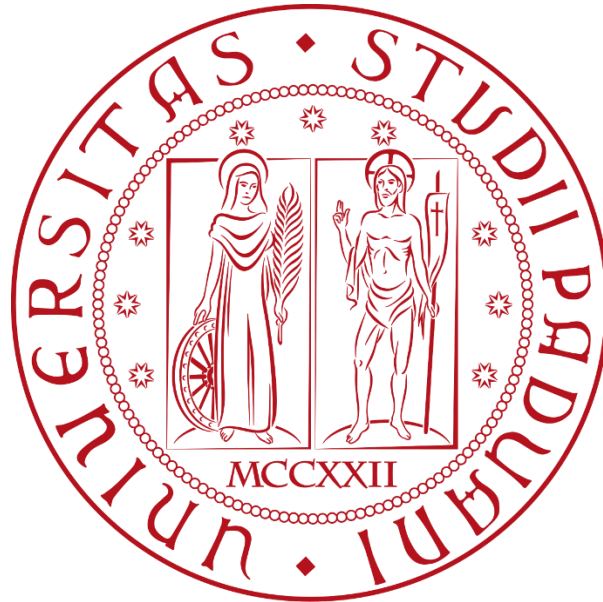


UNIVERSITY OF PADUA

DEPARTMENT OF INDUSTRIAL ENGINEERING



Master degree in Mechanical Engineering

**Acquisition and analysis of engine and rider power output for the
classification of e-bike users and the identification of appropriate
power unit testing**

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ABSTRACT (italian version)

La quantità di biciclette a pedalata assistita che vediamo sui sentieri è aumentata notevolmente negli ultimi decenni, soprattutto nell'ambiente alpino. L'utente di questo tipo di bicicletta può variare, passando dal ciclista esperto che si gode la discesa ma vuole comunque salire da solo al neofita che noleggia la bicicletta per fare un giro in luoghi che non potrebbe raggiungere senza l'aiuto della pedalata assistita.

Il seguente progetto di tesi si propone di esplorare il modo in cui ciclisti con diversi livelli di allenamento e abilità utilizzano la bicicletta, concentrandosi sulla salita, attraverso l'uso di un sistema di telemetria posizionato sulla bicicletta. Questo sistema permette di raccogliere diversi parametri come: coppia erogata dal motore, coppia impartita dall'atleta, tipo di mappatura, tipo di marcia, velocità di rotazione della ruota posteriore e cadenza di pedalata sulla pedivella. I sensori sono posizionati sulla bicicletta e trasmettono il segnale in modalità wireless al ricevitore posto su uno zaino che il ciclista deve indossare per tutta la durata della sessione di test.

In primo luogo è stata misurata la quantità di aiuto che la bicicletta può fornire al ciclista con le varie mappe disponibili, al fine di comprendere meglio i comportamenti della bicicletta. Questi risultati sono stati utilizzati, in combinazione con alcuni test più lunghi con diversi piloti, per valutare il ciclo di funzionamento della mappa del motore di diversi piloti con diversi livelli di allenamento e di abilità. Questi test sono stati condotti per analizzare l'impatto del pilota sulle prestazioni della moto.

Infine, sono stati valutati i profili di coppia della pedalata in diverse condizioni. Questo, in combinazione con i risultati della lunga salita, ha fornito un ampio campo visivo per capire come testare il motore elettrico in-vitro.

INDICE:

- Capitolo 1: Breve introduzione al mondo delle e-MTB e al loro produttore, seguita dalla descrizione del sistema di telemetria e dei metodi di prova.

- Capitolo 2: Descrizione approfondita della bicicletta e del sistema di telemetria, con particolare attenzione ai tipi di sensori utilizzati e ai tipi di dati in uscita.
- Capitolo 3: Presentazione dei percorsi utilizzati durante i test in termini di lunghezza, dislivello e superficie e dei livelli di allenamento e abilità dei ciclisti.
- Capitolo 4: Grafico e confronto della coppia e della potenza misurate per ciascuna mappa del motore.
- Capitolo 5: Analisi dello stile di guida dei diversi piloti durante una lunga salita, con particolare attenzione alla selezione della mappa e della marcia.
- Capitolo 6: Profilo di coppia tipico di diversi ciclisti per costruire un banco di prova per il motore della e-bike al fine di effettuare test al chiuso e in vitro.
- Capitolo 7: Conclusioni sul lavoro svolto e possibili sviluppi futuri.

ABSTRACT (english version)

The amount of pedal-assisted bicycles that we see on the trails has increased significantly in the last decades, especially in the alpine environment. The user of this type of bike may vary, going from the experienced rider who enjoys the descent but still wants to climb on his own to the newbie that rents the bike for a ride in places which he couldn't reach without the help of the pedal assistance.

The following thesis project aims to explore how riders with different levels of training and skills use the bike, focusing on the uphill, through the use of a telemetry system placed on the bike. This system allows to collect different parameters as: torque delivered by the engine, torque imparted by the athlete, type of mapping, type of gear, rotation speed of the rear wheel and pedalling cadence on the crank. The sensors are placed on the bike and transmit the signal wirelessly to the receiver placed on a backpack that the rider must wear throughout the testing session.

In first place was measured the amount of help that the bike can provide to the rider with the various maps available, in order to understand better the bike behaviours. These results were used, in combination with some longer tests with different riders, to evaluate the engine map duty cycle of different riders with different levels of training and different levels of skills. These tests were conducted to analyse the impact of the rider on the bike performance.

Lastly was evaluated the torque profiles of the pedal stroke in different conditions. This, in combination with the results of the long climb, provided a wide field of view to understand how to test the electric motor in-vitro.

INDEX:

- Chapter 1: Brief introduction to the e-MTB world and manufacturer, followed by the description of the telemetry system and the testing methods.
- Chapter 2: In depth description of the bike and the telemetry system focusing on the types of sensors used and the types of data output.

- Chapter 3: Presentation of the trails used during the testing in terms of length, elevation gain and surface and riders' levels of training and skills
- Chapter 4: Graph and comparison of torque and power output measured for each engine map.
- Chapter 5: Analysis of the riding style of different riders during a long climb focusing especially on map selection and gear.
- Chapter 6: Typical torque profile of different riders to build a testing bench for e-bike's motor in order to test indoor and in vitro.
- Chapter 7: Conclusions on the work carried out and possible future developments.

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Chapter 1

INTRODUCTION

1.1 Fantic motor

Fantic was founded in Barzago in 1968 and now is based in Santa Maria di Sala (Venice, Italy). The company started with the production of motorcycles, mini-bikes and go-kart, but over the years converted a lot of his production into e-mobility. Fantic individuates five several categories of e-mtb (Armagnio G. (2023)):

- E-MTB XC/DC studied with lightness as the principal aim.
- E-MTB TRAIL designed for long distances and quite demanding slopes.
- E-MTB ALL MOUNTAIN developed for the perfect combination between balance and versatility use.
- E-MTB ENDURO bike parks and tough downhill are the daily bread.
- E-MTB DOWNHILL manufactured for a unique experience during steep downhill riding
- E-MTB HARD TRAIL studied for the hilly trails.
- TREKKING a model though mainly for moving the bike in the city every day. The design is the key of the success.

It is important to underline that for each model there are different configurations. For example, it is possible to choose carbon frame instead of aluminium frame or a different quality drivetrain.

1.2 Telemetry system

The telemetry is a system that allows to measure and collect information coming from each one of the telemeters. The communication between the acquisition modules can be both wired or wireless, in this case it is wireless for simplicity, in fact having parts rotating in respect to the bike frame, it would have been hard to use wired transmission.

1.2.1 Mantracourt telemetry system

The telemetry system connected to the e-bike is produced by Mantracourt, a British company based near Exeter in the South-West of England. More specifically the system is the T24 Telemetry System. It works with a wireless transmission between the acquisition module attached to the sensor and the base station based on 2.4 GHz band. Every sensor equipped on the bike has its own acquisition module. The base station can receive the signal from multiple acquisition modules, in this case eight. To supply the system each acquisition module is connected to a 3 V battery, more specifically two 1.5 V type INTRODUCTION AAA batteries in series, placed inside a proper battery case and wired to the acquisition module, and the base is connected to a PC that supplies it and also record the data received from every sensor.



Figure 1.1: T24 Telemetry system. Data from Mantracourt [?]

1.2.2 Garmin Edge 130

Besides the Mantracourt telemetry system, a Garmin Edge 130 has been used. With the use of GPS, barometric altimeter and cadence sensors it allowed to record additional information very useful both to have a wider field of view of the track and rider performance and to verify the proper operation of the telemetry system.

It was used also to guide riders through some trails providing a navigation via GPS using the .gpx track.



Figure 1.2: Garmin Edge 130

1.3 Thesis purpose

In this work the main purpose was to acquire and analyse the torque output both from the rider and the electric motor, in particular to understand the usage to classify the typical e-bike's rider.

In the first place the bike response was studied under a constant load trying to understand the amount of torque that was produced by the electric motor given the rider's torque. The results of this first experiment were used also to understand deeper the so called duty cycle evaluated in the second part of the work.

The behaviour of the rider then was studied on a longer climb trying to focus on its management of the bike. Beyond the cyclist's and motor's torque values, the sensor system collects other very important parameters, which are gear, engine map, cadence, speed. These parameters all combined allowed to further analyse the behaviours of the rider.

The last parameter to be studied was the cyclist torque distribution during a pedal stroke for both the left and right crankarms, in order to understand the load that the electric motor.

1. INTRODUCTION

Tests were conducted outdoors and in vivo in different scenarios, mainly uphill because it's where the whole acquisition system was built to work. In the descent, torque outputs are zero, so are cadence and power. In fact, other parameters should be studied in this case such as brake usage and suspension travel.

Chapter 2

MATERIAL AND SENSORS

2.1 Fantic XTF Carbon e-MTB

It is useful to explain the characteristics of the product to be analysed, the e-BIKE. The bike used in the testings is in the trail segment, a large market share. It is the Fantic XTF Carbon 1.5.



Figure 2.1: Fantic XTF Carbon 1.5 e-MTB

It is possible to describe the main features as follows:

- Frame: Carbon fibre, with aluminium rear triangle;
- Motor: Brose S-MAG 36 Volt, Max power of 250 Watt and Max Torque of 90 Nm;
- Battery: Fantic Integra, Lithium Ion, 36 Volt, 720Wh;
- Fork: RockShox 35 GOLD RL e-bike- 29" 150mm;
- Shock: RockShox Deluxe Select+ T205x60 Air;

2. MATERIAL AND SENSORS

- Chain ring: Sram 34t Steel Eagle;
- Cassette: Sram SX Eagle 12V, 11-50;
- Crankarm: FSA CK-7462/IS- 170mm;
- Front brake: Sram GUIDE T 4 Piston disc brake;
- Rear brake: Sram GUIDE T 4 Piston disc brake;
- Wheels: Rodi BlackJack READY27, F 29"/R 29";
- Front tyre: Pirelli SCORPION ProWall Trail-M- 29"x 2.4;
- Rear tyre: Pirelli SCORPION ProWall Trail-R- 29"x 2.4.

For the different types of testing that will be described in the following chapters, two different models and type of pedals were used. Some of the riding was done using standard flat pedals, in particular the VP Components model VPE-506. The other part of testing was carried out with the help of a different type of pedals: the SPD system pedals. This system allows to securely fix the shoe, which must be specially built to accommodate a plate that connects to the pedal. The model used was a Shimano model M540.



(a) *Vp Componets VPE-506*



(b) *Shimano M540*

Figure 2.2: The two model of pedals used

2.2 Telemetry and testing equipment

The telemetry system is based on the T24 Telemetry System produced by Mantracourt. It consists in eight acquisition modules directly connected to each one of the sensors placed on the e-bike and a base station that receives the wireless signal coming from the acquisition modules and send it to a Mini-PC via USB connection. To properly acquire data the base station and the Mini-PC are placed in a backpack that the rider has to wear during the test. To supply the Mini-PC, also a UPS module is positioned inside the backpack. The backpack prevents the system from being cumbersome and it results in a safe and easy ride.

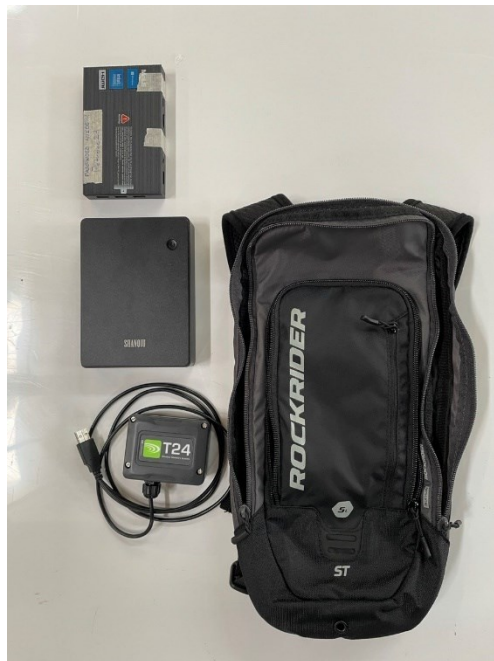


Figure 2.3: Backpack and its content

There are 8 sensors placed on the bike, each one having its own acquisition module and therefore channel. The various channels, with their respective ID and characteristics are described in Table 2.1, that follows.

2. MATERIAL AND SENSORS

Channel number	ID	Characteristic
1	Pot_01	Linear potentiometer
2	Msw_piu_02	Micro switch +
3	Msw__meno_03	Micro switch -
4	Spider_CA_04	Strain gauges on the spider
5	Right_CA_05	Strain gauges on the right crank arm
6	Left_CA_06	Strain gauges on the left crank arm
7	Hall_CA_07	Hall effect sensor on the crank arm
8	Hall_Wheel_08	Hall effect sensor on the rear wheel

Table 2.1: Channels description

The Mantracourt System offers different types of transmitter module depending on the type of sensor connected to it. For the objectives of this telemetry system the following acquisition modules were installed:

- 1 x T24- RAi module;
- 2 x T24- VAi module;
- 3 x T24- SAi module;
- 2 XT24- PAi module.

It is important to know that every transmitter module can be set to a different acquisition frequency. This is useful because the bandwidth of the Base station is limited to 200 messages per second per radio channel. In fact, if a number of modules increases there is more chance of message collision between different channels and so more signals can be lost.

2.2.1 Channel 1 - Linear potentiometer

The Channel 1 consists in a T24 RAi Mantracourt transmitter module and a linear potentiometer wired to it. The potentiometer has its sliding part connected to the cable that moves the rear derailleur, so shifting gear the slider moves and changes the output voltage. This system let identify the gear used.

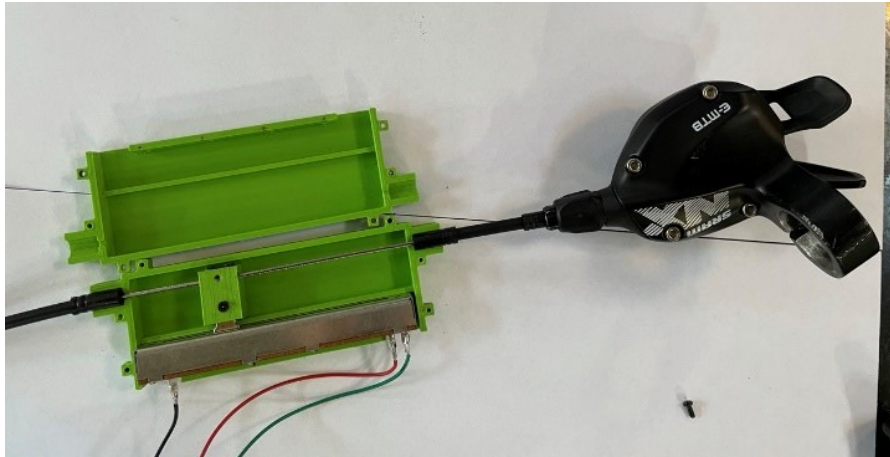


Figure 2.4: linear potetiometer installed on the rear deraulier cable



Figure 2.5: linear potetiometer placement on the bike

The convention used to number the gears stars with GEAR 1 on the smallest cog, which have 10 teeth, and ends with GEAR 12 on the biggest one, which have 50 teeth.

2.2.2 Channel 2 & 3 - Micro switches

Channels 2 and 3 are working with the same sensor: a micro switch. They are placed over the two buttons of the Brose system that change the map configuration of the motor.

Channel 2 corresponds to the + button, while Channel 3 corresponds to the - button. When pressed the microswitches send an electric signal to the Mantracourt transmitter module so it records the rider map's change both up and down.



(a) Example of micro switches



(b) micro switch placement

Figure 2.6: Channel 2 and Channel 3

2.2.3 Channel 4 & 5 & 6 - Strain gauges

These three channels are used to find the torque i.e. rider's left and right torque and total torque, using the elastic deformation of some bike components. The four electrical resistance strain gauges that make up the single channel are connected to each other in a full Wheatstone bridge.

Strain gauges connected to Channel 4 are placed in the spider, that part that connects the crankarm, in the case of an e-bike the motor, to the chainring (De Lazzari N. (2021). "Field data acquisition during downhill and assisted pedalling events for the fatigue life prediction of modern e-MTB components"). This system is also used in some commercial powermeters and permits to evaluate the total torque output transmitted to the chain.

