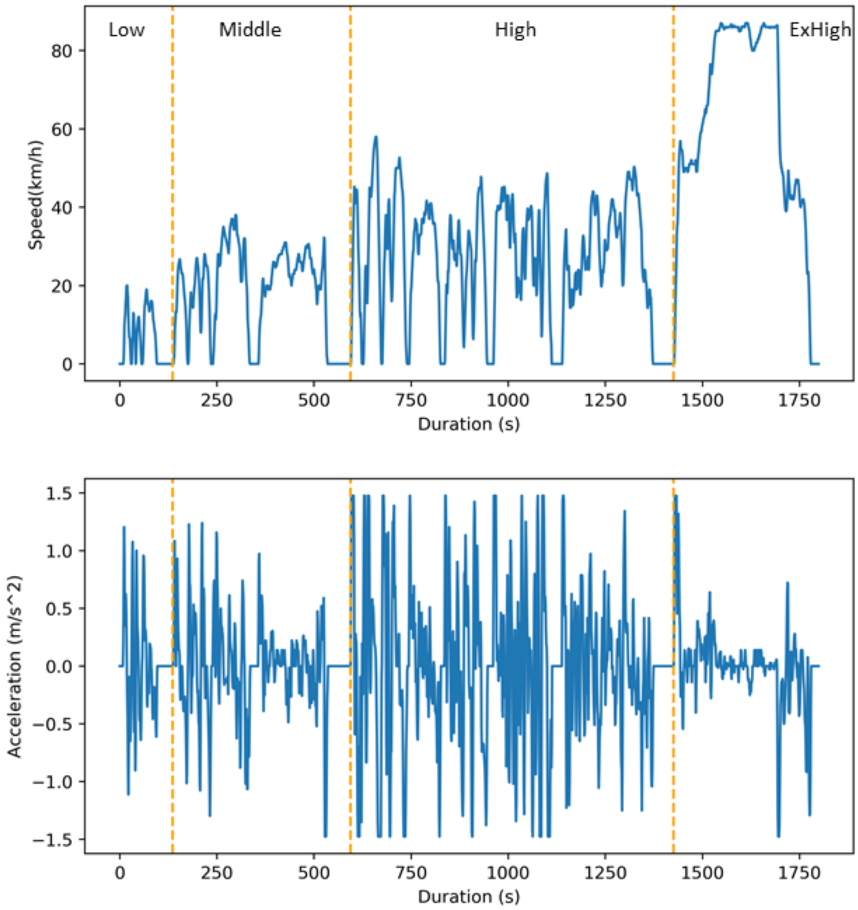

Figure 3.14: Target Cycle V1.1

3.5.2 Target cycle V1.1

Target cycle V1.1 is the cycle taking limitations of cycle V1.0. Its peak accelerations have been smoothened and limited to the range between +1.475 $[m/s^2]$ and -1.475 $[m/s^2]$. Acceleration peaks have been diffused while keeping the local integral value.

3.6 Conclusion

Following the methodology used for WLTC building permitted to find a cycle representing data gathered on cars driving in Brussels.

As harvested data of driving patterns showed losses of GPS sand speed signals, corrective steps have been implemented to recover a clean database. This clean database has then been resampled at 1 [Hz] both to avoid high frequency noise and have a 1 [s] time step reducing CPU time for upcoming calculations.

This clean database has been separated in short trips, analysed, and then labelled by speed categories. An analysis on short trip duration and idling duration has been conducted in order to find the structure of the target cycle representing driving patterns in Brussels. Candidate short trips combinations were tested in a chi-square goodness of fit to find the best one representing each speed category.

After that, corrections on accelerations and order of the target cycle have been implemented. These are mandatory to obtain a test cycle possible for implementation in test-labs on a rolling bench.

This methodology is all about finding the best speed versus time curve mimicking driving behaviours in Brussels. There will always be a trade-off between statistical represantativeness of the data collected and possibility to reproduce the cycle in lab.

In the following chapter the results obtained with target cycle V1.1 will be discussed and analysed.

Chapter 4

Results Analysis

Target cycle V1.1 presented in fig. 3.14 is the result of implementation of the WLTC building methodology. During 1800 [s] it is expected to mimic during 1800 [s] the behaviour of Brussels drivers, represented by data collected in previous chapter.

It is composed of 16 short trips portions and 17 idling portions. Low, Middle and High speed phases represents city driving with a lot of stop and go traffic. Low and middle speed categories presents relatively smooth acceleration profiles compared to high ones. Extra high speed phase is a cruise with even smoother acceleration than in low and middle phases. Top speed is located on the extra high speed phase and is equal to 87 [km/h].

In this chapter the results from the methodology followed to obtain Target cycle V1.1 will be studied.

Firstly, we will start with a comparison between parameters of target cycle and those from database. This comparison will show if similarities or differences are perceptible.

Secondly, RDE criteria will be applied to the target cycle V1.1. This will give an idea if the target cycle is suitable for a RDE test.

Then, a comparison of energy needs between WLTC and target cycle V1.1 will be studied.

4.1 Comparison target cycle vs database

4.1.1 Parameters comparison

In tab. 4.1 is presented a comparison between target cycle V1.1 and the database is presented.

We see that the mean speed is in each category is very close between parameters from database and the target cycle.

	Target cycle				Database			
	Low	Middle	High	ExHigh	Low	Middle	High	ExHigh
Mean speed [km/h]	6.22	18.19	26.20	61.63	7.63	17.94	26.80	64.53
Idling ratio [%]	38.24	19.43	13.48	5.87	26.83	17.20	14.40	5.93
Max speed [km/h]	20	38	58	87	20	40	80	185.71
RPA [-]	0.18	0.13	0.24	0.07	0.20	0.19	0.25	0.17

Table 4.1: Characteristics of target cycle V1.1

The target cycle is always a compromise between statistical representation of collected data and drivability on test bench, which is why some parameters are rather different.

Even if the parameters comparisons between data and the target cycle is globally on the same order of magnitude, a more specific analysis is needed to verify if the estimation of the database by the target cycle is representative of said database. This analysis is done in the following section.

4.1.2 Speed - Acceleration distribution comparison

A comparison between speed-acceleration distributions is performed in this section. A chi-square goodness of fit analysis has been applied between the cycle of interest (target cycle V1.1) and the database of short trips in Brussels. This test is basically comparing scatter plots for each speed category between those from the database (see appendix. 7.5.1) and the ones from target cycle V1.1 (see appendix. 7.5.2).

A goodness of fit test is defined by [18] :

- χ^2 : the chisquare value of the test as computed in 3.5.
- α : level of significance for the test, conventionally set at 0.05.
- H_0 : null hypothesis.
- $\chi^2_{\alpha,dof}$: value of the chisquare distribution with degree of significance α and degree of freedom dof.
- dof : degree of freedom.

H_0 is not rejected if $\chi^2_{\alpha,dof} > \chi^2$ and we can conclude that the data does not present sufficient evidence to indicate that H_0 is false.

In the case of these tests, we state:

- H_0 : the speed - acceleration distribution of the speed category in the target cycle represents speed-acceleration distribution from its speed category.

Speed category	dof	χ^2	$\chi^2_{0.05,dof}$	H_0 rejected
Low	142	52.0871	170.809	False
Middle	278	260.531	317.888	False
High	589	322.758	646.569	False
ExHigh	927	798.143	998.943	False

Table 4.2: Goodness of fit test parameters

We see in tab 4.2 that H_0 is never rejected, the data does not present sufficient evidence to indicate that the speed-acceleration distributions of the target cycle categories does not represent speed acceleration distributions from data.

4.1.3 Synthesis

Parameters comparison between target cycle V1.1 and the database shows on a global scale similarities between the two. Some of them are different, due to the fact that the optimization algorithm to find the best candidates combination is based only on speed-acceleration profile comparison.

A chi squared goodness of fit test is applied between target cycle V1.1 and the database for each speed category. This test does not show evidence to reject the hypothesis that target cycle V1.1 represents the speed acceleration distribution of the data collected.

4.2 Target cycle vs RDE

In this section, RDE validity criterias are applied to target cycle V1.1. This analysis is conducted to determine if the target cycle V1.1, which is representative of Brussels driving patterns, is complying with RDE testing methodology.

First, we have a look at the trip specifications and then analyze the boundaries of RDE criteria. Lastly the RDE trip boundaries are compared to cycle V1.1 parameters.

4.2.1 Trip specifications

Table 4.3 shows characteristics of target cycle V1.1 compared to specifications for validity of a trip in the frame of the RDE policy. We must note that no speed sample in the target cycle is above 90 [Km/h], hence no data is computed for the motorway RDE speed category.