For Channel 5 and 6, strain gauges are placed on the right and left crankarms respectively: they acquire the torque output from the rider of both legs.

2. MATERIAL AND SENSORS

In the case of a non-pedal-assisted bike the value of torque from Channel 4 is equal to the sum of Channel 5 and Channel 6. Considering a pedal-assisted bike this equation is not working because Channel 4 also considers the electric motor contribution. For this reason, the motor torque is the difference between Channel 4 and the sum of Channel 5 and Channel 6.

These sensors require a static calibration that was carried out in previous work (Armagno G. (2023). “Design, validation and testing of a telemetry system to measure electric motor torque usage profiles from modern e-bikes”, pp. 31-59) and the results are shown in Table 2.2.

Channel ID	Calibration constants [mV/V]
Spider_CA_04	168.56
Right_CA_05	714.29
Left_CA_06	769.23

Table 2.2: Static calibration results

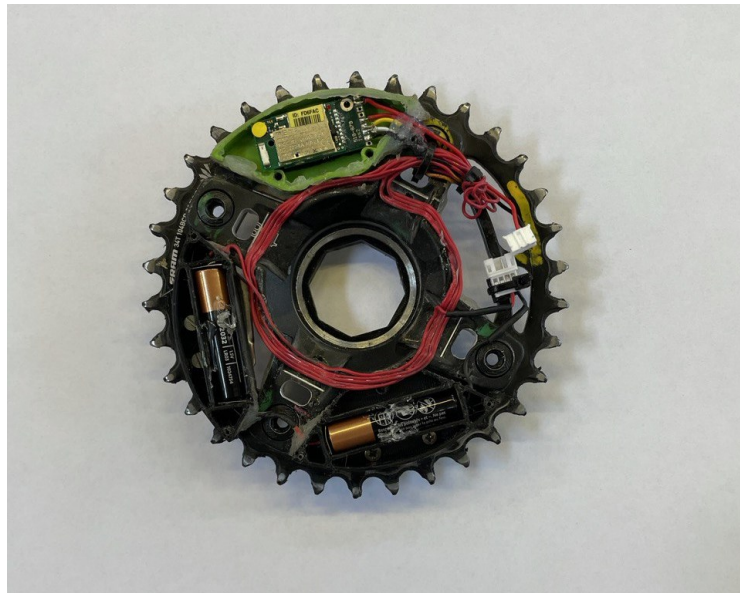


Figure 2.7: Spider equipped with strain gauges



(a) Strain gauges placement (b) crankarm equipped with sensor

Figure 2.8: Crankarms strain gauges

2.2.4 Channel 7 & 8 - Hall effect sensors

The sensors and acquisition modules for these two channels are placed on the left chainstay and a magnet is placed on the left crankarm and one on the rear wheel. All combined, using two common digital hall effect sensors, measure the rear wheel cadence (Channel 7) and the crankset cadence (Channel 8).

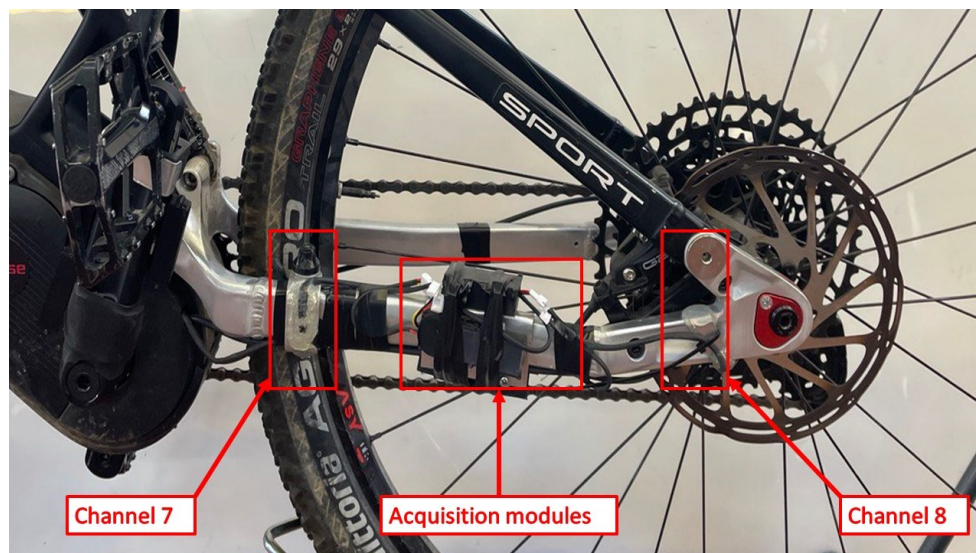


Figure 2.9: Hall effect sensors placement

2.2.5 Testing equipment

The combination of the 8 sensors with their respective acquisition modules placed on the bike and the content of the backpack (Mini-PC, basestation and UPS) form the testing equipment used during the test rides. In addition, it is necessary a laptop and an HDMI cable with USB capture card in order to connect the Mini-PC to the laptop to launch the Mantracourt software and start logging the session.

The Mini-PC used is the “Mele Quiter2 Fanless”: it’s a very light and compact PC working on Windows 10 Pro software where Mantracourt program can be installed. The biggest downside of this Mini-PC it’s the lack of a monitor and, as anticipated, an additional PC, i.e. a laptop, is necessary to use it.

Mantracourt provides two different software which are T24 Toolkit and Mantracourt Log1000. Mantracourt Log1000 was chosen because it records every channel separately producing a CSV file with the value of each channel for every instant of time.

The UPS module chosen is the “Shanqiu Mini UPS” storing 20000 mAh with a 12V, 2A usb-C port needed for the Mini-PC.

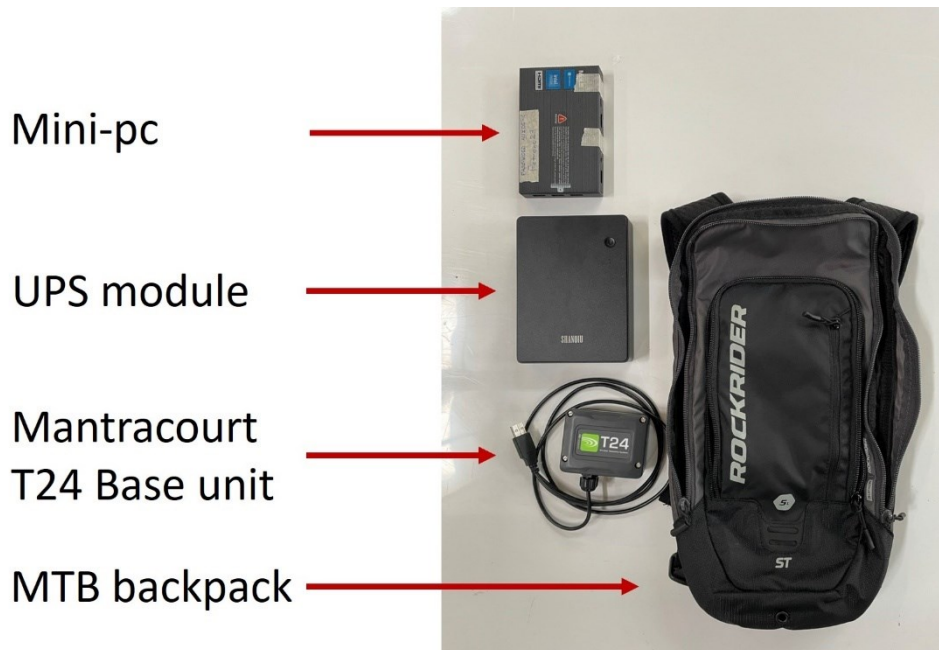


Figure 2.10: Testing equipment

Some of the component of the telemetry system, such as acquisition modules or potentiometer housing, were printed using a 3D printer, located in the Design Machine laboratory, in Padua.

2.3 Recording procedure

After turning on all the sensors which are powered by two AAA batteries, connect the Mini-PC to the laptop and open OBS Studio software on the laptop to see the display output of the Mini-PC. Launch the Mantracourt software and check if all the sensors are working properly. Turn on the bike, put it on the OFF engine map and in the smaller cog on the cassette. Zero all the sensors from the software and start logging. Disconnect the Mini-PC from the laptop, make the rider wear the backpack and start riding.

Once done with the testing ride, reconnect the Mini-PC and stop logging. The software will automatically save a .CSV file in the Mini-PC.

2.4 Matlab code to analyse data from telemetry

The .CSV file saved must be analysed with a MATLAB code that converts the raw electric signals acquired into usable output data.

Chapter 3

TRAILS SELECTION AND DESCRIPTION

3.1 The trails

During the testing phase, different trails were chosen to optimize the data acquisition process and ensure a good evaluation of both the bike's and rider's performance under varying conditions.

Because the help of a laptop was needed to start and stop the logging procedure on the Mini-PC that the rider has to carry during the testing phase, an additional person was needed to start the recording process with the rider and reach him at the end of the ride to stop the recording. This approach was necessary because it would have been impractical and cumbersome for the rider to carry the laptop themselves while also focusing on maintaining a steady pace and controlling the bike during the ride.

As mentioned earlier, the main focus was to test the bike going uphill which is the most revealing scenario for the acquisition of data. A flat track couldn't be used because even a not particularly trained person would easily reach the speed of 25 kilometres per hour, a speed at which the electric motor stops working.

To gather diverse and representative data, two distinct trails were selected, each with unique characteristics.

The first trail, called "Susegana Castle Uphill", is a relatively short climb with paved ground. While not particularly demanding, both physically or technically, it was ideal to collect valuable bike parameters. It was used to determine the torque and the power delivery of the electric motor at different power settings.

On the other hand, the second trail, the "Monte Pizzoc Uphill", was much longer and more challenging, with a varied surface that alternated between asphalt, concrete, and rocky terrain. This trail represented a more realistic riding experience as the terrain varied

3. TRAILS SELECTION AND DESCRIPTION

not only in terms of surface type but also in gradient, offering both steep and moderate sections. The mixture of surfaces, including the rocky patches, provided an additional level of complexity necessary to get a better understanding of the bike and rider system all together. The extended length of the climb also allowed for a more comprehensive evaluation of battery performance, motor consistency, and the rider's endurance over a longer and more demanding ascent.

3.1.1 Susegana Castle Uphill

Starting from the center of Susegana, the trail climbs towards the top of the nearby hill where historic Castello San Salvatore stands.

Figure 3.1 shows the map of the relatively short track, while figure 3.2 shows the elevation gain which is fairly constant, especially in the middle section.

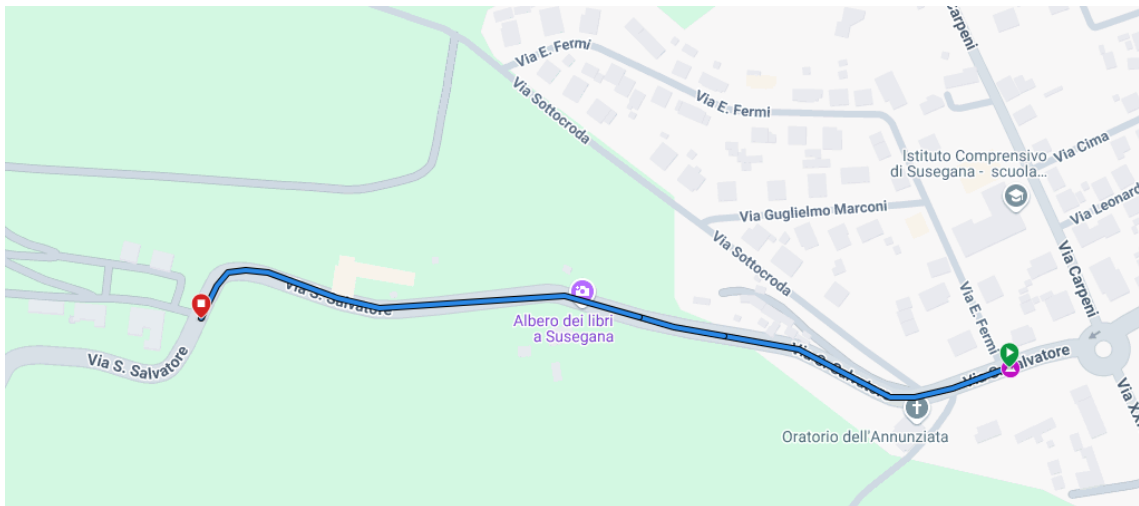


Figure 3.1: Susegana Castle Uphill map

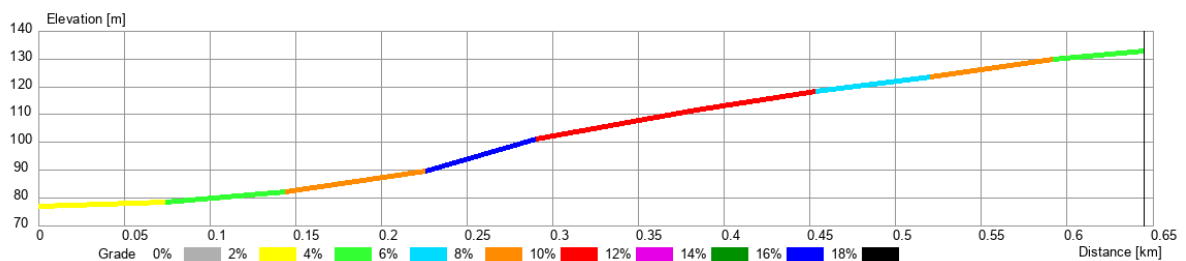


Figure 3.2: Susegana Castle Uphill slope in function of the distance

- Length: 650 metres
- Total ascent: 57 metres
- Average slope: 9%

The trail itself is relatively short, spanning a length of 650 meters, with a total ascent of 57 meters. The average slope of the climb is around 9%, which provides a moderate yet consistent gradient throughout.

This trail was mainly used to evaluate the motor behaviours with the maps available. Given the fairly consistent slope throughout the climb, it provided a stable environment in which to test the bike's response to varying levels of motor assistance. One of the key advantages of this trail was that it was not overly demanding, this allowed to repeat the climb four times in a row by the same rider keeping a constant cadence and output.

3.1.2 Monte Pizzoc from Serravalle

The “Monte Pizzoc Uphill” starts in Serravalle di Vittorio Veneto, located at an elevation around 140 meters above sea level, to reach the top of Monte Pizzoc, located at 1565 meters above sea level in the municipality of Fregona.

The first section (from PLAY to A in Figure 3.3) consists of a paved road, which includes some ups and downs that lead the rider to the centre of Fregona. This portion provides a relatively smooth start, with gradual variations in elevation.

From the centre of Fregona starts the second section (From A to B in Figure 3.3) that consists in a mule track in the forest characterised by an alternation of concrete sections and rocky sections with some switchbacks. This is the most demanding section due to its steepness: it averages 14% and reaches a 16% peak, as Figure 3.4 shows. Also, the rough terrain has a big role here: some sections require some technique in order to roll over rocks and bumps. The fairly generous section of the bike tires and the rear suspension really help in this type of situations. The second section goes on until it reaches Casa Forestale Cadolten.

Now the trail turns again into a paved road. Third and last section (From B to STOP in figure 3.3) leads all the way to the top, at 1565 meters above sea level, following the paved road that reaches the Rifugio Città di Vittorio Veneto, near the top of Monte Pizzoc, from Passo Crosetta, a location of the municipality of Caneva.