Trip specifics		Provision set in legal text	Cycle V1.1
Total trip duration	all	between 90 and 120 [min]	30 [min]
distance	urban	> 16 [km]	10.44 [km]
	rural	> 16 [km]	4.57 [km]
	motorway	> 16 [km]	0 [km]
trip composition	urban	29% to 44% of distance	69.5 %
	rural	23% to 43% of distance	30.5 %
	motorway	23% to 43% of distance	0 %
average speed	urban	15 to 40 [km/h]	23.49 [km/h]
	rural	60 to 90 [km/h]	82.35 [km/h]
	motorway	>90 km/h (>100 km/h for at least 5 min)	N/A

Table 4.3: Distance and speed specifications comparison

The total trip duration criterion is not respected, because the duration of the target cycle is set to 30 [min.]. On the distance and trip composition criteria, since cycle target cycle V1.1 has a maximum speed of 87 [km/h], these are invalid too. Average speed conditions are valid for urban and rural categories, but they are not applicable for motorway for reasons mentioned above.

4.2.2 Trip boundaries

The trip boundaries for RDE testing are compared in fig. 4.4. Payload, altitude, altitude difference, cumulative altitude gain, ambient temperature and use of the auxiliary systems are not relevant in the comparison as the target cycle is only composed of a speed versus time curve. On the other hand, conditions on stop percentage and maximum speed are fulfilled.

Fig. 4.1 and 4.2 show that conditions on $(v*a)_k$[95] and RPA for target cycle V1.1 are respected except for motorway speed category where no data is available.

	Parameter	Provision set in legal text	target cycle V1.1
Payload	all	<= 90 % of maximum vehicle weight	N/A
Altitude	Moderate	0 to 700 [m]	N/A
	Extended	Between 700 and 1300 [m]	N/A
Altitude difference		no more than 100 [m] altitude difference between start and finish	N/A
Cumulative altitude gain		1200 m/100 km	N/A
Ambient temperature	Moderate	0 to 30 [°C]	N/A
	Extended	From –7 to 0 [°C] and 30 to 35 [°C]	N/A
stop percentage		between 6 and 30 % of urban time	16.3 %
Maximum speed		145 [km/h] (160 [km/h] for 3% of motorway driving time)	87 [km/h]
Use of axiliary systems		Free to use as in real life (not recorded)	N/A

Table 4.4: Trip boundaries comparison

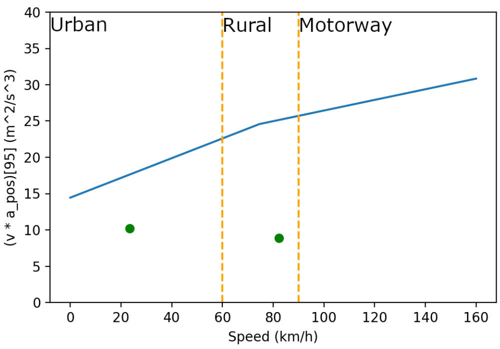

Figure 4.1: Conditions on $(v * a)_k[95]$

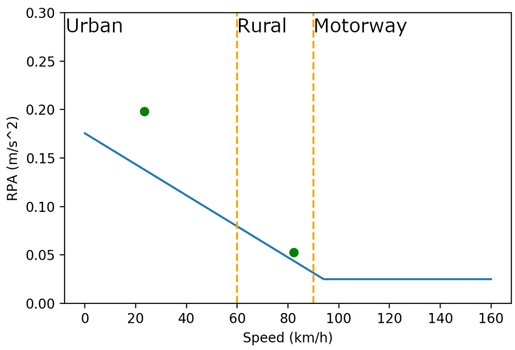

Figure 4.2: Conditions on RPA

4.2.3 Synthesis

Regarding RDE criteria, target cycle V1.1 is not valid. It is too short, both in duration and distance. Also, there is no motorway sections in the cycle as stated in RDE methodology (i.e. $v_i > 90[km/h]$), which makes the average speed and trip composition criteria not valid, even if the average speed is in the RDE boundaries for rural and urban categories.

We can clearly see 2 main families of constrains that lets the target cycle not valid on the RDE testing point of view. The first one is the minimum length of a trip, which is not surprising as one of the main reasons for trip exclusion in master thesis [9] on RDE testing in Brussels was that trips were too small. The second one is the definition of speed categories where the target cycle does not fit. As driving patterns in Brussels are mainly related to urban driving, meaning low speeds. It is what represents target cycle with its maximum speed reaching 87 [km/h]. This also leads to the non-respect of trip composition criteria because motorway speed category is not represented.

This Statement confirms the conclusion of last year's thesis analysing trips driven in Brussels stating that all the trips recorded were invalid regarding RDE criteria [9]. The most unfulfilled criteria were in order of importance: minimal distance, stop portion and average speed.

4.3 Target cycle vs WLTP

Tab. 4.6 and 4.5 presents respectively target cycle V1.1 and WLTC class 3 characteristics. we see that target cycle V1.1 is more aggressive from the acceleration point of view, confirmed by a higer RPA for the whole trip. On the other hand, WLTC presents more higher speed characteristics with a mean speed of 46.5 [km/h] versus 30.03 [km/h] for target cycle V1.1. These differences in acceleration and mean speed are explained by the fact that target cycle is based on city driving while WLTC includes characteristics coming from driving patterns outside the city.

An energetic analysis is conducted in the following section in order to find the energetic differences between the two test cycles. This comparison is motivated by the fact that power at wheel is correlated to CO2 rejections of a car and fuel economy [11].

	Low	Middle	High	ExHigh	Total
Duration [s]	589	433	455	323	1800
Mean speed [km/h]	18.9	39.2	56.7	92.0	46.5
Distance [km]	3.09	4.76	7.16	8.25	23.27
RPA (-)	0.2046	0.1904	0.1223	0.1249	0.1480

Table 4.5: WLTC characteristics from [16]

	Low	Middle	High	ExHigh	Total
Duration [s]	136	458	831	375	1800
Mean speed [km/h]	6.21	18.88	26.19	61.63	30.03
Distance [km]	0.23	2.31	6.04	6.41	15.01
RPA (-)	0.1857	0.1309	0.2444	0.0758	0.1539

Table 4.6: Target cycle V1.1 characteristics

4.3.1 Energetic analysis

In this section energetic influences of the parameters of WLTC versus target cycle V1.1 is discussed. Vehicle energy demand at wheel is compared between the two cars described in section 2.1.2 and with parameters in tab. 2.1. VED is computed by time integration of equation 2.2 following either WTLC and target cycle V1.1 speed - time curve.

Fig. 4.3 and 4.4 represent VED per kilometer by speed categories. As speed categories are defined by lower speed boundaries in the target cycle, we observe that generally in every speed category VED is lower for target cycle. The only exception is in high speed category in diesel powered car. Target cycle presents lower VED on the whole cycle. VED for diesel car on the whole target cycle is at 454 [kJ/km] when under WLTC it is equal to 531 [kJ/km]. The same pattern is observed with gas powered car with 486 [kJ/km] under target cycle and 603 [kJ/km] under WLTC.

Fig. 4.5 and 4.6 present breakdown of VED contribution for the factors in equation 2.2. As a reminder, F0 and F1 represents mainly rotational inertia and road friction, F2 represents aerodynamic drag and the inertia term represents $m \cdot a$ term of Newton's second law of movement (see section 2.1.2).

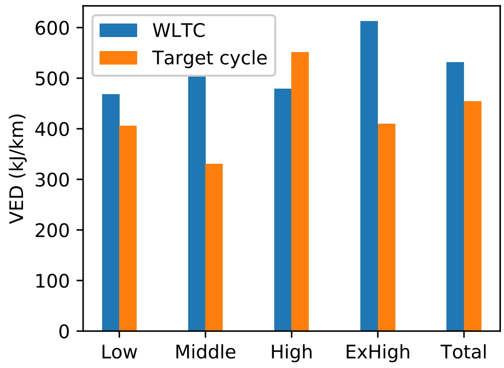

Figure 4.3: Diesel powered car VED breakdown per speed category

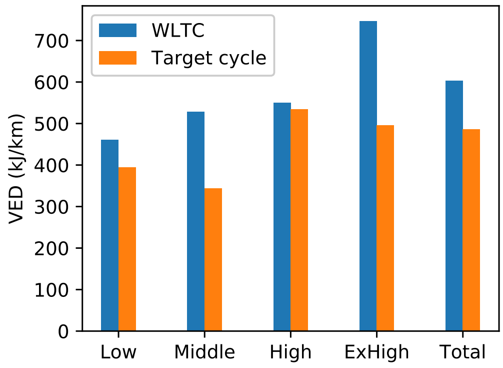

Figure 4.4: Gas powered car VED breakdown per speed category

Contribution of F0 and F1 in VED of target cycle is smaller than in WLTC for the two cars. This is rather expected as these terms are respectively constant and proportional to the speed in road loads determination while mean speed of target cycle is smaller than in WLTC. It is clear that F2 contribution in VED for both cars is lower in target cycle. The difference in F2 VED contribution between WLTC and Target cycle is 56 % for gas car and 55 % for diesel. It is also explained by the lower speed reached in target cycle, while the bigger difference in VED contribution is due to the fact that this contribution is proportionnal to the square of the speed. On the other hand, VED contribution of the inertia term is higher in target cycle. This is explained by the more aggressive acceleration profile of target cycle. This more aggressive acceleration profile is confirmed by a higher total RPA value of target cycle compared to the one of WLTC.

4.3.2 Synthesis

Comparison between the two test cycles shows that speed profile and thus mean speed is lower in test cycle V1.1 than for WLTC. This is not surprising as test cycle is about representing driving behaviours in Brussels, which is mainly composed of city driving. These lower speeds imply that from an energetic point of view less energy is demanded at the wheel for target cycle because of lower resistance forces.

On the other hand, more aggressive acceleration profile in target cycle V1.1 compared to WLTC means that more energy at the wheel is used to build kinetic energy in acceleration phase, which will later be wasted under braking.

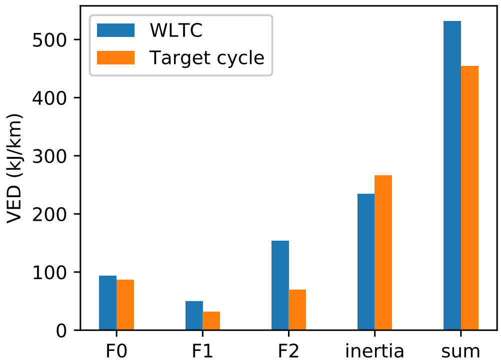

Figure 4.5: Diesel powered car VED breakdown per factor

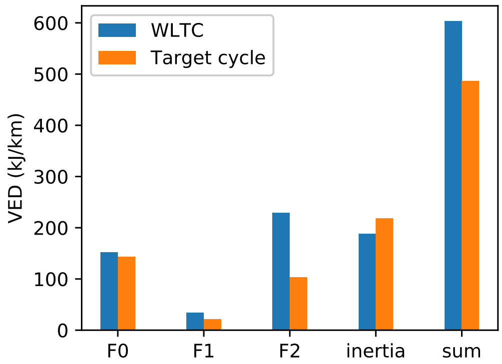

Figure 4.6: Gas powered car VED breakdown per factor

On the total energy demand, target cycle V1.1 is expected to demand lower VED than WLTC.

4.4 Conclusion

This chapter is the natural suite of ch. 3. It is a finer analysis of the results obtained there.

The study of target cycle V1.1 shows similar parameters to the database of trips driven in Brussels. Some differences are present, induced by the fact that the algorithm tasked to find the better short trip candidates combination is based on speed-acceleration comparison. Hence all other trips parameters are not optimized.

A separate chi square goodness of fit test has been done between database and target cycle V1.1 . This has been done for every speed category. This test does not show evidence to reject the hypothesis that target cycle V1.1 represents the speed acceleration distribution of the data collected.

RDE crieteria have been applied to target cycle V1.1. As expected, target cycle V1.1 is considered invalid from this point of view. This goes in the sense of last year master thesis applying these criteria to trips driven in Brussels [9] stating that all of them were invalid. Two major families of constrains lets target cycle invalid regarding RDE criteria. The first one is the minimal distance and time duration. The second one is RDE definition of speed categories which dosn't fit target cycle ones.

From the energy point of view, we see that target cycle V1.1 will ask less VED than WLTC on the whole cycle. This is due to lower speeds meaning lower resistance forces both mechanical and aerodynamical. The only factor implying more VED in target cycle V1.1 than in WLTC is the more aggressive acceleration profile, meaning more kinetic energy used for acceleration and then wasted under braking.

Chapter 5

Statistics on harvested data

As driving conditions and population of data harvested in 2019 are not the same as the ones in 2020 because od the coronavirus pandemic context, a statistic analysis on short trips parameters is made.

This analysis is based on hypothesis testing. The H_0 hypothesis states that the two independent samples (here distributions of parameters from 2019 and 2020) tested were selected from populations having the same distribution. The Mann–Whitney U [2] test is used in every subsection as all samples studied here are not normally distributed (see quartile quartile plot [15] in every section), thus excluding t-test to compute the p-value.

The p-value resulting from the test is the indicator of whether H_0 is valid or not. The decision intervals are :

- $p \leq 0.01$: very high presumption against H_0.
- $0.01 < p \leq 0.05$: high presumption against H_0.
- $0.05 < p \leq 0.1$: low presumption against H_0.
- $p > 0.1$: no presumption against H_0.

The parameters studied below are mean the and maximum speed, RPA, distance travelled, duration of short trips. Idling durations are also inspected.

5.1 Mean speed

H_0 is defined in this section as stating that the 2019 and 2020 distribution of mean speed comes from populations having the same mean speed distribution.

Q-Q plot on fig. 5.1 shows that mean speed is not normally distributed with a deviation at low and high mean speed. Mann–Whitney U test is therefore computed and gives a p-value of 0.000357702 . This gives us a very high presumption against H_0.

We can observe on fig 5.2 that the distribution of mean speed has rather a close shape for 2019 and 2020. Nevertheless, the head of distribution presents a difference in the two cases with $P(X \leq 6) = 20.5[\%]$ for 2019 measures while $P(X \leq 6) = 24.5[\%]$ in 2020 measures. This difference is attenuated with increasing mean speed with $P(X \leq 40) = 95.3[\%]$ for 2019 measures while $P(X \leq 40) = 93.2[\%]$ in 2020.

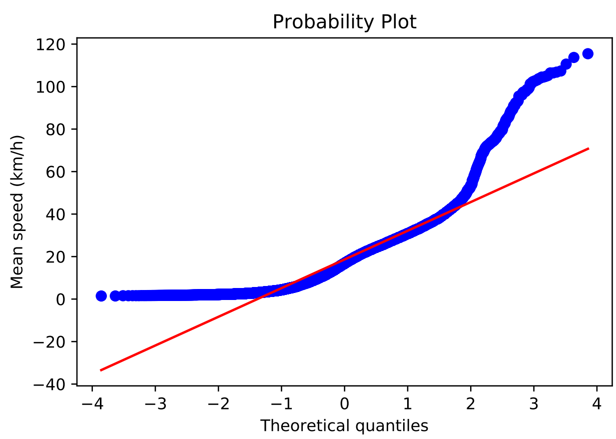

Figure 5.1: Q-Q plot for total mean speed distribution

This difference in mean speed distribution between the two years could be explained either by the fact that road traffic was less dense in 2020 due to confinement (as 2020 trips were recorded during confinement period) or the fact that the six drivers recorded in 2020 have different driving behaviour than the ones in 2019 concerning mean speed.

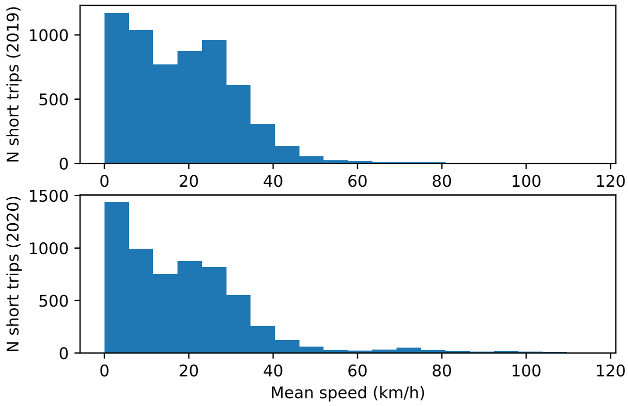

Figure 5.2: Mean speed distribution

5.2 Maximum speed

H_0 is defined in this section as stating that the 2019 and 2020 distribution of maximum speed comes from populations having the same maximum speed distribution.

The Q-Q plot in fig 5.3 shows deviation from normal distribution in the maximum speed distribution. Mann–Whitney U test p-value is computed in this case and is equal to 0.0199621. There is a high presumption against H_0.