3. TRAILS SELECTION AND DESCRIPTION

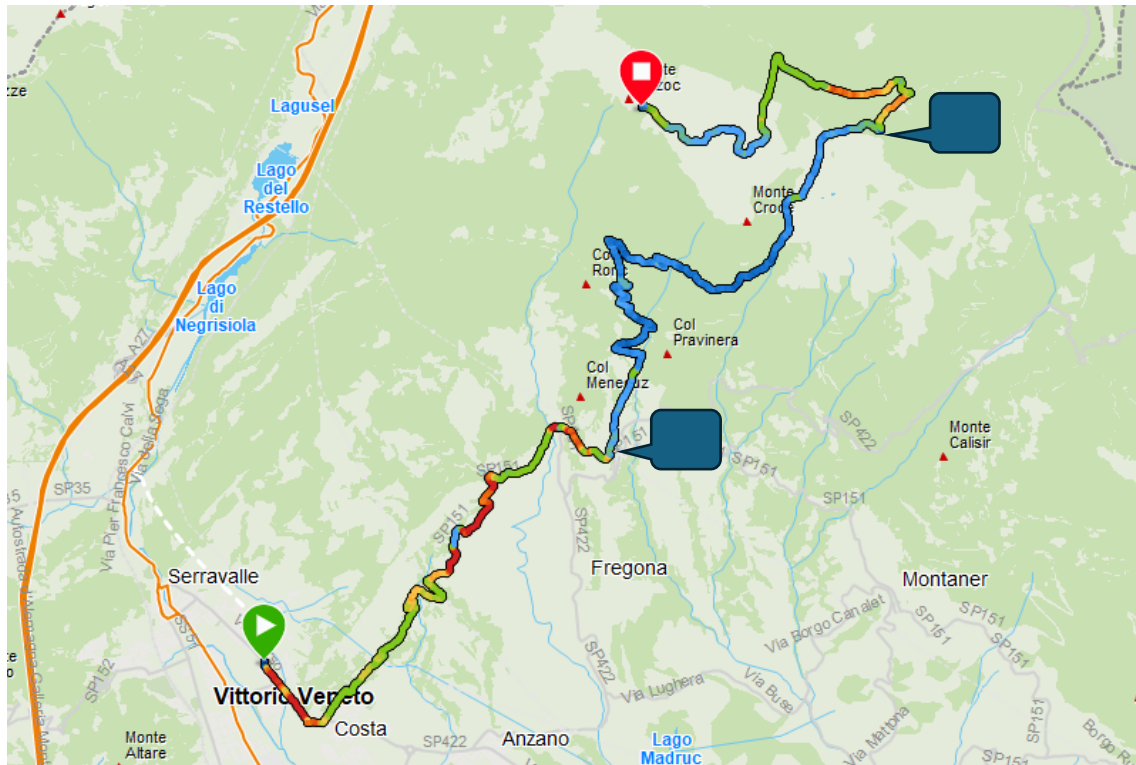


Figure 3.3: Monte Pizzoc Uphill map

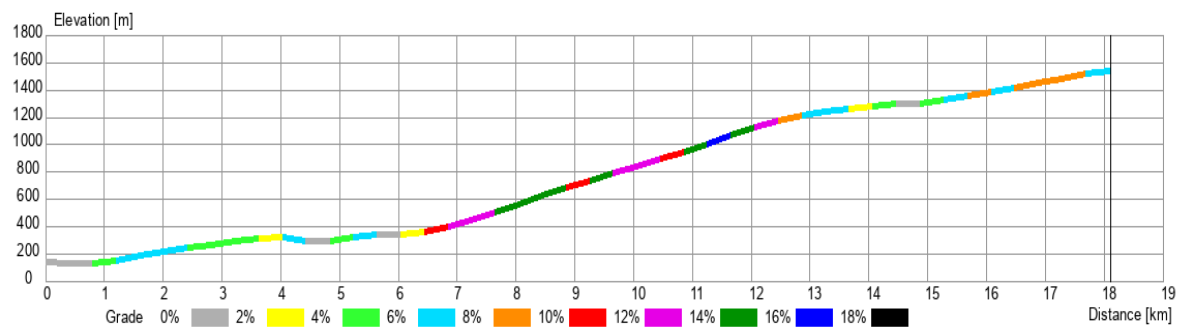


Figure 3.4: Monte Pizzoc Uphill slope in function of the distance

- Length: 17 kilometres
- Total ascent: 1470 metres
- Average slope: 10%
- Maximum slope: 16%

It's a very demanding ascent because of the elevation gain and the slope, as Figure 3.4 clearly shows, that reaches the 16% in a section. In this case the main focus was to understand how the riders used the bike, so there are different ground types that require, at times, a bit of technique and focus.

This trail represents one of the type of situations where even a trained cyclist would choose to ride an e-bike: the trail was repeated by one of the riders with a non-pedal-assisted bike.

3.1.3 Torque profile evaluation climb

To evaluate the torque profile, described in Chapter 6, an additional small climb has been used. It consists of a 20 meters long climb with gravel surface on the riverbank of Piave. This climb has a constant slope of around 5% that allowed the rider to keep a constant pace without an extremely high effort considering that the climb was repeated multiple times with the engine off.

3. TRAILS SELECTION AND DESCRIPTION

Chapter 4

ENGINE TORQUE OUTPUT MAPPING

4.1 Testing procedure

To understand how much power and torque the electric motor can output at different maps a short and with a constant grade climb was used. The track was deeply described in the previous chapter (section 3.1.1 “Susegana Castle Uphill”). It consists of a 650 meters section averaging a 9% slope. The road is paved which minimizing the possibility of choosing different lines for the uphill and reduce the effort for the rider to keep a constant pace, thereby limiting external variables.

In order to eliminate the rider’s impact factor, the uphill was repeated by the same rider using all the available maps of the Brose motor: ECO, TOUR, SPORT, BOOST. During each climb, the rider attempted to maintain a constant cadence and effort as consistently as possible, reducing the impact of physiological variations or fatigue between attempts. The rider was using standard flat pedals.

According to the motor’s datasheet, the Brose motor can deliver a maximum torque of 90 Nm and provide assistance up to 380% of the rider’s power output. These theoretical figures served as a reference point for comparing the measured values during the tests, allowing an evaluation of the performance of each assistance mode.

4.1.1 Engine torque evaluation

Since the telemetry system only records torque data from the crankset and the spider the engine torque is not directly measured by the system itself. In fact the Engine Torque (ET) is calculated as the difference between the total torque (TT) and the cyclist torque (CT), that is the sum of the left and right components of the torque, as described by Equation 4.1

$$ET = TT - CT$$
$$ET = TT - (CT_L + CT_R)$$

Equation 4.1

4.2 Torque results

To ensure accurate and consistent data for comparison, only the last 25 seconds of the climb were used to evaluate both the rider's and motor's torque. This approach was necessary to avoid discrepancies caused by signal interruptions recorded during other parts of the test.

The collected data clearly illustrate the differences in torque values across the various maps (ECO, TOUR, SPORT, BOOST) for both the motor and the cyclist. These values were processed and visualized as graphs, generated using MATLAB. The resulting graphs provide a clear and immediate visual representation of the motor-cyclist system's performance under each configuration, offering a solid foundation for further analysis of the motor's capabilities and the efficiency of each assistance map.

4.2.1 ECO

For the ECO map the average cadence was between 82 and 88 RPM.

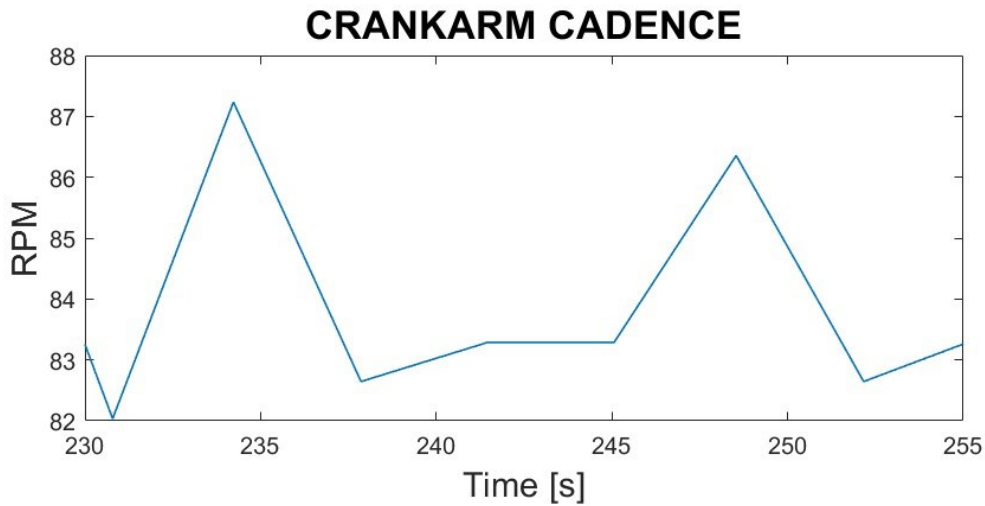


Figure 4.1: ECO map cadence

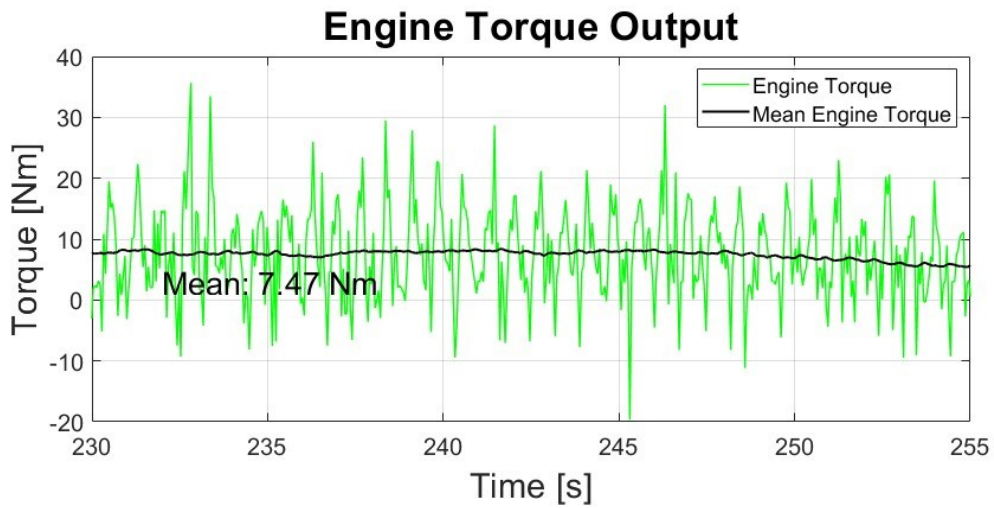
The average values of torque are:

- Engine Torque: $ET = 7 \text{ Nm}$
- Cyclist Torque: $CT = 29 \text{ Nm}$
- Total Torque: $TT = 35 \text{ Nm}$

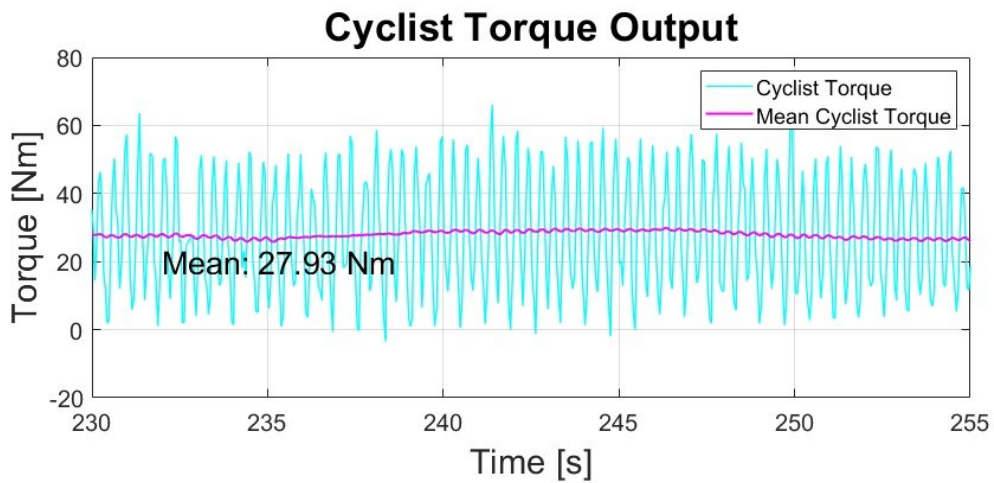
as shown in Figure 4.2, [a], [b], [c].

It's clear from the graph, Figure 4.1, that the values are quite consistent throughout the whole 25 seconds interval analysed.

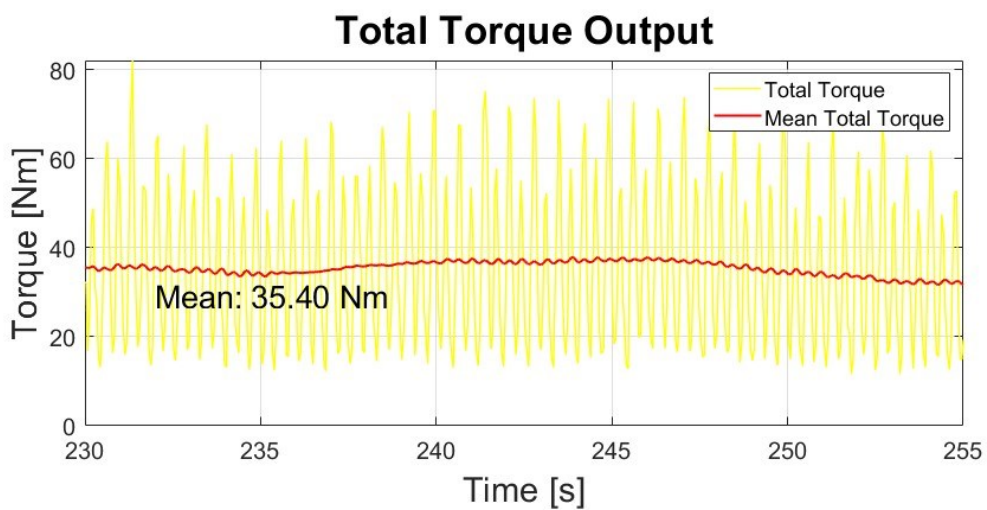
The amount of Engine Torque is quite small compared to the Cyclist Torque. The rider reported that the effort was similar, or even higher, to the one needed to push a non-assisted mountain bike.



[a] ECO Engine Torque



[b] ECO Cyclist Torque



[c] ECO Total Torque

Figure 4.2: Torque and Torque mean values in function of time for the ECO map

4.2.2 TOUR

For the TOUR map the average cadence was between 85 and 93 RPM.

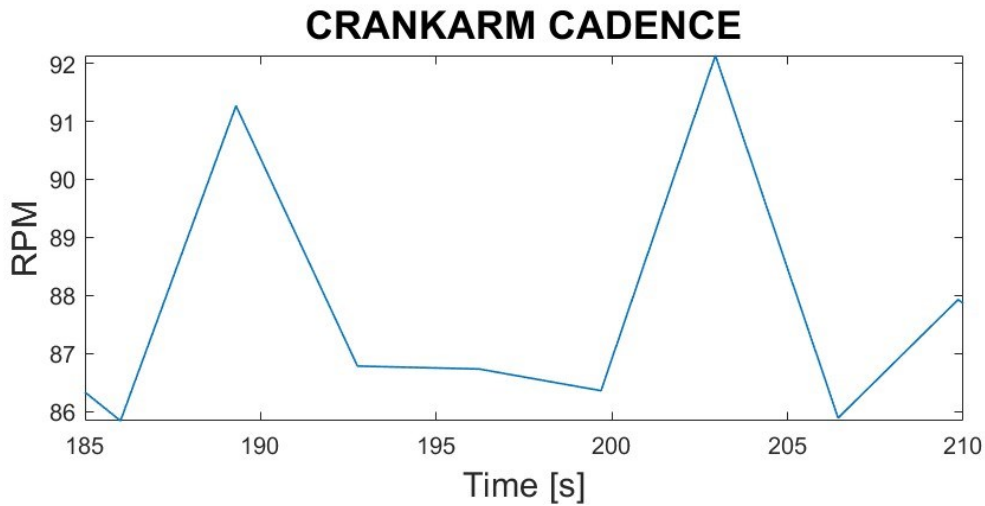


Figure 4.3: TOUR map cadence

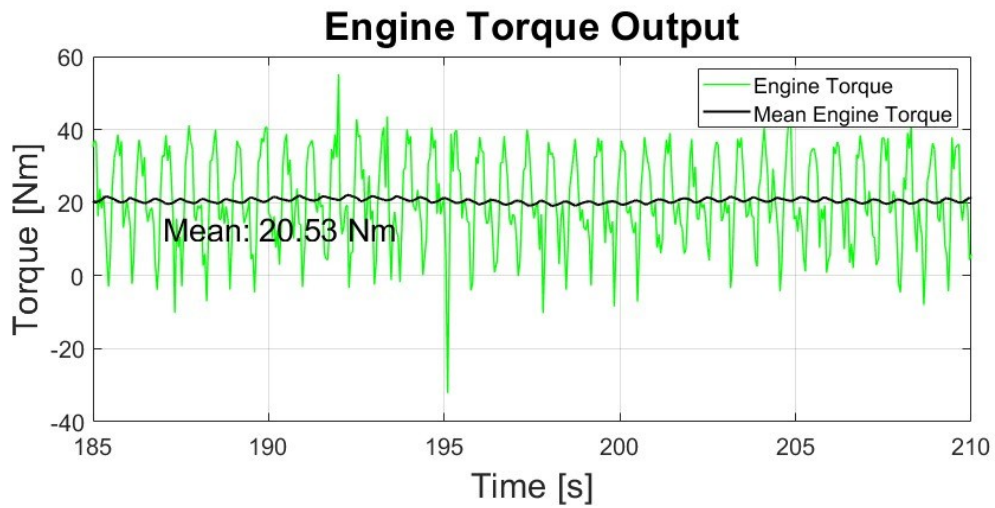
The average values of torque are:

- Engine Torque: $ET = 21 \text{ Nm}$
- Cyclist Torque: $CT = 40 \text{ Nm}$
- Total Torque: $TT = 56 \text{ Nm}$

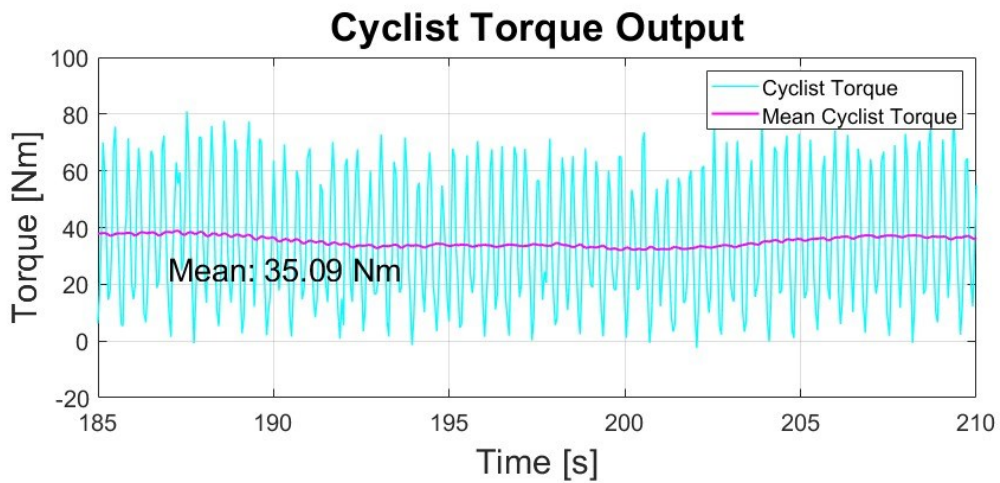
as shown in Figure 4.4, [a], [b], [c].