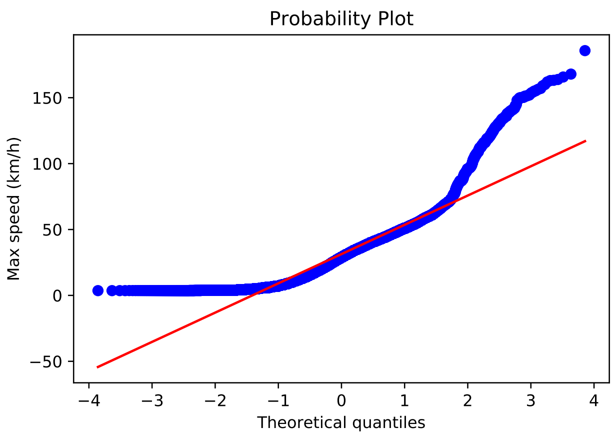

Figure 5.3: Q-Q plot for maximum speed distribution

Similarities in the two distributions on fig. 5.4 can be detected. On the other hand, the head of distribution is different with $P(X \leq 10) = 19.8[\%]$ for 2019 while $P(X \leq 10) = 24.0[\%]$ in 2020. Also, the tail of 2020 maximum speed distribution presents more occurrences than the one in 2019.

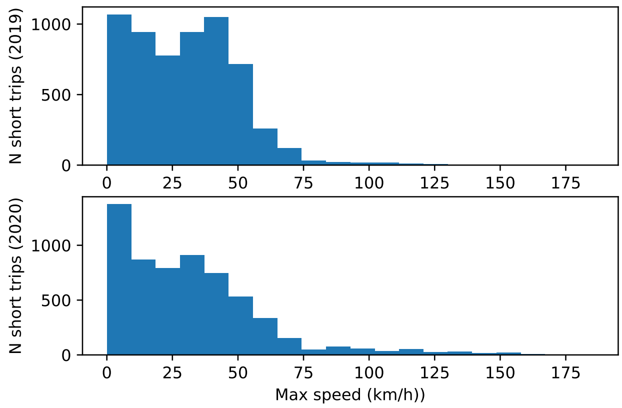

Figure 5.4: Maximum speed distribution

5.3 RPA

H_0 is defined in this section as stating that the 2019 and 2020 distribution of RPA comes from populations having the same RPA distribution.

Q-Q plot in fig 5.5 shows a deviation from normal distribution at low and high values of RPA. We compute the Mann–Whitney U test p-value which is equal to 0.00100864. There is a very high presumption against H_0.

We see on fig. 5.6 that distribution of RPA in 2020 has slightly more sort trip proportion with $RPA < 0.2$, with $P(X \leq 0.2) = 31.4[\%]$ in 2019 while $P(X \leq 0.2) = 37.5[\%]$ in 2020. This gives an idea on why despite an overall concordant shape between the two distributions we still have very high presumption against H_0.

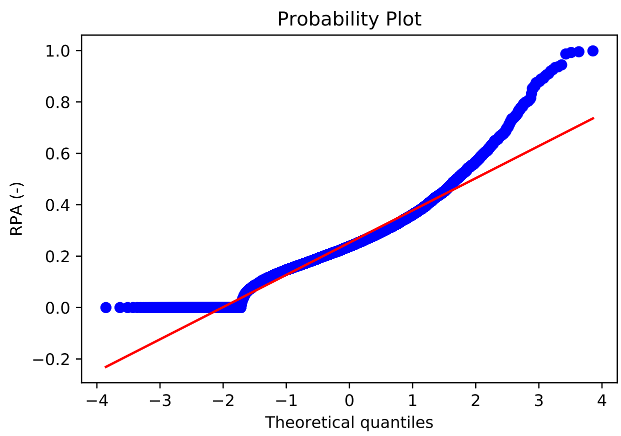

Figure 5.5: Q-Q plot for RPA distribution

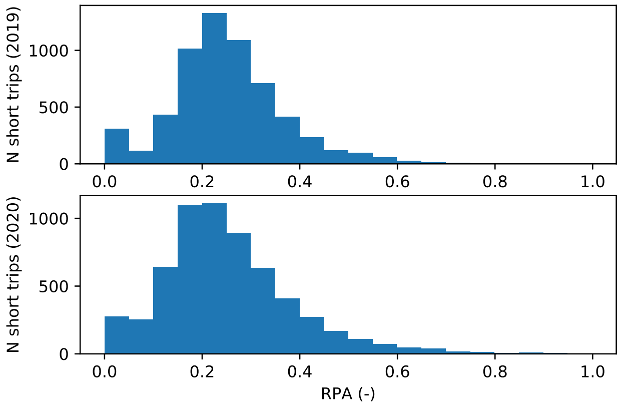

Figure 5.6: RPA distribution

5.4 Short trip distance

H_0 is defined in this section as stating that the 2019 and 2020 distribution of short trip distances comes from populations having the same short trip distance distribution.

As Q-Q plot 5.7 shows no convergence of the two distributions towards a normal distribution, Mann–Whitney U test is applied and returns a p-value equal to 0.103562. This p-value above 0.1 gives us no reasons against H_0, while no further conclusion can be drawn by this p-value.

We can certainly see no big difference in the shape of the two distributions in fig. 5.8.

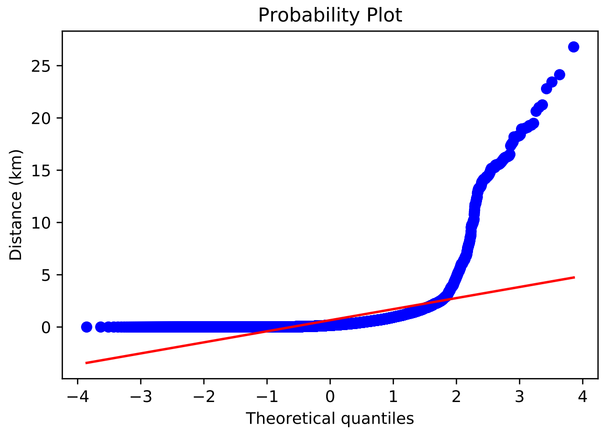

Figure 5.7: Q-Q plot for distance distribution

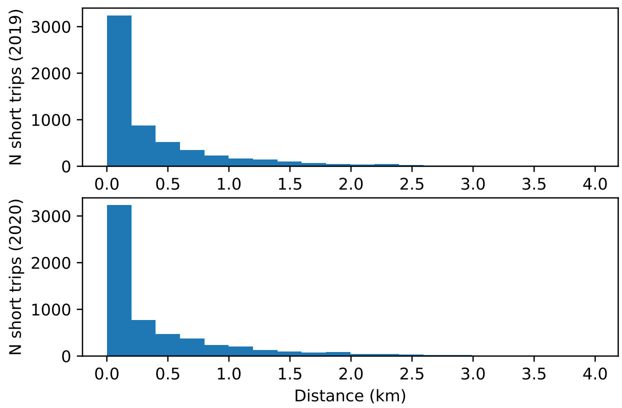

Figure 5.8: distance distribution

5.5 Idling duration

H_0 is defined in this section as stating that the 2019 and 2020 distribution of idling duration comes from populations having the same idling duration distribution.

Q-Q plot in fig. 5.9 shows that data does not presents normal distribution characteristics. Taking this into consideration the Mann–Whitney U test is performed with the two datasets. P-value is equal to 0.0182941, which gives a high presumption against H_0.

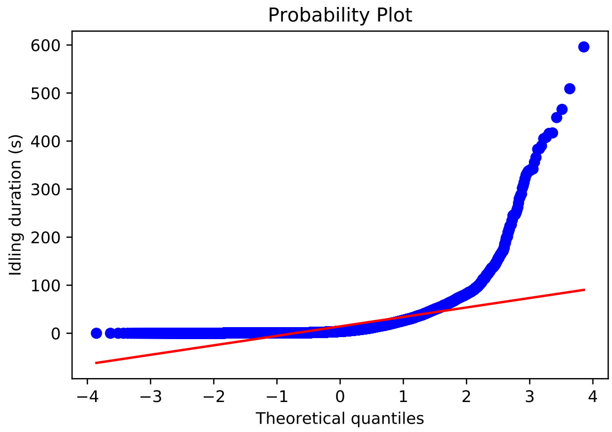

Figure 5.9: Q-Q plot for idling distribution

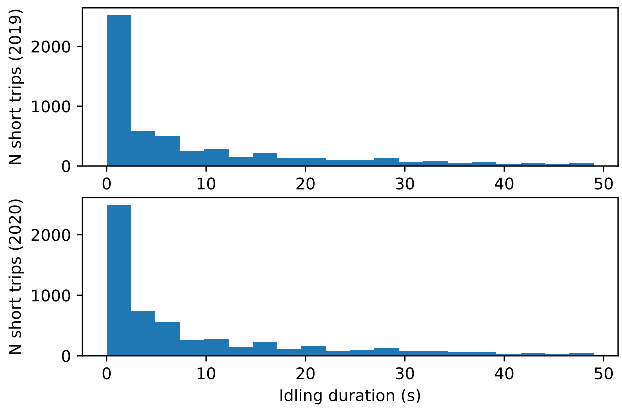

Figure 5.10: idling distribution

5.6 Short trip duration

H_0 is defined in this section as stating that the 2019 and 2020 distribution of short trip duration comes from populations having the same short trip duration distribution.

We see on 5.11 that the distribution of all the samples does not fit a normal distribution. Again, the Mann–Whitney U test is performed and gives 0.000263521 for p-value, which gives us a very high presumption against H_0.

Concerning the head of the distribution (see fig. 5.12) where $P(X \leq 50) = 64.7[\%]$ in 2019 while we see that it drops to $P(X \leq 50) = 60.0[\%]$ in 2020, which is a big difference.

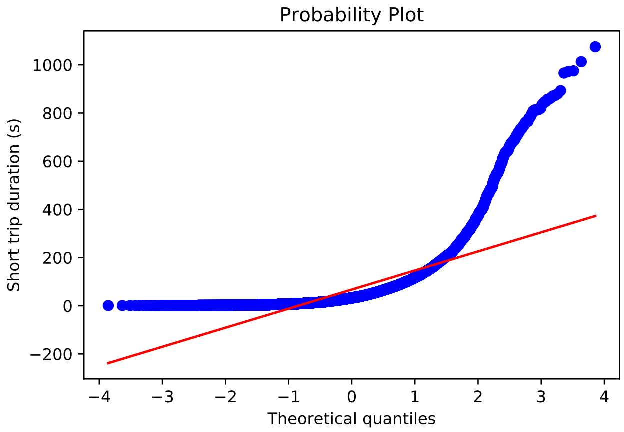

Figure 5.11: Q-Q plot for short trip duration distribution

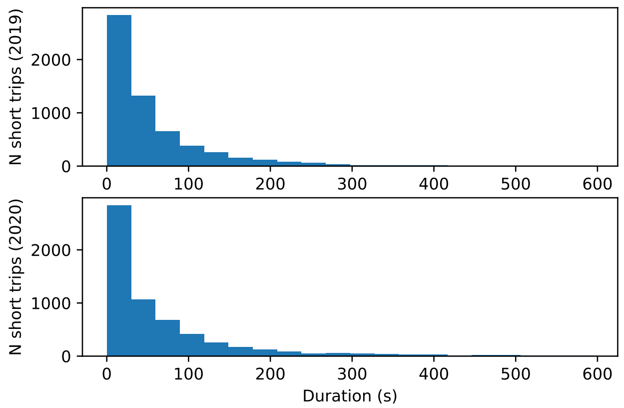

Figure 5.12: Short trip duration distribution

5.7 Conclusion

In this chapter seven parameters describing short trip and idling databases were analysed. A H_0 hypothesis stating that for each parameter the 2020 and the 2019 samples distributions come from populations having the same distribution.

As all distributions were not normally distributed, The Mann–Whitney U test has been used to compute p-values. A synthesis table of these is presented in tab. 5.1 . The short trip distance distribution is the only one presenting no presumption against H_0, while Mean speed presents a very high presumption against H_0. The four other parameters present a high against H_0.

We cannot conclude that the short trips parameters come from different distributions in 2019 versus 2020 as p-value are not too low, neither can we conclude the opposite.

In fact, this result is not surprising, as short trips parameters distribution in 2019 and 2020 are rather close but not exactly the same. There is suspicion that they come from slightly different distributions. This difference could come either from a different type of driver recorded in 2020 or a change in driving condition due to coronavirus-related lockdown or a combination of both.

Parameter	p-value	Presumption of H_0 rejection
Mean speed	0.000357702	very high
Maximum speed	0.0199621	high
RPA	0.00100864	high
ST distance	0.103562	no
Idling duration	0.0182941	high
ST duration	0.0182941	high

Table 5.1: P-value synthesis for short trips parameters distribution

Chapter 6

Conclusion

The goal of this master thesis was to build a test cycle speed versus time curve representing driving patterns in Brussels. Data coming from cars driving in Brussels was harvested, filtered and resampled in a clean and ordered database. An algorithm was developed to find a 1800 [s] target cycle retaining the most characteristics of the database using chi-square goodness of fit testing.

Corrections have been made to the target cycle in order to be able to reproduce this speed versus time on a rolling bench with the tested car. These corrections are mainly maid by limiting acceleration and deceleration values to avoid wheel spin and wheel lock of the car.

The final version of test cycle numbered V1.1 presents similar speed and acceleration characteristics than the database of trips driven in Brussels while some minor differences are perceptible. These differences are due to the fact that target cycle is a compromise between statistical representativeness of database and reproducibility in lab.

When applying RDE validity criteria on target cycle V1.1, we are not surprised to see that it is considered as invalid (as stated in [9]). The main parameters making the cycle invalid are the minimum distance and duration in combination with the speed categories defined by RDE not representative of speed distributions encountered in Brussels. The conclusion on RDE testing is that it does not represents driving patterns in Brussels.

On the vehicle energy demand at wheel point of view, we see a lower VED demand for target cycle V1.1 compared to WLTP because of lower speeds, meaning lower mechanical and aerodynamical resistance. The only aspect demanding more VED for target cycle V1.1 is the more aggressive acceleration profile, meaning more energy wasted under braking, which is quite expected for a cycle representing city driving (target cycle) compared to a WLTP modelling city, extra urban and motorway patterns.

Statistical hypothesis testing between data on driving patterns was conducted. Also, data from 2019 was recorded under normal driving conditions while data from 2020 was mostly recorded during coronavirus lockdown. The conclusion is that while the two datasets seem to come from different populations having nonequal driving parameters distribution, the two are not fundamentally different. These little differences could be due to different driving conditions in 2020, but could also come from the fact that the two populations have slightly different driving habits.

This thesis was a good opportunity to get know-how on vehicle testing procedures. While theoretical results show a lower energy demand for cars tested under target cycle V1.1 than under WLTP, in lab validations about this assumption could be very interesting.

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Chapter 7

Appendix

7.1 Data loggers

7.1.1 Datalogger V1.0

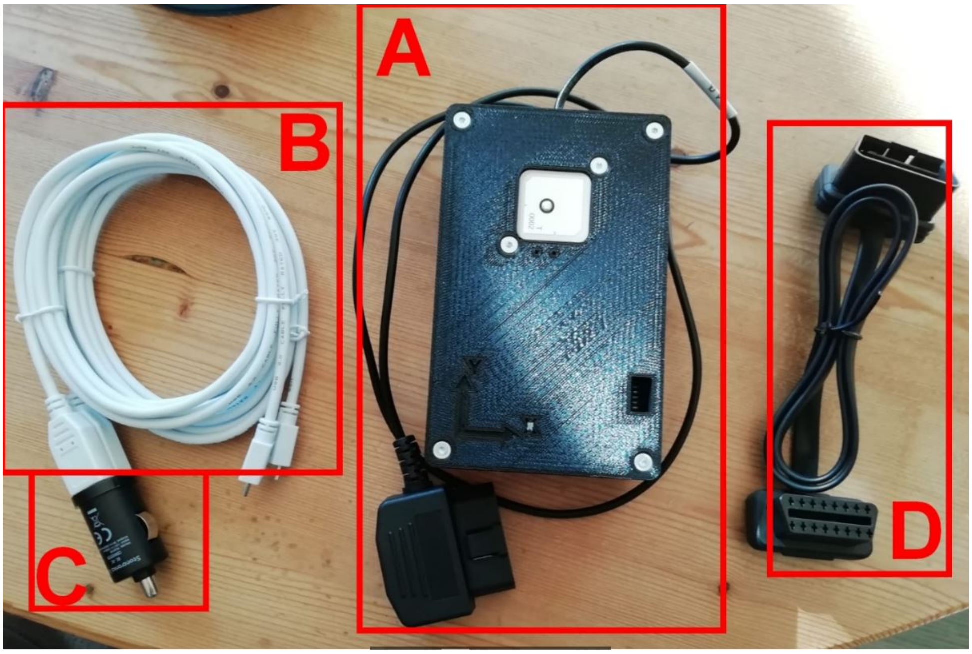

Figure 7.1: Data logger V1.0

- A : DataLogger composed by the battery, GPS chip and Arduino inside the box.

- B : Alimentation cables.

- C : 12 V alimentation socket.

- D : OBD2 socket extender cable.