It's clear from the graph, Figure 4.3, that the values are quite consistent throughout the whole 25 seconds interval analysed.

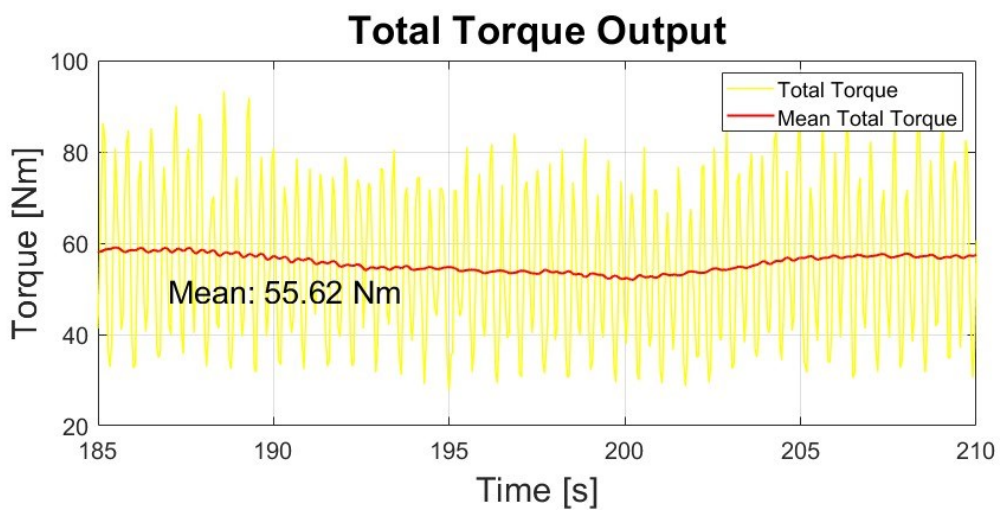
In this case the torque output of the engine is around the half of the Cyclist Torque.



[a] TOUR Engine Torque



[b] TOUR Cyclist Torque



[c] TOUR Total Torque

Figure 4.4: Torque and Torque mean values in fuction of time for the TOUR map

4.2.3 SPORT

For the SPORT map the average cadence was between 89 and 99 RPM.

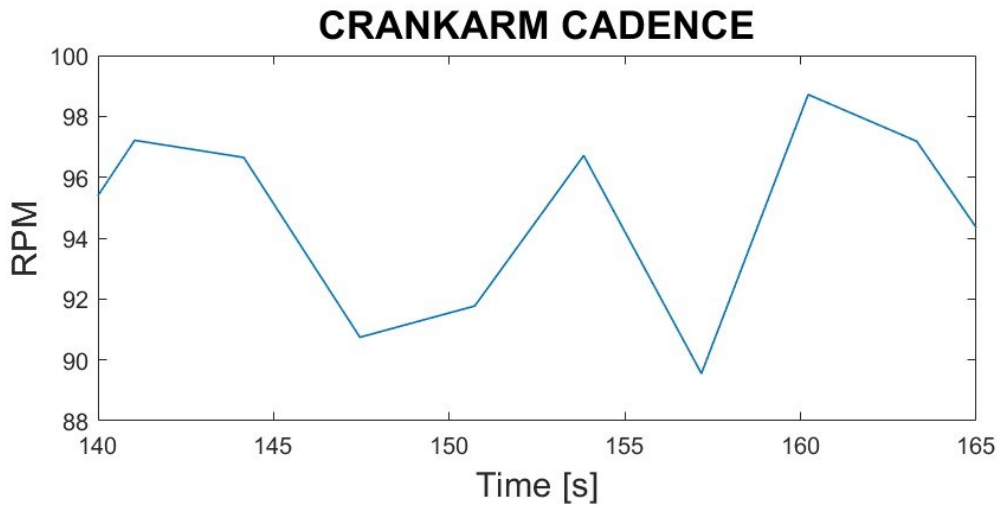


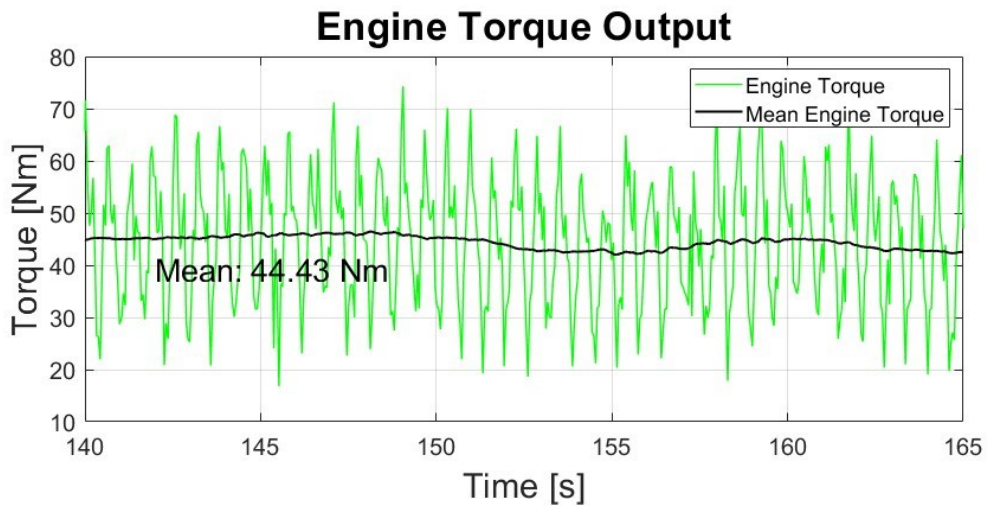
Figure 4.5: SPORT map cadence

The average values of torque are:

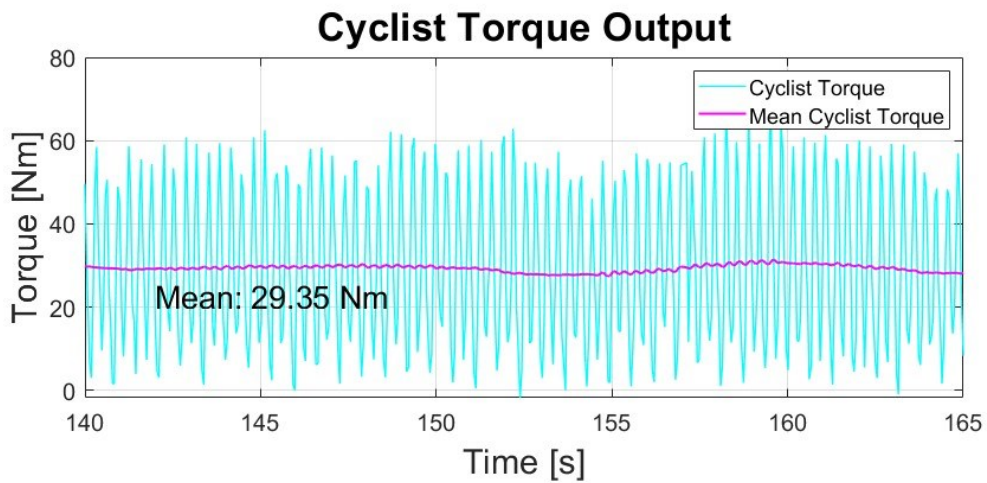
- Engine Torque: ET = 43 Nm
- Cyclist Torque: CT = 29 Nm
- Total Torque: TT = 74 Nm

as shown in Figure 4.4, [a], [b], [c].

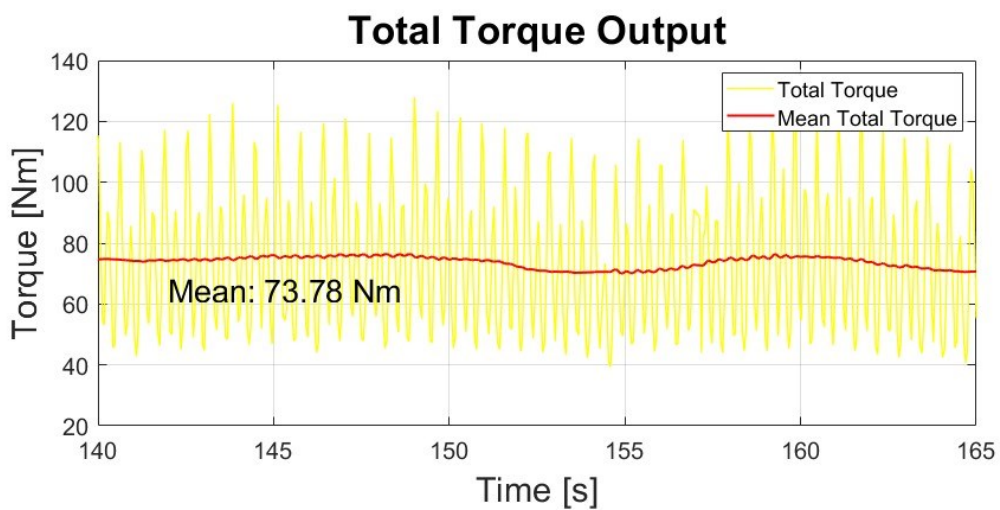
It's clear from the graph, Figure 4.5, that the values are quite consistent throughout the whole 25 seconds interval analysed.



[a] SPORT Engine Torque



[b] SPORT Cyclist Torque



[c] SPORT Total Torque

Figure 4.6: Torque and Torque mean values in fuction of time for the SPORT map

4.2.4 BOOST

For the BOOST map the average cadence was between 85 and 92 RPM.

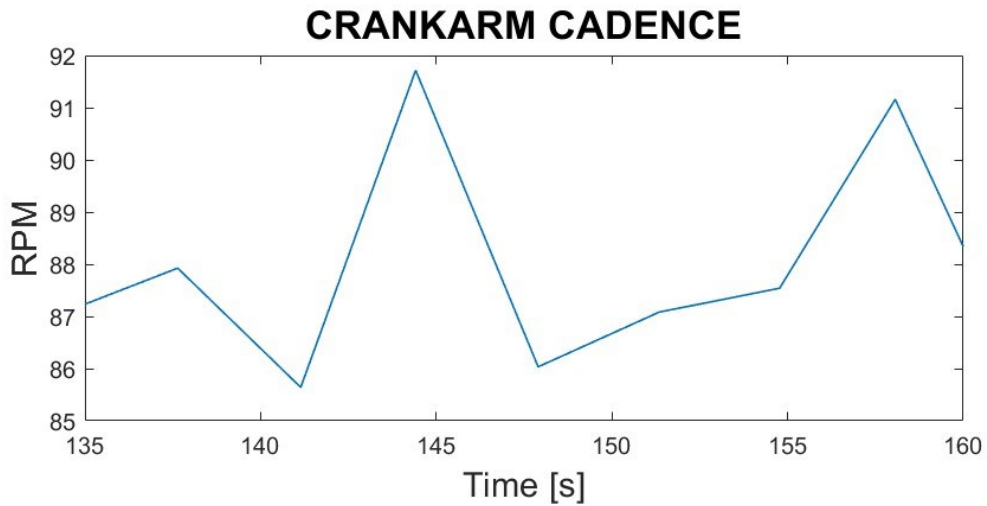


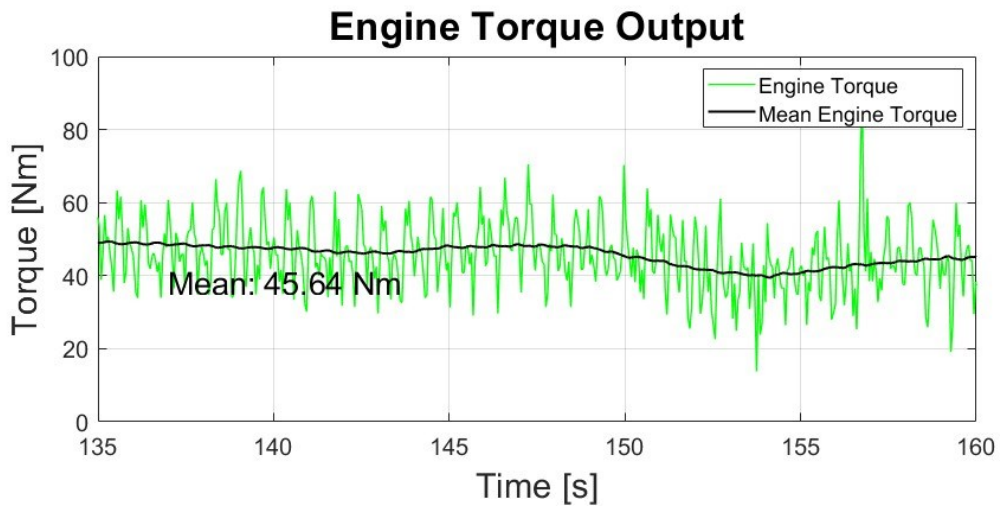
Figure 4.7: BOOST map cadence

The average values of torque are:

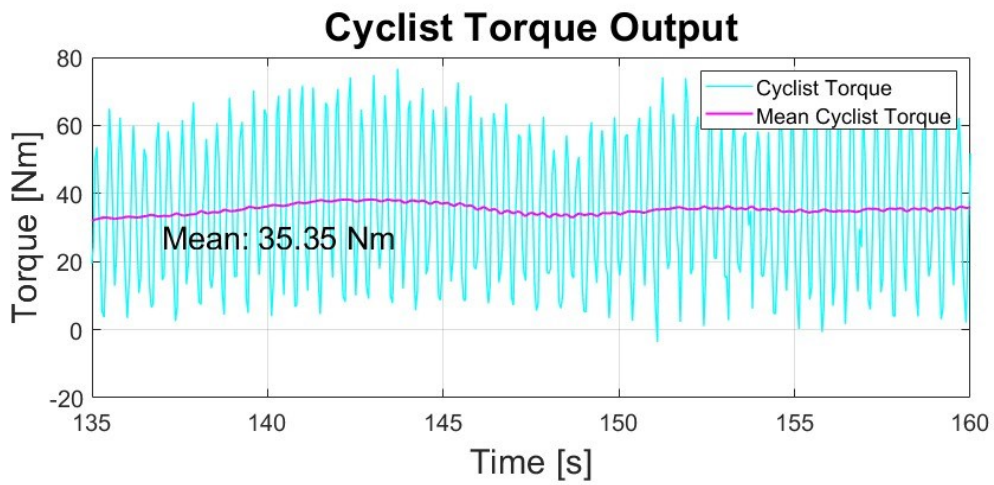
- Engine Torque: ET = 45 Nm
- Cyclist Torque: CT = 33 Nm
- Total Torque: TT = 81 Nm

as shown in Figure 4.8, [a], [b], [c].

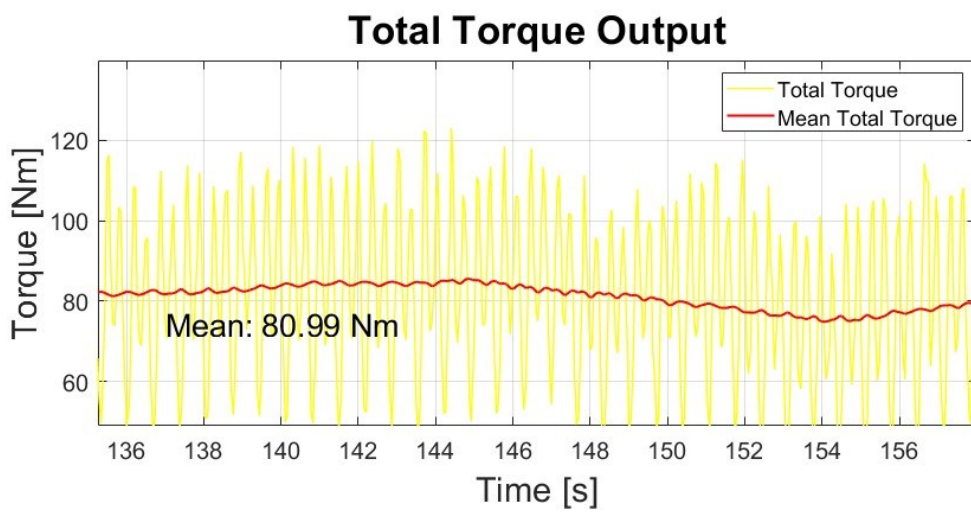
It's clear from the graph, Figure 4.7, that the values are quite consistent throughout the whole 25 seconds interval analysed.



[a] BOOST Engine Torque



[b] BOOST Cyclist Torque



[c] BOOST Total Torque

Figure 4.8: Torque and Torque mean values in function of time for the BOOST map

4.2.5 Assistance level

Is now useful to introduce the assistance percentage described as

$$A\% = \frac{\text{Engine Torque}}{\text{Cyclist Torque}} \cdot 100$$

Equation 4.1

which clearly represents how much the motor is helping the rider. A value next to 380% was expected to be found when riding with the BOOST map.