7.1.2 Datalogger V2.0

Figure 7.2: Data logger V2.0

7.2 Short trip duration distributions

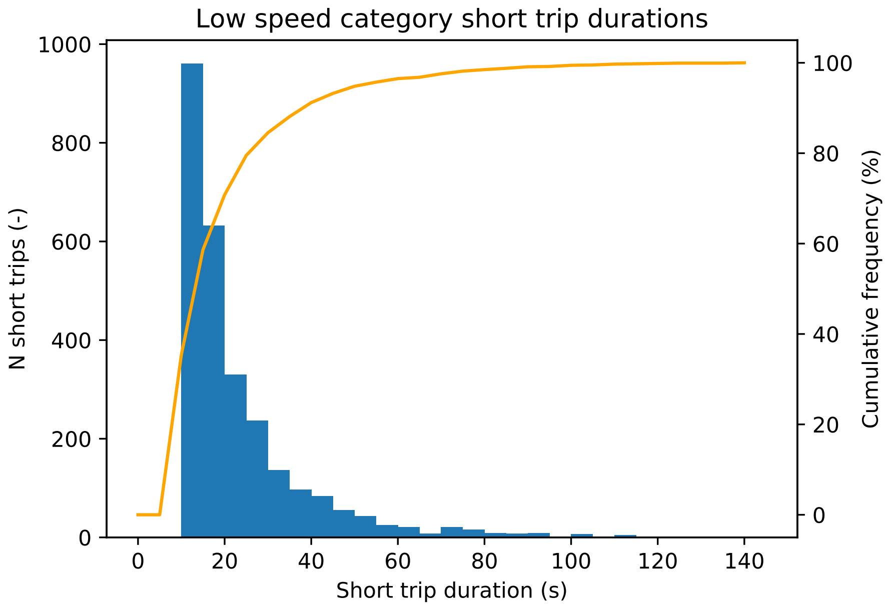

Figure 7.3: Low Speed category short trip durations

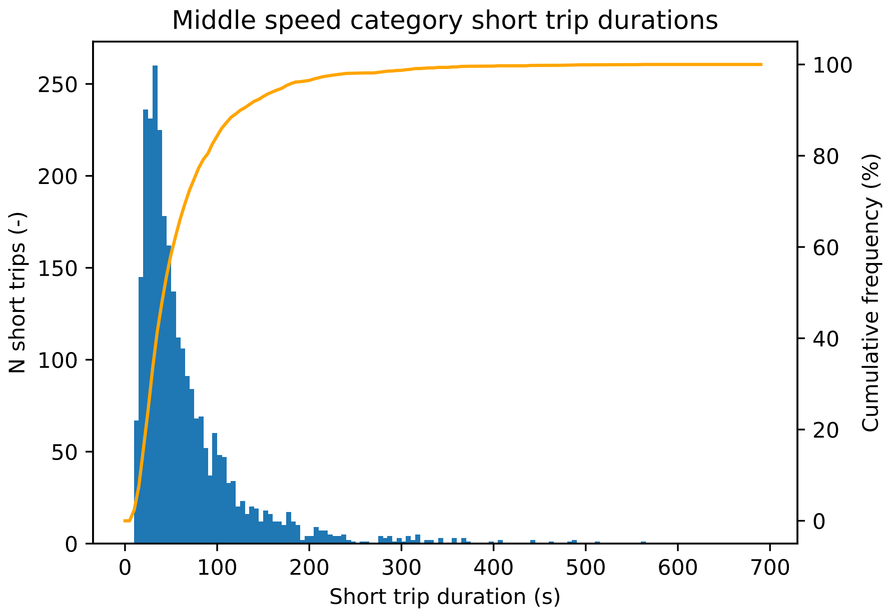

Figure 7.4: Middle Speed category short trip durations

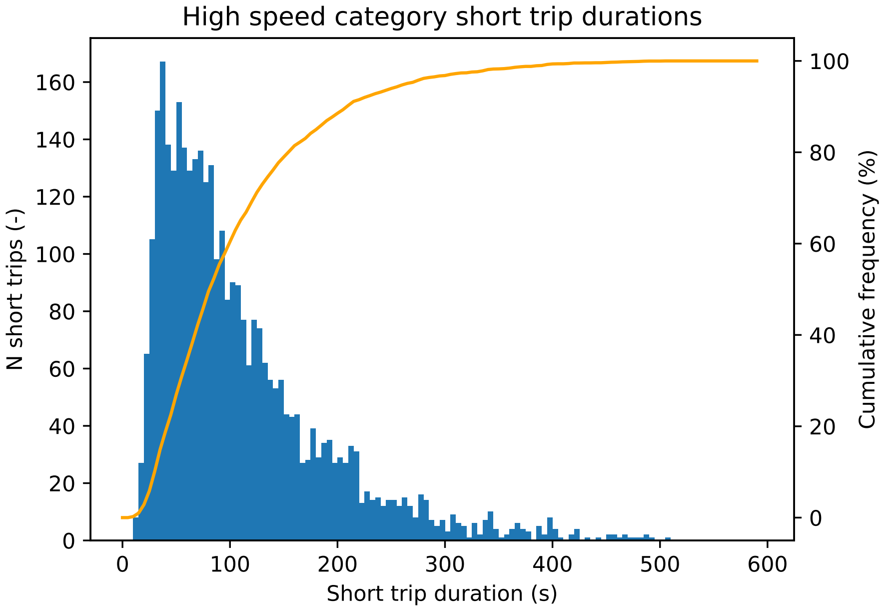

Figure 7.5: High Speed category short trip durations

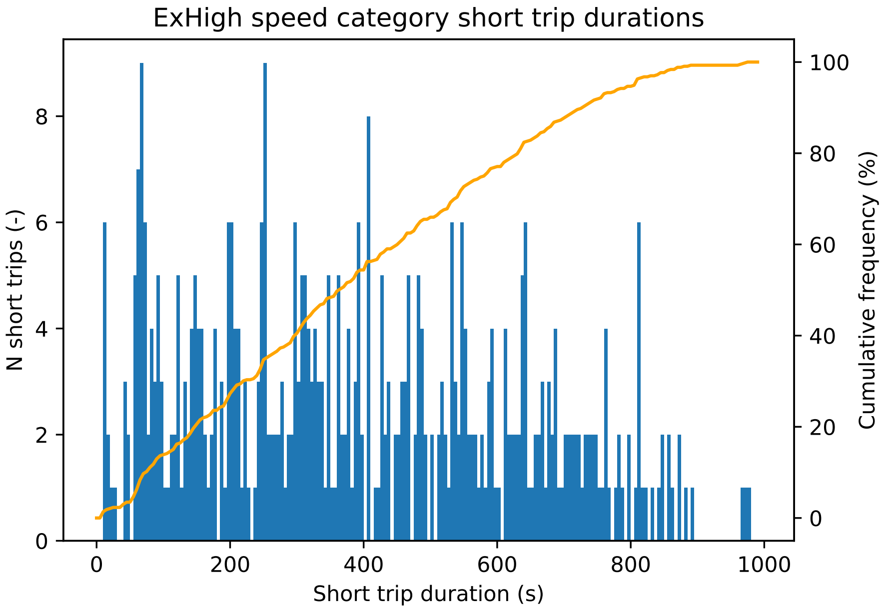

Figure 7.6: Ex High Speed category short trip durations

7.3 Idling duration distributions

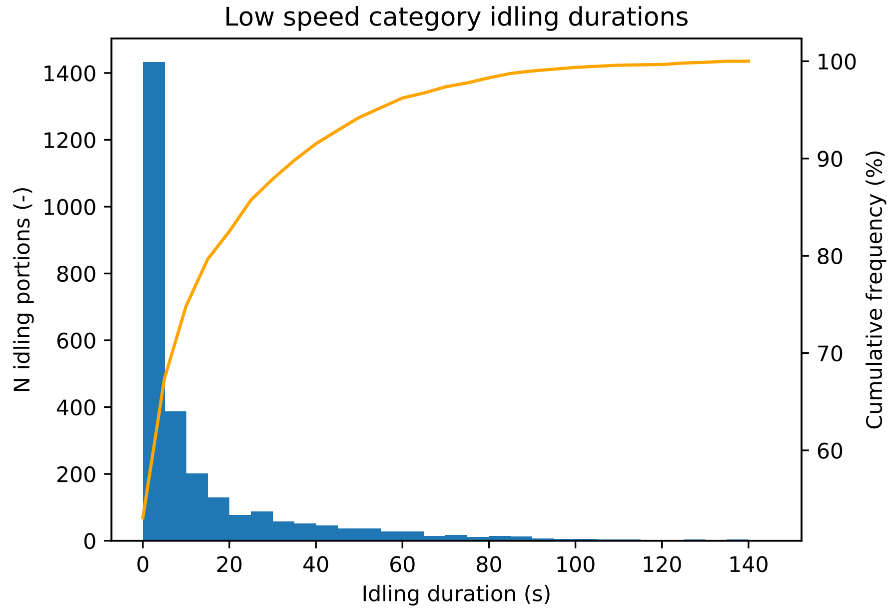

Figure 7.7: Low Speed category idling durations

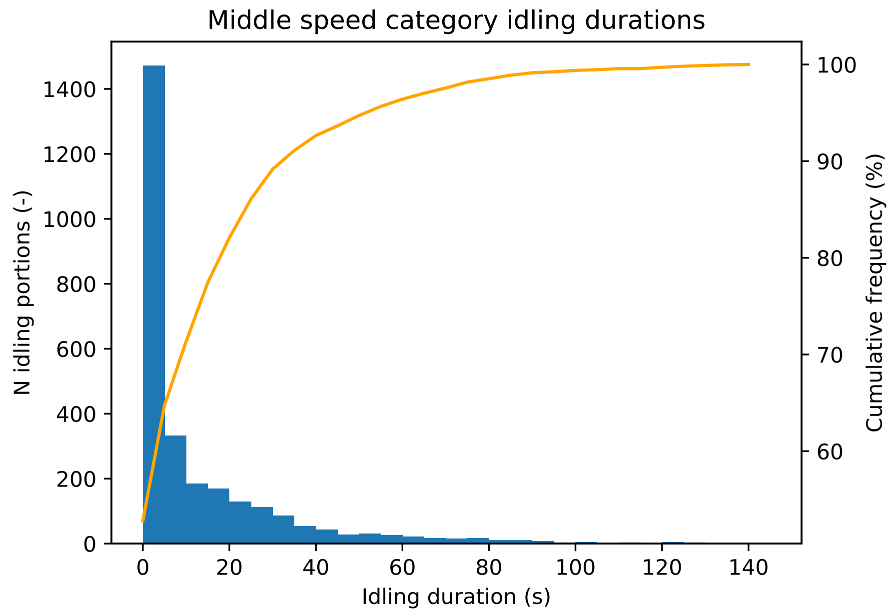

Figure 7.8: Middle Speed category idling durations

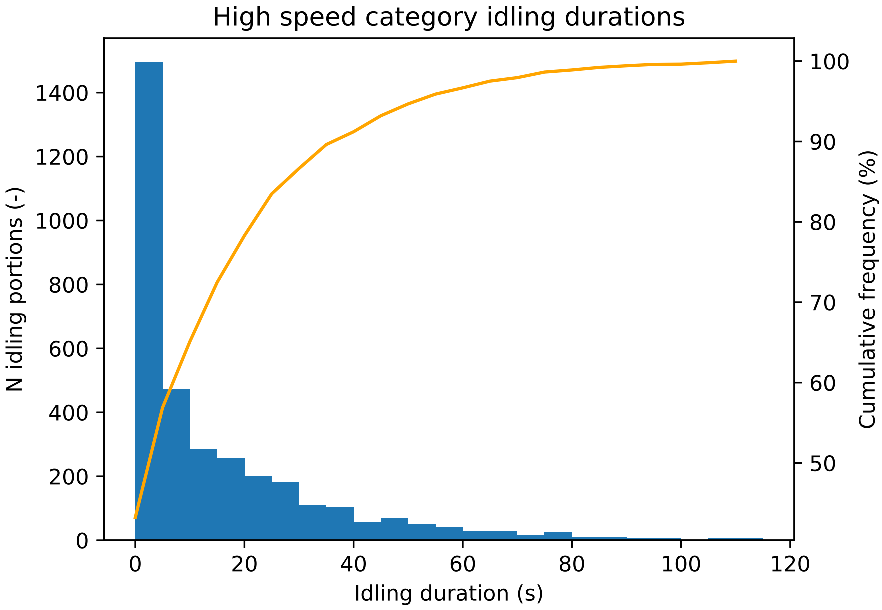

Figure 7.9: High Speed category idling durations

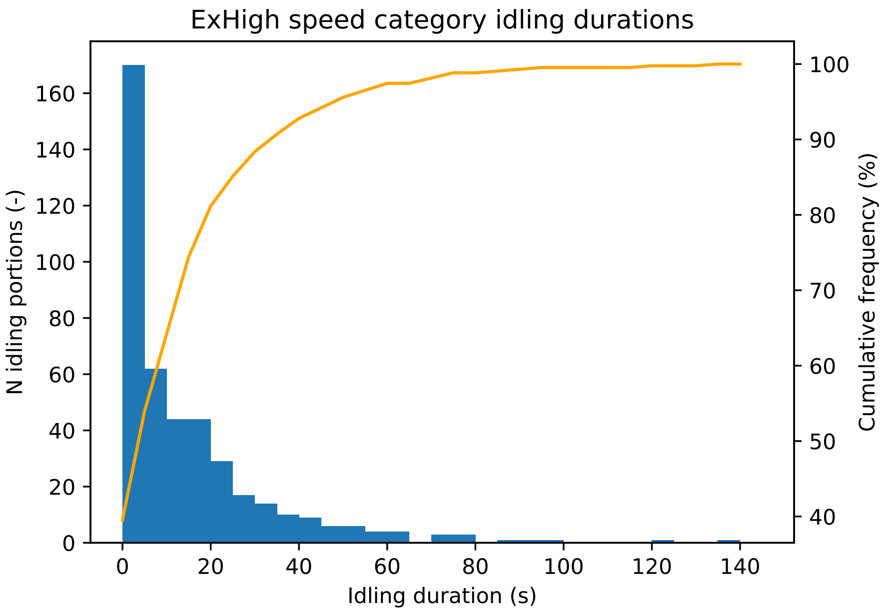

Figure 7.10: Ex High Speed category idling durations

7.4 Detailed durations for each short trip

Name	Speed category	Type	Duration (s)
IDLE1	Low	idling	1
ST1	Low	Short trip	10