Map	Engine Torque [Nm]	Cyclist Torque [Nm]	A%
ECO	8	27.93	26.75
TOUR	21	29.35	69,95
SPORT	43	35.09	126.62
BOOST	45	35.35	129,11

Table 4.1: Torques and Assistance level for different maps

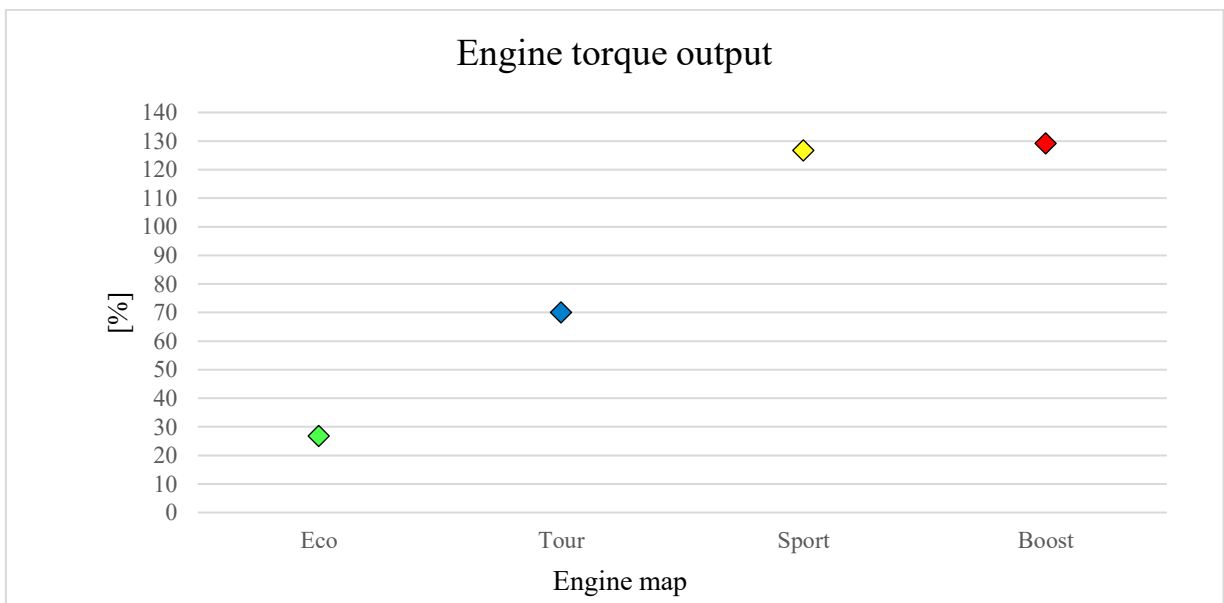


Figure 4.9: Assistance level for different maps

It's clear from Table 4.1 and the graph, Figure 4.9, that the assistance level stops at around 130%, with a maximum torque of 45 Nm. The average Cyclist Torque for the BOOST map, the one that should provide the 380% of assistance, was 33 Nm. The engine should output over 125 Nm to reach the assistance level declared that actually exceeds the declared value of 90 Nm of maximum torque.

Hence for a constant cadence and cyclist torque we can assume that the values of assistance level are:

- 25% for the ECO map
- 70% for the TOUR map
- 125% for the SPORT map
- 130% for the BOOST map

The results of the tests, highlighted by Figure 4.9, clearly demonstrate a noticeable increase in torque output from the electric motor as the assistance mode is switched between the various available maps. However, the magnitude of the increase is not uniform across all transitions. Specifically, the difference in torque output between the ECO map and the TOUR map is relatively modest, whereas the gap between the TOUR map and the SPORT map is significantly larger. This non-linear progression in torque levels was also confirmed by the subjective feedback provided by the riders, who consistently noted these variations during their climbs.

Although at first glance the SPORT and BOOST maps may appear nearly identical in terms of their torque output, this similarity holds true only under conditions where the cyclist maintains a constant speed. When the rider accelerates, the motor's response becomes distinctly different, a pattern that was consistently reported by all the test participants at the conclusion of their rides. This divergence highlights the importance of considering dynamic situations, such as acceleration phases, to fully understand the motor's behaviour and the specific advantages offered by each assistance mode.

To pinpoint the exact conditions under which the motor reaches its maximum assistance level, it is essential to analyse scenarios involving acceleration rather than steady-state efforts. For instance, examining a standing start performed with the BOOST map reveals the motor's torque delivery characteristics during rapid changes in speed.

4. ENGINE TORQUE OUTPUT MAPPING

The following graph provides a detailed representation of the torque generated by both the motor and the cyclist during the initial phase of testing with the BOOST map. This data offers valuable information on the motor's responsiveness and the better understanding of the declared assistance level. The mean Engine Torque values presented in Figure 4.10 are calculated by the MATLAB code using movmean function that calculates the average value of torque in a 5 seconds interval. The crank RPM was not measured because the rider in this phase was accelerating from a stationary position.

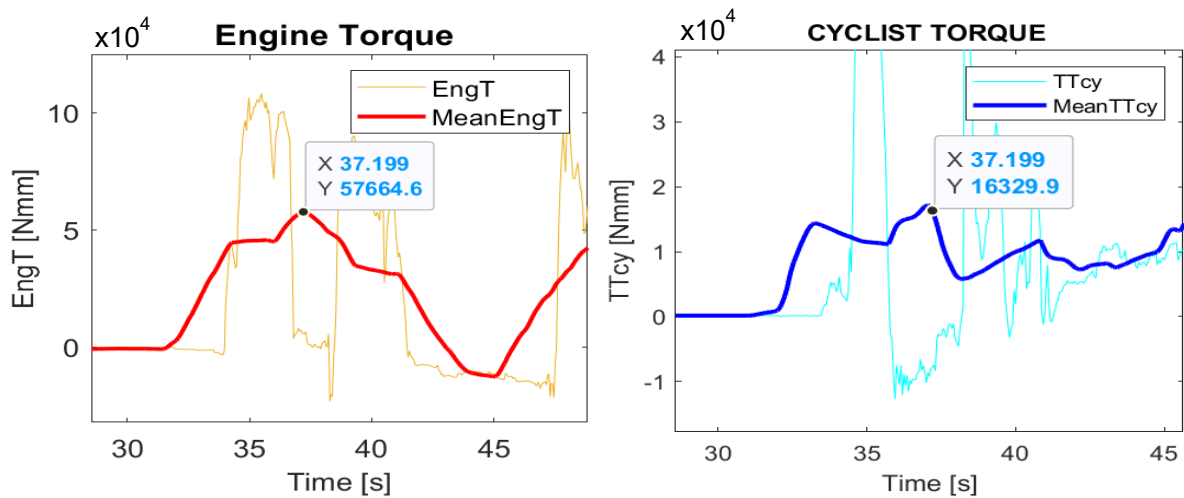


Figure 4.10: Engine and Cyclist Torque during standing start

As represented in the graphs the Engine Torque reaches the value of 57,5 Nm while the Cyclist Torque only gets to 16,3 Nm. Calculating the associated assistance lever it has a value of 353%, not far from to the declared value of 380%.

From these graphs it appears that the maximum Engine Torque has a small delay from the Cyclist Torque, as reported by riders.

The power output of the cyclist and the motor can be calculated by multiplying the torque by the cadence. Of course the cadence of the engine and the rider are the same, so what previously described for the torque can be transferred to the power. The assistance percentage for power can be written as:

$$A\%_{power} = \frac{Engine\ Power}{Cyclist\ Power} \cdot 100 = \frac{Engine\ Torque \cdot Cadence}{Cyclist\ Torque \cdot Cadence} \cdot 100$$

$$A\%_{power} = \frac{Engine\ Torque}{Cyclist\ Torque} \cdot 100 = A\%_{cadence}$$

Equation 4.2

4.2.6 Absolute assistance level

To give a better understanding of the Motor assistance, another parameter can be introduced that is the Absolute Assistance Level defined as:

$$AA\% = \frac{Engine\ Torque}{Total\ Torque} \cdot 100$$

Equation 4.3

Map	Engine Torque [Nm]	Total Torque [Nm]	%
ECO	7.47	35.40	21,1
TOUR	20.53	55.63	36.9
SPORT	44.43	73.78	60.2
BOOST	45.64	80.99	56.39

Table 4.2: Torques and absolute assistance level for different maps

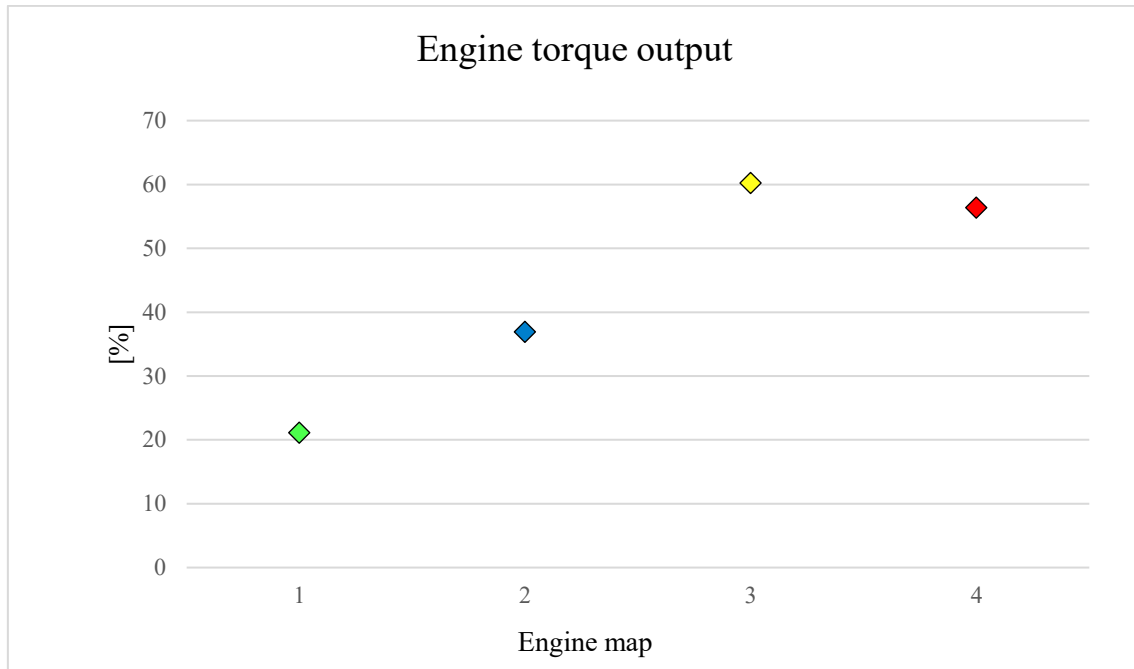


Figure 4.11: Absolute assistance level for different maps

As expected, there is an increasing amount of assistance available at the increase of map as shown by Table 4.2 and Figure 4.10. Results show also similar trends seen on the assistance level based on the cyclist torque: there is a very small difference between SPORT and BOOST maps while between these two and the OFF setting the maps are evenly distributed.

- 20% for the ECO map
- 35% for the TOUR map
- 60% for the SPORT map
- 55% for the BOOST map

4.3 Power

The power output of the cyclist and the motor can be calculated by multiplying the torque by the cadence. Of course the cadence of the engine and the rider are the same, so what previously described for the torque can be transferred to the power. The assistance percentage for power can be written as:

$$A\%_{power} = \frac{Engine\ Power}{Cyclist\ Power} \cdot 100 = \frac{Engine\ Torque \cdot Cadence}{Cyclist\ Torque \cdot Cadence} \cdot 100$$

$$A\%_{power} = \frac{Engine\ Torque}{Cyclist\ Torque} \cdot 100 = A\%_{Cadence}$$

Equation 4.4

This synchronization ensures that the assistance level provided by the motor, in terms of power, directly corresponds to the levels observed during the torque analysis. However, examining the power output offers additional insights into the motor's functionality, providing a more comprehensive understanding of its performance characteristics.

To analyse the power output, the values were calculated using a straightforward method. Specifically, the torque values, both for the motor and the cyclist, were multiplied by the cadence. Since the cadence was originally measured in rotations per minute (RPM), a conversion was performed to express it in radians per second (Rad/s). This conversion is essential because, when torque is measured in Newton-meters (Nm) and multiplied by cadence in Rad/s, the resulting value is expressed in Watts, which is the standard unit of power.

By applying this calculation, it becomes possible to derive precise power output values for both the motor and the cyclist. These results not only corroborate the findings from the torque analysis but also reveal aspects of how the motor operates under various conditions. Power output analysis thus serves as a complementary perspective, enriching the overall understanding of the motor's efficiency and performance capabilities.

4.3.1 ECO

Mean values, presented in Figure 4.11, Figure 4.13, Figure 4.14:

- Cyclist Power: 245 Watt
- Engine Power: 65 Watt
- Total Power: 312 Watt

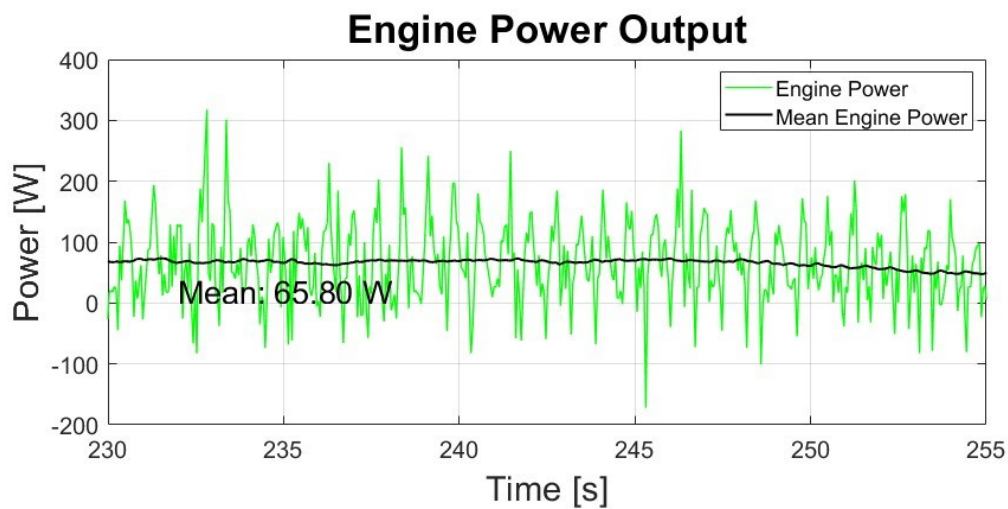


Figure 4.12: Engine Power Output for ECO map

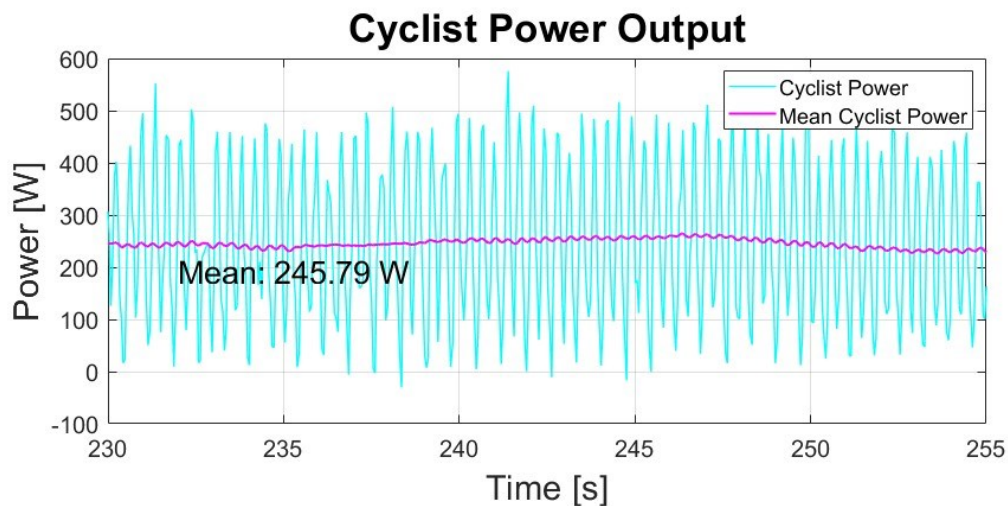


Figure 4.13: Cyclist Power Output for ECO map

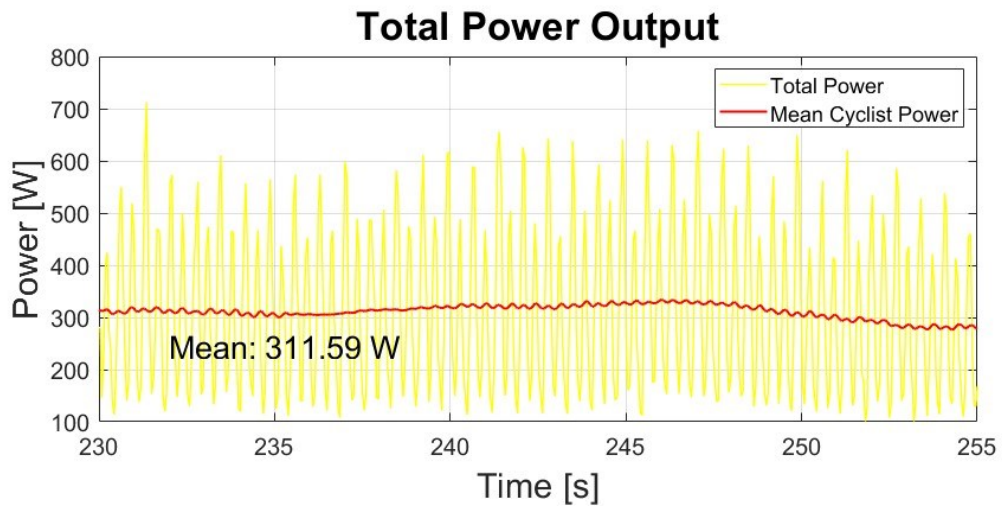


Figure 4.14: Total Power Output for ECO map

4.3.2 TOUR

Mean values, presented in Figure 4.14, Figure 4.15, Figure 4.16:

- Cyclist Power: 323 Watt
- Engine Power: 189 Watt
- Total Power: 512 Watt

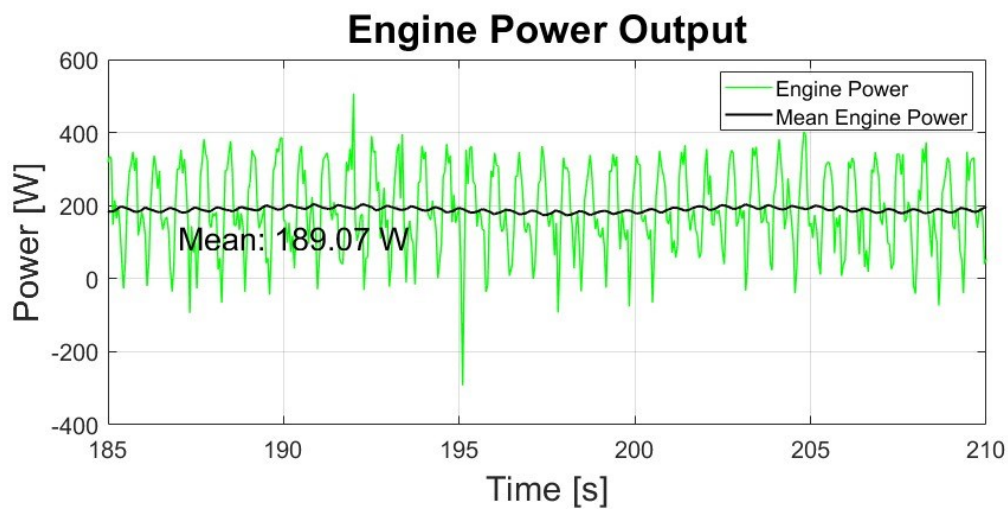


Figure 4.15: Engine Power Output for TOUR map

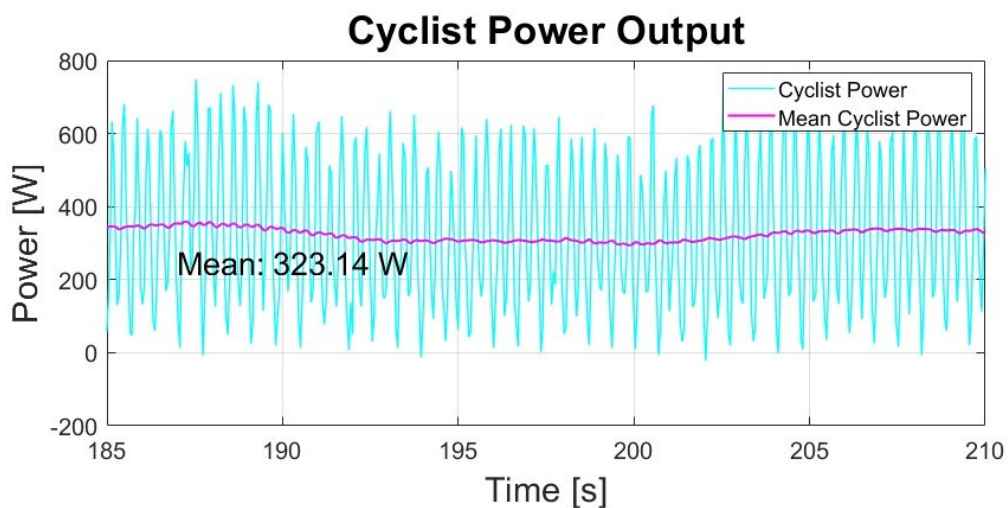


Figure 4.16: Cyclist Power Output for TOUR map

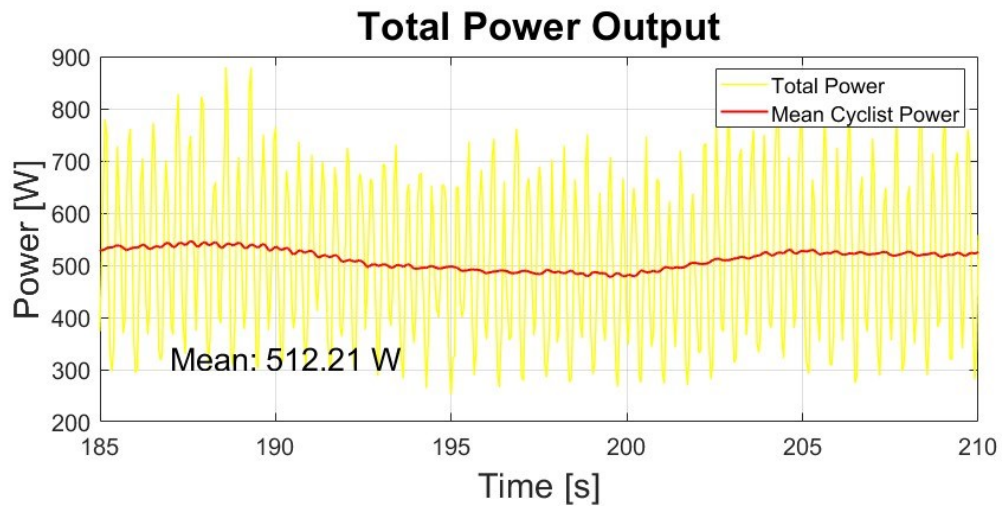


Figure 4.17: Total Power Output for TOUR map

4.3.3 SPORT

Mean values, presented in Figure 4.17, Figure 4.18, Figure 4.19:

- Cyclist Power: 290 Watt
- Engine Power: 440 Watt
- Total Power: 730 Watt

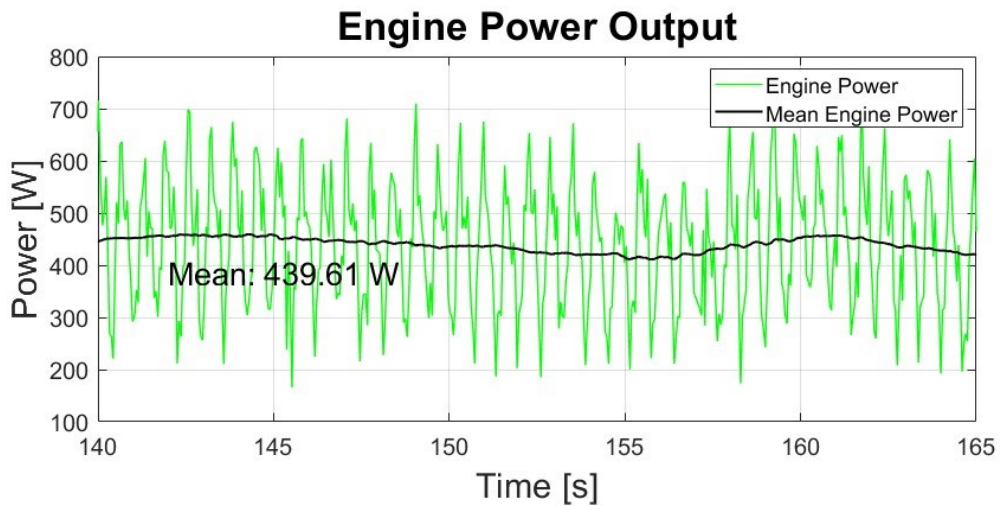


Figure 4.18: Engine Power Output for SPORT map

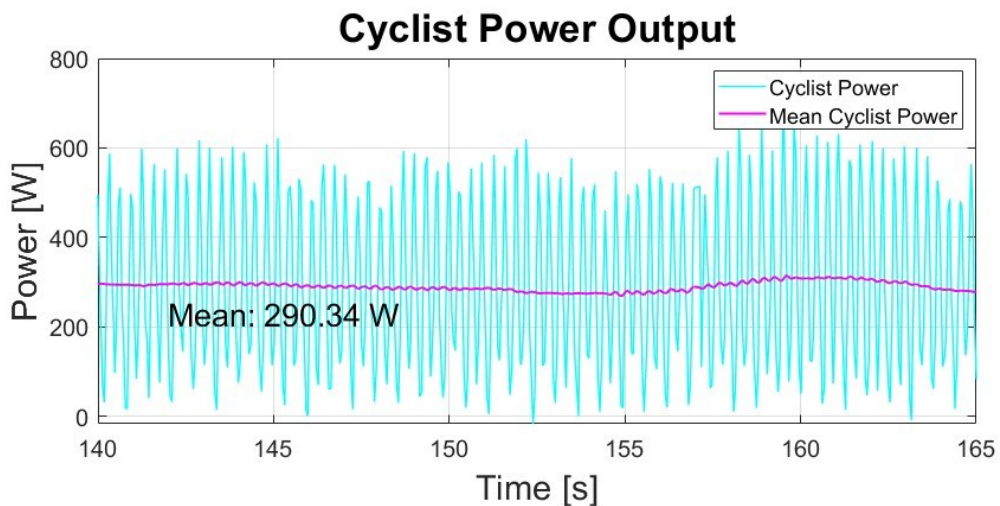


Figure 4.19: Cyclist Power Output for SPORT map

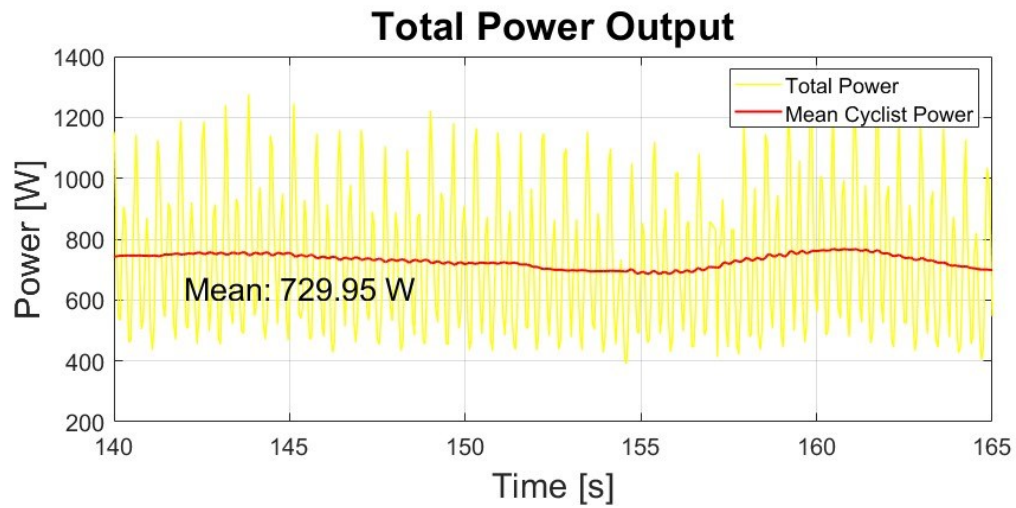


Figure 4.20: Total Power Output for SPORT map

4.3.4 BOOST

Mean values, presented in Figure 4.20, Figure 4.21, Figure 4.22:

- Cyclist Power: 325 Watt
- Engine Power: 420 Watt
- Total Power: 746 Watt

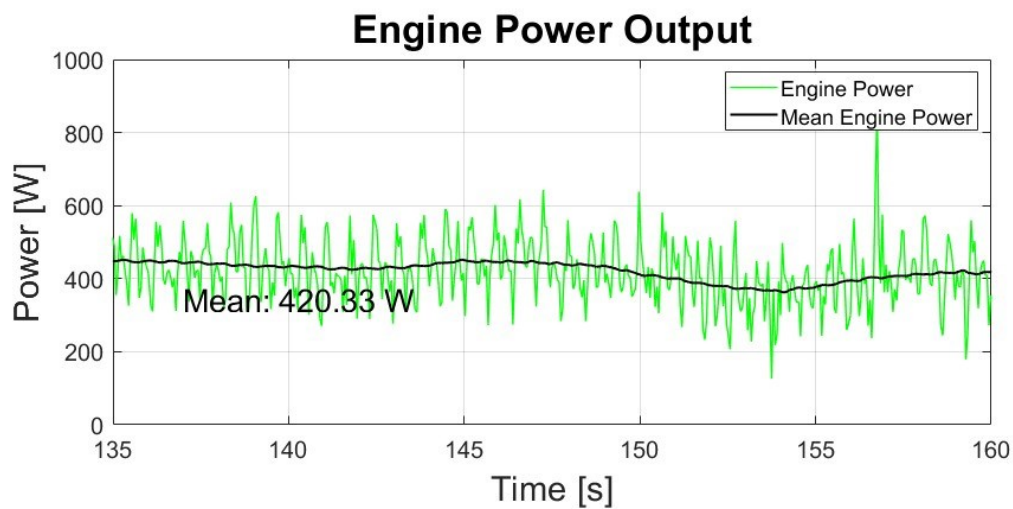


Figure 4.21: Engine Power Output for BOOST map

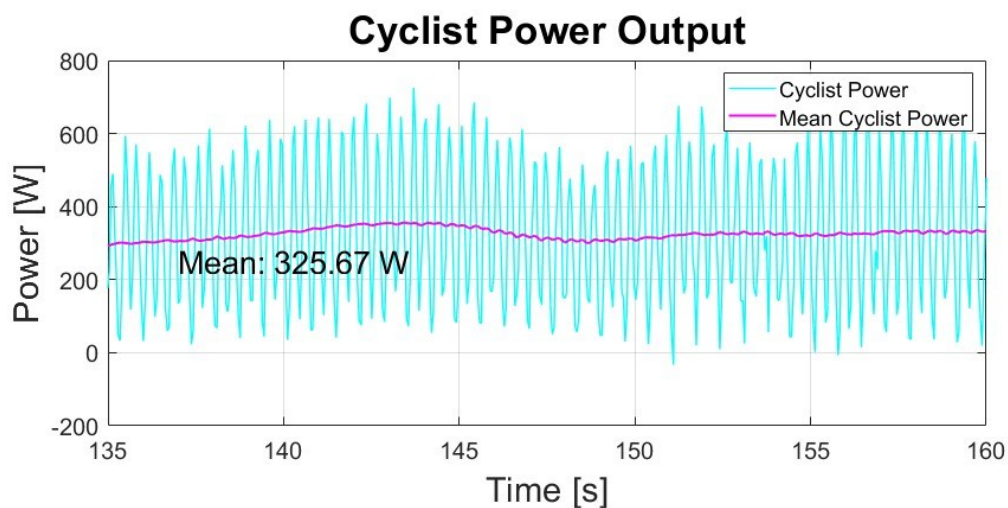


Figure 4.22: Cyclist Power Output for BOOST map

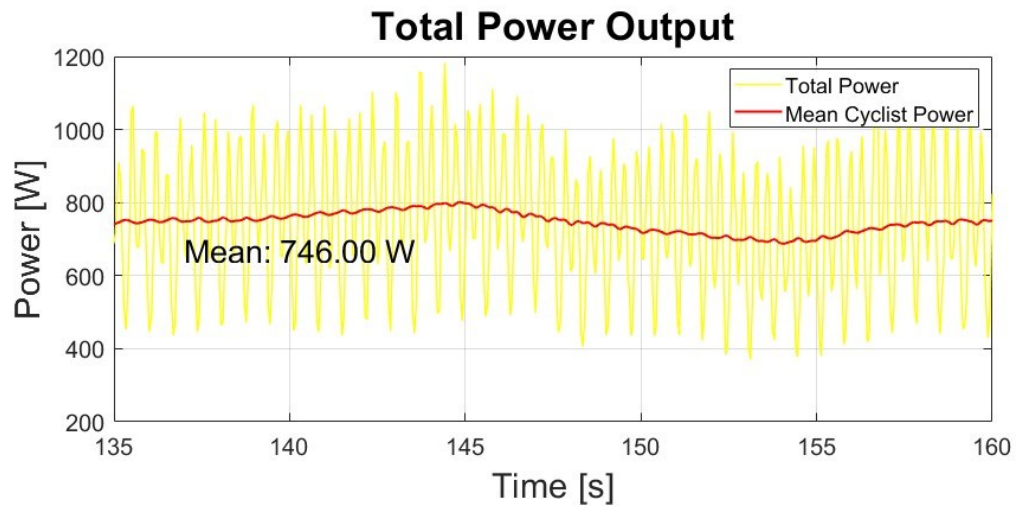


Figure 4.23: Total Power Output for BOOST map

4.3.5 Power results

The power output graphs, as anticipated, display trends that closely align with the results observed in the torque analysis. This similarity underscores the relationship between torque and power, as both metrics are inherently linked through cadence. However, upon closer inspection, the power output across the different rides reveals notable variations, despite the rider's efforts to maintain a steady pace throughout the testing sessions.