IDLE2	Low	idling	1
ST2	Low	Short trip	14
IDLE3	Low	idling	4
ST3	Low	Short trip	20
IDLE4	Low	idling	10
ST4	Low	Short trip	37
IDLE5	Low	idling	39
IDLE1	Middle	idling	2
ST1	Middle	Short trip	36
IDLE2	Middle	idling	2
ST2	Middle	Short trip	58
IDLE3	Middle	idling	6
ST3	Middle	Short trip	94
IDLE4	Middle	idling	22
ST4	Middle	Short trip	179
IDLE5	Middle	idling	59
IDLE1	High	idling	1
ST1	High	Short trip	30
IDLE2	High	idling	1
ST2	High	Short trip	47
IDLE3	High	idling	2
ST3	High	Short trip	64
IDLE4	High	idling	5
ST4	High	Short trip	82
IDLE5	High	idling	10
ST5	High	Short trip	110
IDLE6	High	idling	16
ST6	High	Short trip	149
IDLE7	High	idling	27
ST7	High	Short trip	230
IDLE8	High	idling	53
IDLE1	ExHigh	idling	2
ST1	ExHigh	Short trip	353
IDLE2	ExHigh	idling	20

Table 7.1: Duration for each short trip and idling of the target cycle

7.5 Speed - acceleration scatter plots

7.5.1 Trips database

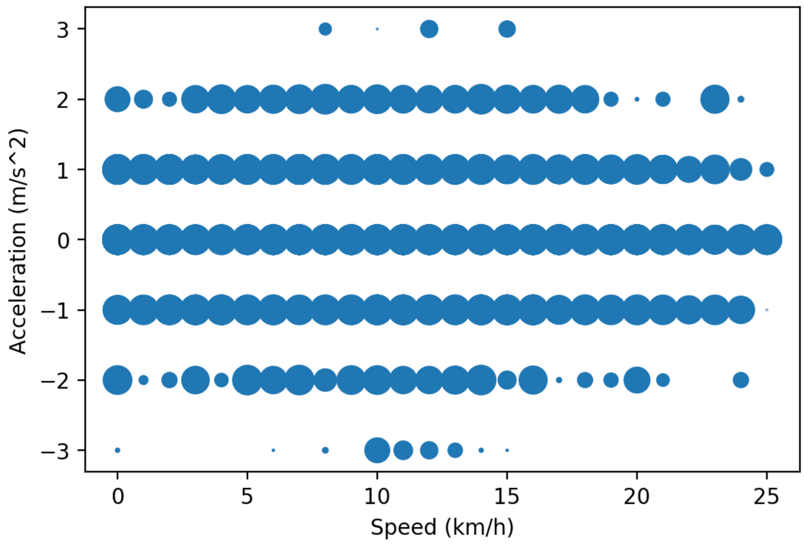

Figure 7.11: Speed acceleration scatter plot for low speed short trips in database