The average power output recorded during the tests ranged significantly, from a minimum of 245 Watts to a maximum of 325 Watts. This substantial difference highlights the impact of the motor's assistance levels, as well as the rider's physiological response under different conditions. The lower average power output, observed during the ECO mode, can likely be attributed to the reduced assistance provided by this map. With less support from the motor, the rider was required to exert greater effort independently. By the time the final 25 seconds of the climb were reached—used for data analysis—the accumulated fatigue may have affected the rider's ability to sustain a higher output, leading to the lower power values recorded.

This observation emphasizes the interplay between motor assistance and rider's performance, demonstrating how varying levels of support can influence not only instantaneous power output but also the rider's overall endurance during prolonged efforts. Understanding these dynamics is crucial for evaluating the practical implications of each assistance mode in real-world scenarios.

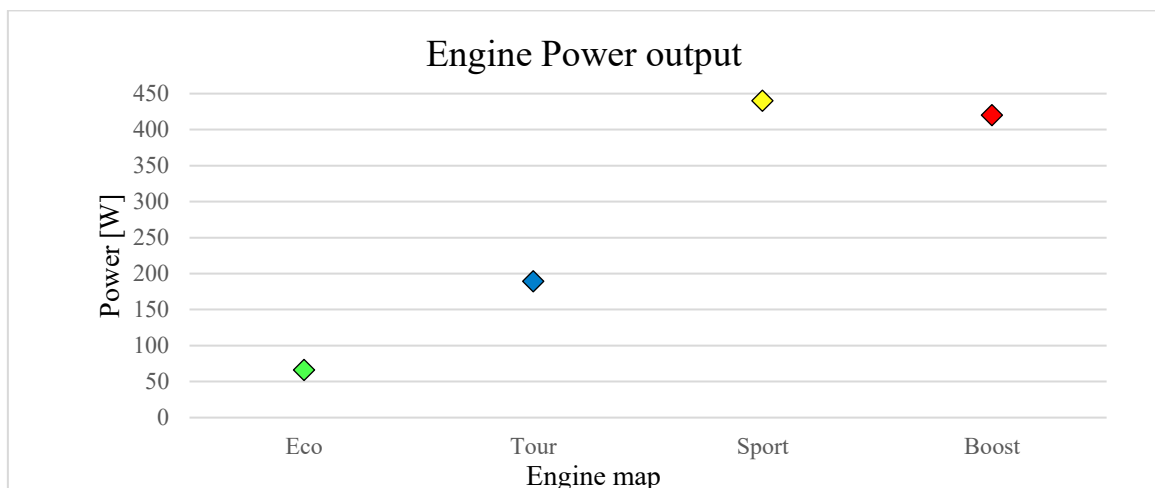


Figure 4.24: Engine Power output for different maps

Chapter 5

LONG CLIMB TESTS

Besides the electric motor output and behaviours, the telemetry systems used in this testing also allow to evaluate the rider's output and overall performance on the bike. This system provides the ability to track other parameters, such as the selection of motor maps and the choice of gears during the ride, those work as indicators of the rider's profile in terms of training, skills and cycling technique.

The parameters tracked by the telemetry systems are not limited to just power output and torque, but also include more subtle aspects such as cadence consistency, shifting patterns, and the rider's ability to adapt to different motor settings. For instance, the way a rider selects different motor maps (ECO, TOUR, SPORT, BOOST) and utilizes gears can provide a detailed picture of their cycling strategy, energy management, and experience with different terrain types. These behaviours give us a window into the rider's tactical approach to using the motor assistance and how well they are able to optimize the system's potential based on their abilities.

To understand how these parameters vary in function of training and skills, the test was conducted by four different riders with different levels of training and skills. Every rider is described in the following table, Table 5.1, with its own ID. By including a relatively wide range of levels of training and skills, the study aimed to capture full range of rider behaviours and to assess how these factors influence their interaction with the motor system.

The main focus of the study was to understand how rider's parameters influence the bike usage focusing in particular on the engine map selection, the gear usage and the engine torque output.

5. LONG CLIMB TESTS

RIDER ID	TRAINING LEVEL	SKILLS LEVEL
RIDER_1	Low	High
RIDER_2	Medium	Low
RIDER_3	Medium	Medium
RIDER_4	Medium to high	High

Table 5.1: Riders level of trainig and level of skills

The map selection and gear usage should depend on the level of skills: a skilled rider should change the map and gear according to slope and terrain to keep the effort constant, whereas a non-particularly skilled one tends to keep the map and gear steadier.

It might also be useful to give more information about the riders such as age, gender and weight, represented in Table 5.2, that are all factors that affect the bike duty cycle, the average torque and the battery consumption.

RIDER ID	TRAINING	SKILLS	GENDER	AGE	WEIGHT
RIDER_1	Low	High	F	23	60 Kg
RIDER_2	Medium	Low	M	26	90 Kg
RIDER_3	Medium	Medium	M	24	84 Kg
RIDER_4	Medium to high	High	M	25	82 Kg

Table 5.2: Other riders carachteristics

Each rider was asked to use the bike in the Monte Pizzoc Hill like they would have in normal conditions. In order to simulate a real-world cycling experience, the riders were instructed to approach the test with minimal intervention or alteration to their usual riding habits. They were provided with just few information before the start of the ride: the total length of the course, the elevation gain and a target time. This target time was estimated by the Garmin software that calculates it from the .gpx file of the track. The purpose of the target time was not to pressure the riders but to give them a benchmark that let them

understand the amount of effort they needed to complete the test, especially for the less experienced ones.

Another thing to consider is the different choice in pedal, and shoes accordingly, type: Rider_1 and Rider_4, given the higher level of skills and extended experience, choose to use SPD pedals, while Rider_2 and Rider_3 decided to stick to standard flat pedals.

To ensure the reliability and consistency of the test results, all the tests were conducted starting of with a fully charged bike battery making sure there was not any motor's performance alteration because of the different battery output. As following results show, a full charge was necessary to complete the ride with a bit of leftover battery. The climb, because of its length and quite high elevation gain, can consume up to 80% of the battery depending on the riding style. Additionally, to eliminate any potential discrepancies related to sensor lack of power because of low tension, the AAA batteries in all sensors were replaced with fresh ones before each ride.

The recording procedure used was the standard one (described in Appendix). All the sensors must be turned on by switching ON all the battery cases. The Mini-PC and the laptop had to be turned on. Once both on, OBS Studio was launched on the laptop and the Mini-PC was connected to it using the USB video capture device. The Mantracourt software were launched on the Mini-PC and the correct operation of each sensor was checked. The bike was set in the OFF map with the GEAR 1 and all the sensors were zeroed. The recording was started, the Mini-PC was disconnected from the laptop and placed on the backpack that the rider was wearing. At this point the rider could start its test ride. At the end of the test ride the Mini-PC was connected again to the laptop to stop the recording.

Throughout each ride, a set of all the parameters that the telemetry system is able to acquire was tracked and analysed. For every rider, key metrics such as the time taken to ascend the hill, the map selection (i.e., which motor mode they used during the climb), gear usage, cadence, and the remaining battery life at the end of the test were carefully recorded. Tracking these parameters provided a comprehensive dataset that enabled an analysis of the motor's overall functionality, as well as an assessment of the riders' performance and efficiency under various conditions.

5.1 RIDER_1

It was the rider with the lower level of training of the group, but still with a high level of skills because of her background on the MTB competitions.

- TIME: 1h 5min 35s

Rider_1 completed the climb in 1 hour, 5 minutes and 35 seconds. Surprisingly it is the fastest time among all the riders. As following results show the assistance of the electric motor was used extensively during the climb.

- Leftover bike battery: 22%

Similar to what time result indicates the capability of the bike has been used intensively resulting in the lowest level of battery at the end of the ride, which was unexpected because Rider_1 was the lighter of the set.

- Average Cyclist Torque: 13,1 Nm
- Average Total Torque: 36,1 Nm

5.1.1 RIDER_1 map selection

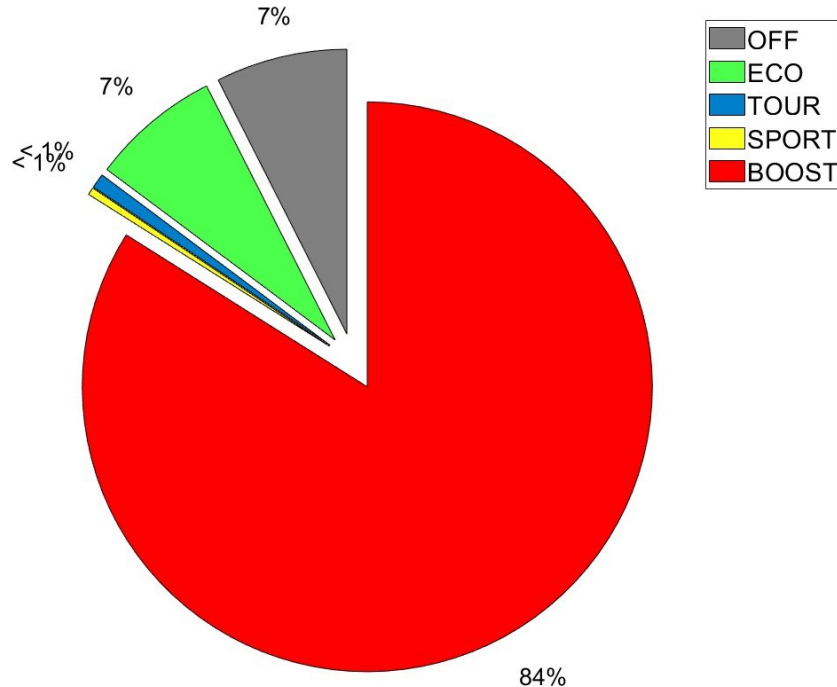


Figure 5.1: RIDER_1 maps duty cycle

5. LONG CLIMB TESTS

ENGINE MAP	Time (s)	%
Off	323	7
Eco	317	7
Tour	36	1
Sport	18	1
Boost	3642	84

TOTAL TIME	4336 s
------------	--------

Table 5.3: RIDER_1 maps duty cycle

Rider_1 decided to use for most part of the track the BOOST map, the most aggressive setting available for the Brose power system. This map provides the maximum assistance from the motor, resulting in a significantly faster ascent compared to the other riders, that in theory should have been faster. It was in fact the fastest time among all the riders by almost 15 minutes from the second fastest. Even though her skills are quite good, emphasized by the remarkable ascending time, there was a poor map management. This could be due to two different factors: the habit of riding lightweight and fast bikes and the first approach to a pedal-assisted mountain bike. The combination of these two factors led to this aggressive riding style.

The choice of using the bike in BOOST configuration for most of the time caused a leftover battery at the top of the climb of just the 22%. Considering it was the lighter of the group of riders, it highlights the higher consumption that the electric motor has in this map configuration.

5.1.2 RIDER_1 gear

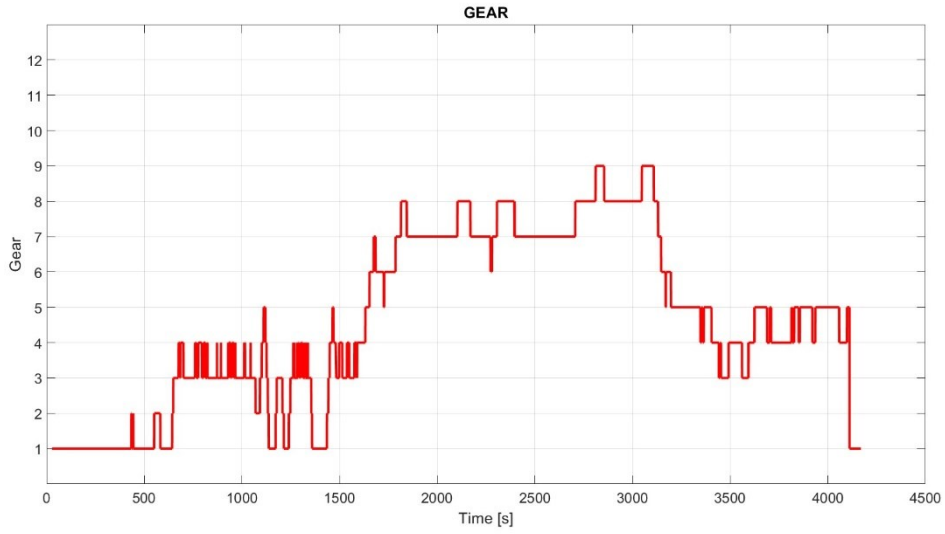


Figure 5.2: RIDER_1 gear in function of time

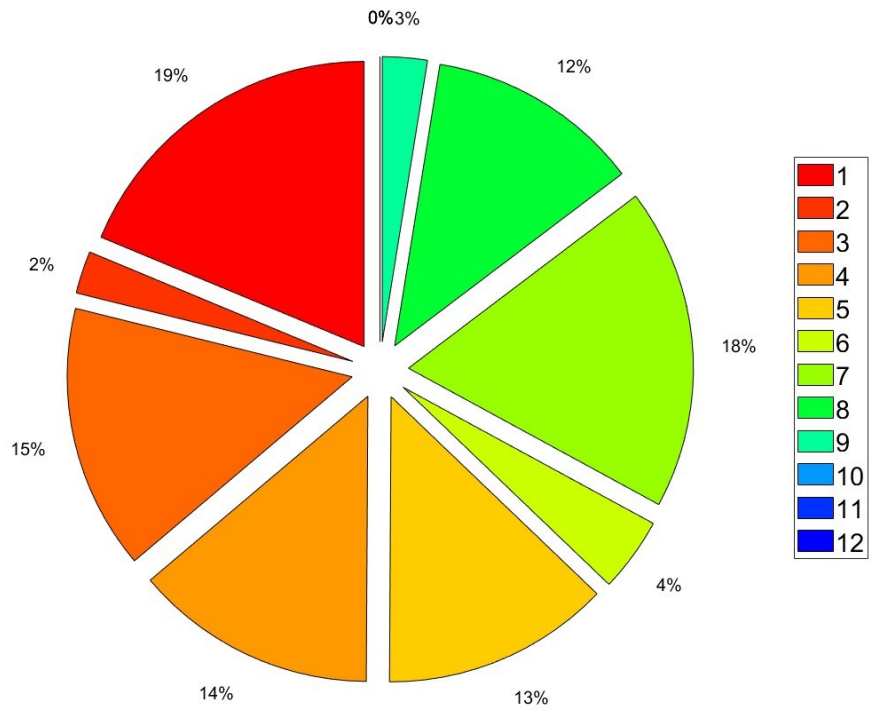


Figure 5.3: RIDER_1 gear usage

As result of using BOOST map for a higher amount of time, more specifically for the 84% of the time, RIDER_1 only used gears ranging from 1 to 9. The high level of assistance ensured by the BOOST map allowed her to use only part of the 12 gears available. It provided a high speed throughout the whole ascent without increasing the cadence excessively.

In contrast, with a non-pedal-assisted bike, it would be quite difficult to avoid using the higher gears, such as 10, 11, and 12, especially on a long or challenging climb where maintaining a good cadence becomes necessary. With a non-pedal-assisted bike it's quite hard not to use gear 10, 11 and 12 and, even with a pedal-assisted bike, with the other maps available, such as ECO, a well-trained rider would struggle to keep it.

5.1.3 RIDER_1 torque usage

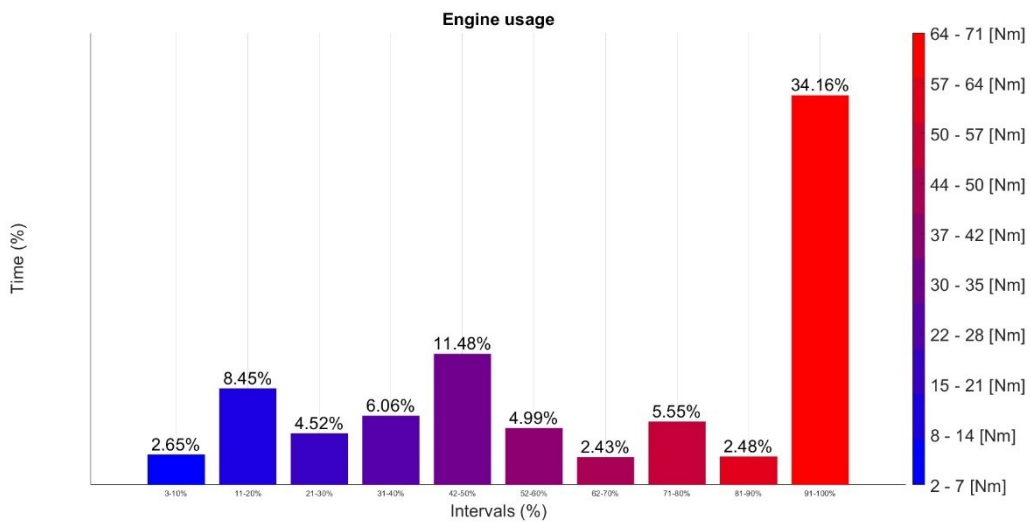


Figure 5.4: RIDER_1 Torque over time

From the data shown in Figure 5.4, it is evident that RIDER_1, utilizing high assistance maps, forced the engine to operate at a significantly high torque level for extended periods. Notably, over 34% of the total time is spent in the 91-100% torque range, which represents more than 90% of the maximum torque capacity used during the ride, that reaches the value of 71 Nm. This high proportion of operation near the upper torque limit highlights the demanding nature of these rides and the intensive workload

placed on the engine. This insight underscores the heavy reliance on peak torque performance when utilizing high assistance maps, which have implications for energy consumption.