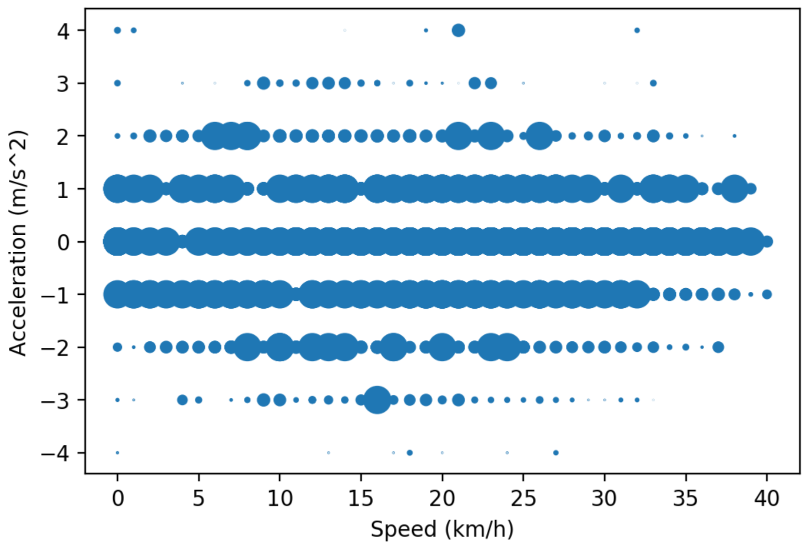

Figure 7.12: Speed acceleration scatter plot for middle speed short trips in database

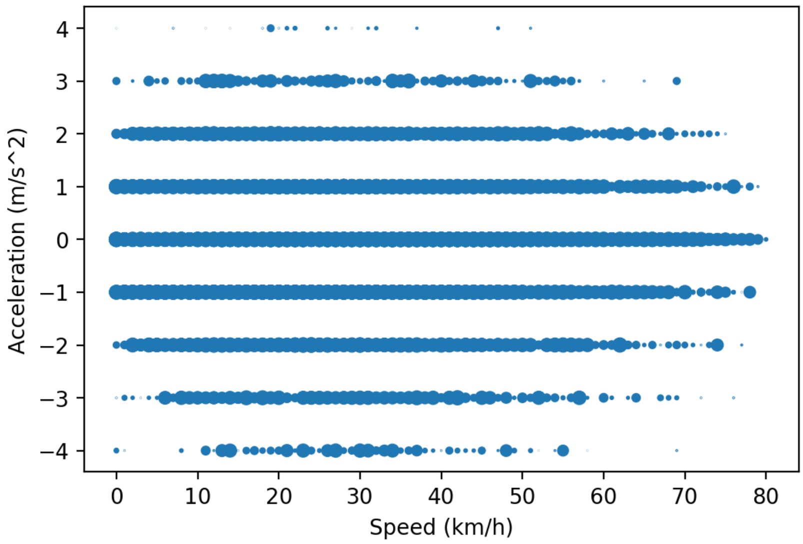

Figure 7.13: Speed acceleration scatter plot for high speed short trips in database

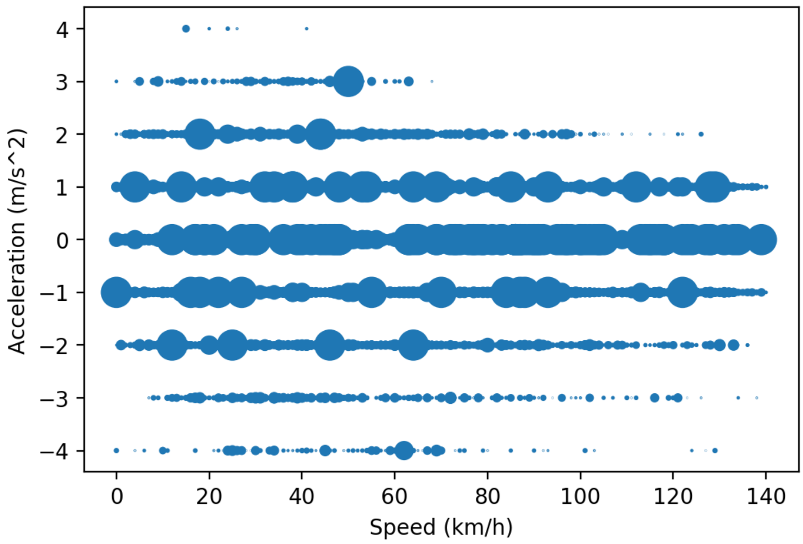

Figure 7.14: Speed acceleration scatter plot for extra high speed short trips in database

7.5.2 Target cycle V1.1

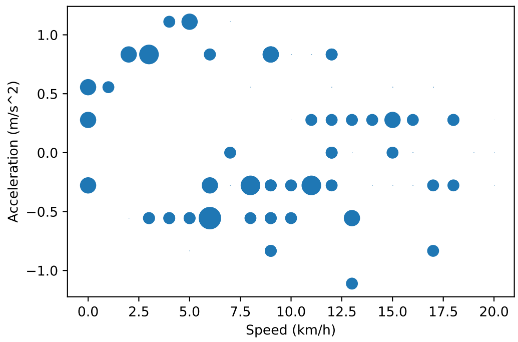

Figure 7.15: Speed acceleration scatter plot for low speed short trips in database

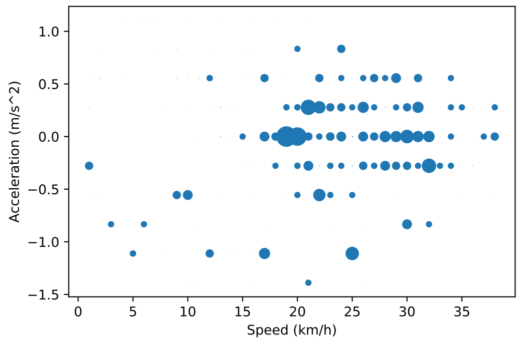

Figure 7.16: Speed acceleration scatter plot for middle speed short trips in database

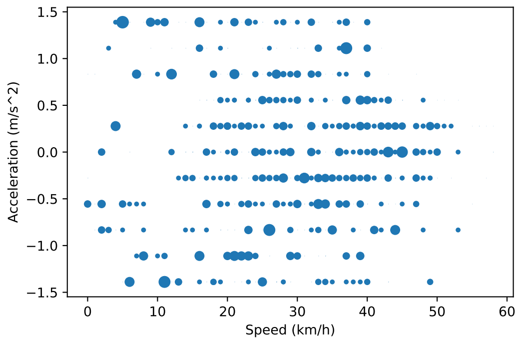

Figure 7.17: Speed acceleration scatter plot for high speed short trips in database

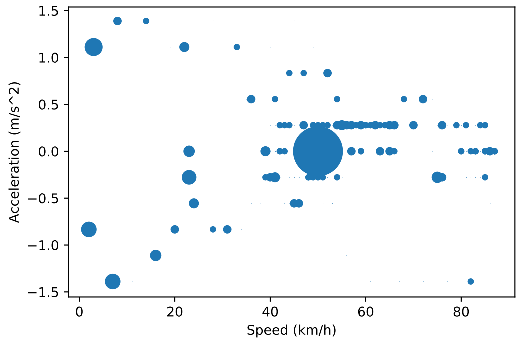

Figure 7.18: Speed acceleration scatter plot for extra high speed short trips in database

7.6 Energetic analysis data

	F0 [kJ/km]	F1 [kJ/km]	F2 [kJ/km]	inertia [kJ/km]	sum [kJ/km]
WLTC	93.436502	49.590309	153.528639	234.769767	531.325218
Target	86.658890	31.535344	69.633111	266.551692	454.379037

Table 7.2: Diesel powered road load factors energetic breakdown

ST Type	Low [kJ/km]	Middle [kJ/km]	High [kJ/km]	ExHigh [kJ/km]	Total [kJ/km]
WLTC	467.820490	510.854335	479.015669	612.314992	531.325218
Target	405.581152	330.964216	551.078161	409.551236	454.379037

Table 7.3: Diesel powered speed category energetic breakdown

	F0 [kJ/km]	F1 [kJ/km]	F2 [kJ/km]	inertia [kJ/km]	sum [kJ/km]
WLTC	151.881545	33.695102	229.610979	187.885649	603.073275
Target	142.901950	21.530966	103.806821	218.487298	486.727034

Table 7.4: Gas powered car road load factors energetic breakdown

ST Type	Low [kJ/km]	Middle [kJ/km]	High [kJ/km]	ExHigh [kJ/km]	Total [kJ/km]
WLTC	460.336272	528.192482	549.564913	746.157900	603.073275
Target	394.827407	344.370918	534.804862	496.106833	486.727034

Table 7.5: Gas powered speed category energetic breakdown

7.7 Other appendices

A folder called Bertrand_44881400_2020_Appendix1.zip has been submitted with this thesis. It contains:

- TargetCycleV1.1.csv: A file containing the data points of target cycle V1.1, i.e. speed, acceleration and short trips labels.
- CarsList.xlsx : List of cars recorded.
- Trips : A folder containig all the trips recorded in 2019 and 2020.
- TripsFormat.txt : A file describing nomenclature for trips numeration.

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