5.2 RIDER_2

Rider_2 can be considered a mediumly trained athlete, but lacking experience on riding bike, in particular in mountain biking.

- TIME: 1h 26min 42s

Rider_2 completed the climb in 1 hour, 26 minutes, and 42 seconds. This is the slowest time recorded: that could be attributed to the limited mountain biking experience. The slow time might be a consequence of not a perfect distribution of the effort.

- Leftover bike battery: 28%

The battery consumption was relatively high, but given the fact that it was the heaviest rider, it can be considered in line with the other results.

- Average Cyclist Torque: 24,5 Nm
- Average Total Torque: 46,6 Nm

5.2.1 RIDER_2 map selection

The Rider_2 was able to manage the engine map considerably better than Rider_1, resulting in a more efficient use of the motor and consequently a lower battery consumption. This was especially notable considering the weight difference between the two riders. Despite this disparity in weight, which could have led to greater energy consumption for Rider_2, the rider's more strategic approach to using the motor resulted in a more efficient ride, as reflected in the lower battery usage.

ENGINE MAP	Time (s)	%
Off	151	3
Eco	433	8
Tour	3003	58
Sport	41	1
Boost	1570	30

TOTAL TIME	5198
------------	------

Table 5.4: RIDER_2 maps duty cycle

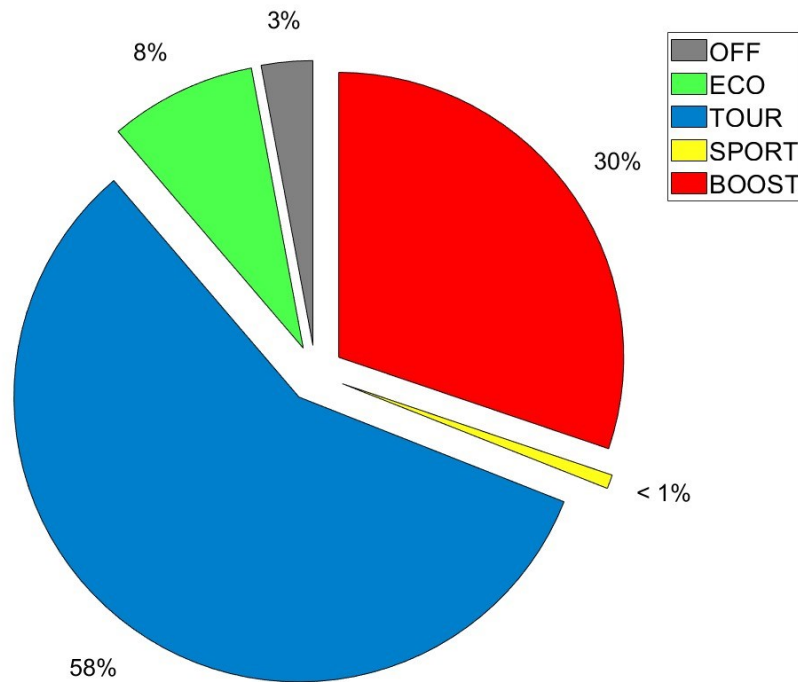


Figure 5.5: RIDER_2 maps duty cycle

The Rider_2 still used for a fair amount of time, more precisely 30% of the time, BOOST configuration, completely avoiding SPORT map. Previous result showed that BOOST and SPORT engine maps are quite similar to each other in terms of output with a constant load: the tendency to prefer the BOOST map over the SPORT map highlights the lower level of skills of Rider_2 who was not able to feel the marginal difference that was found in these types of applications, that are steady pace and slope. Even though the map management were better than Rider_1 one, there is still a small amount of time spent in ECO mode, showing that Rider_2 was not particularly focusing on battery management, that in rides of this kind can be crucial at times.

5.2.2 RIDER_2 gear

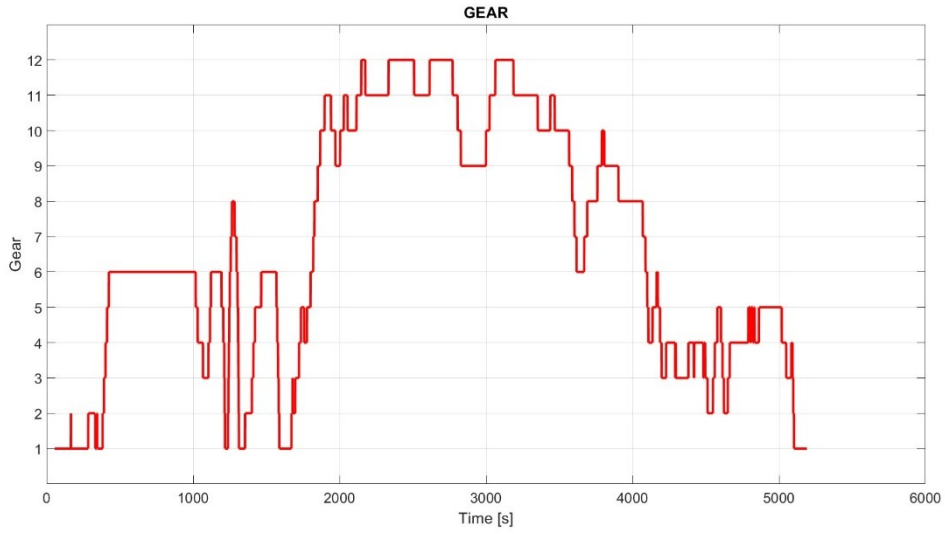


Figure 5.6: RIDER_2 gear in function of time

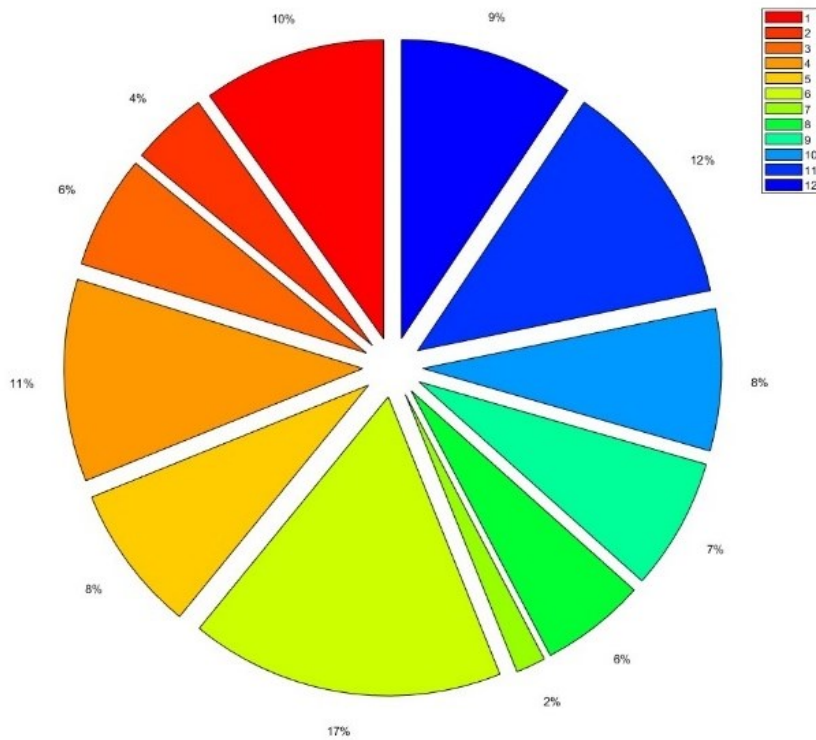


Figure 5.7: RIDER_2 gear usage

Despite a sub-optimal engine map from Rider_2, there is a good gear usage. The rider used the whole spectrum of the twelve gears available with a good time distribution for each gear. As figure 5.7 shows, there is an even distribution of time for gears ranging from GEAR 8 to GEAR 12, meaning that the rider was actively trying to keep the effort and the cadence relatively constant during the roughest section of the track, the second one.

5.2.3 RIDER_2 torque usage

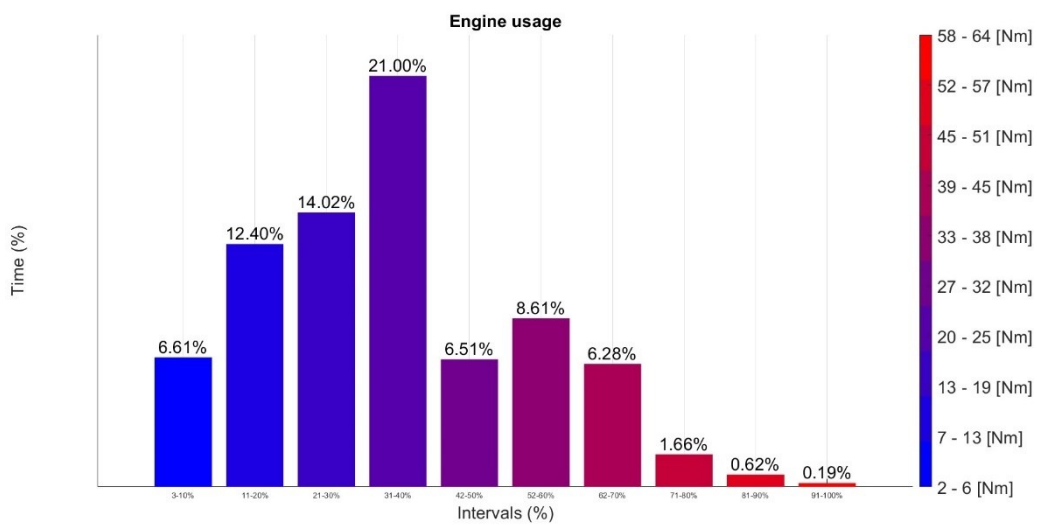


Figure 5.8: RIDER_2 Torque over time

The engine torque usage respect to what seen on the engine map selection: a high usage of lower middle of the maximum torque output of the ride, but a still visible usage of higher middle of the range, representing well the extensive use of TOUR and BOOST maps. The highest torque generated by the engine reaches the value of 64 Nm, as visible on the side scale of Figure 5.8, still a reasonably high value.

5.3 RIDER_3

Rider_3 has a comparable level of training to Rider_2, but more experience in riding mountain bikes.

- TIME: 1h 22min 12s

Rider_3 completed the climb in 1 hour, 22 minutes, and 12 seconds, which is a notable improvement over Rider_2's time. The faster ascent can likely be attributed to their enhanced MTB skills.

- Leftover bike battery: 33%

At the end of the climb the leftover battery was at 33%, a slight improvement over the Rider_2, probably because of a small weight difference but mainly because of a better management.

- Average Cyclist Torque: 22,6
- Average Total Torque: 47,4

5.3.1 RIDER_3 map selection

The pie chart, Figure 5.9, shows the distribution of engine map usage during a ride, highlighting the prominent reliance on TOUR and SPORT modes, which together account for over 70% of the total time.

ENGINE MAP	Time (s)	%
Off	102	2
Eco	794	15
Tour	1987	38
Sport	1744	33
Boost	586	11

TOTAL TIME	5213
------------	------

Table 5.5: RIDER_3 maps duty cycle

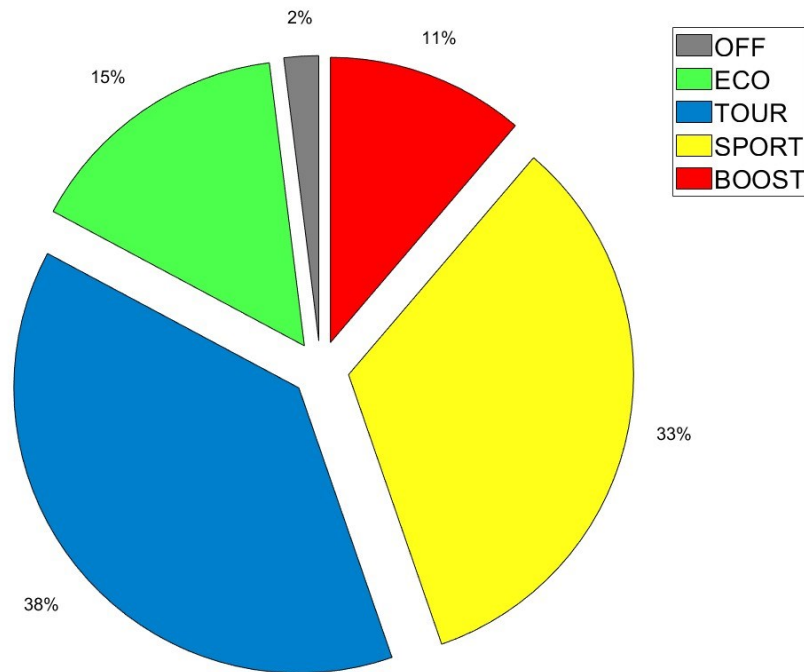


Figure 5.9: RIDER_3 maps duty cycle

When comparing this usage pattern with data from Rider_1 and Rider_2, there is a noticeable reduction in the use of the BOOST mode. The BOOST map, characterised by its high power output and energy consumption, is used marginally in this case, for only the 11% of the total time.

This pattern of usage suggests a more calculated and strategic approach to selecting engine maps. By reserving BOOST for situations where it is absolutely necessary, the rider achieves a more efficient balance, extending battery life. This shift demonstrates a refined understanding of when and how to use different levels of assistance, resulting in a more effective and thoughtful utilization of the engine's capabilities.

5.3.2 RIDER_3 gear

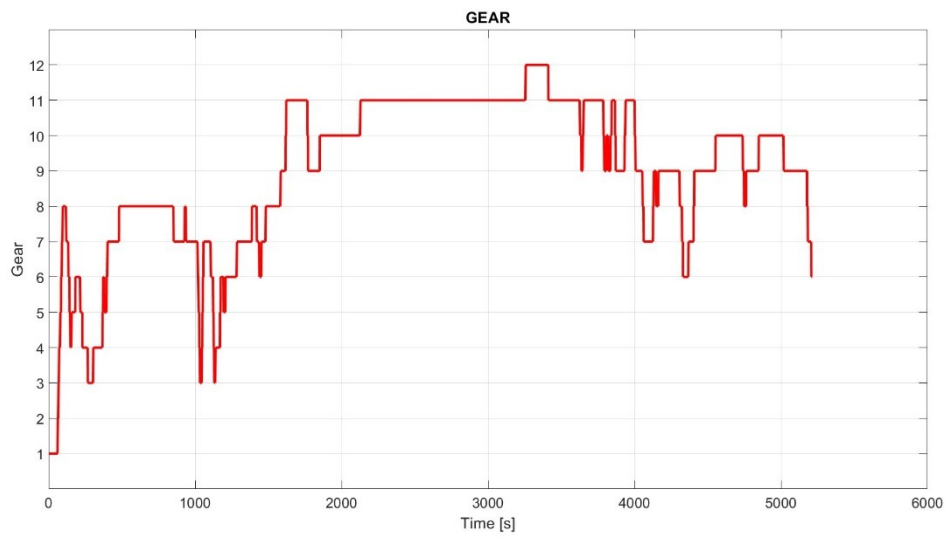


Figure 5.10: RIDER_3 gear in function of time

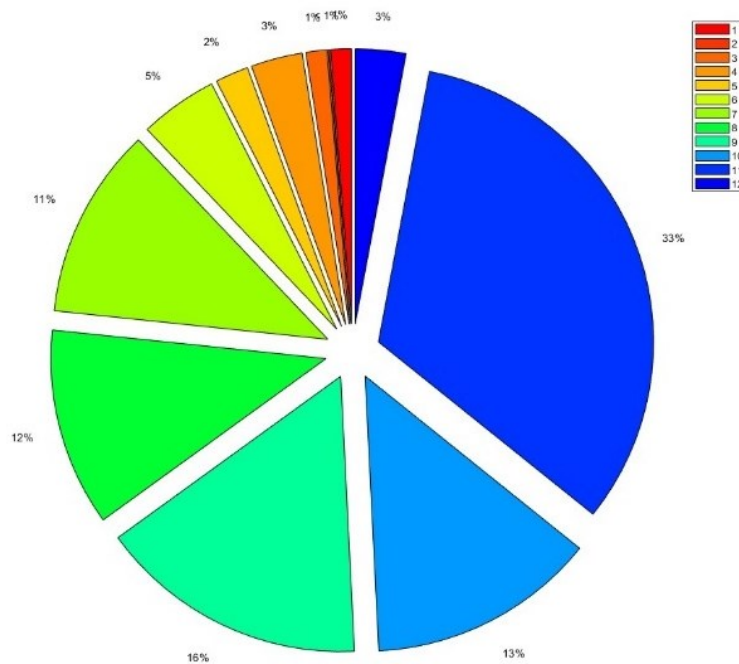


Figure 5.11: RIDER_3 gear usage

RIDER_3, as Rider_2 did, also used the full range of gears available but with a different distribution over time. For the second section of the climb, the hardest one, he mainly stuck to GEAR 11 (Figure 5.10). From Figure 5.11 it is visible that lower gears, from GEAR 1 to GEAR 6, have not been used extensively, reaching all together around the 10% of the total time.

5.3.3 RIDER_3 torque usage

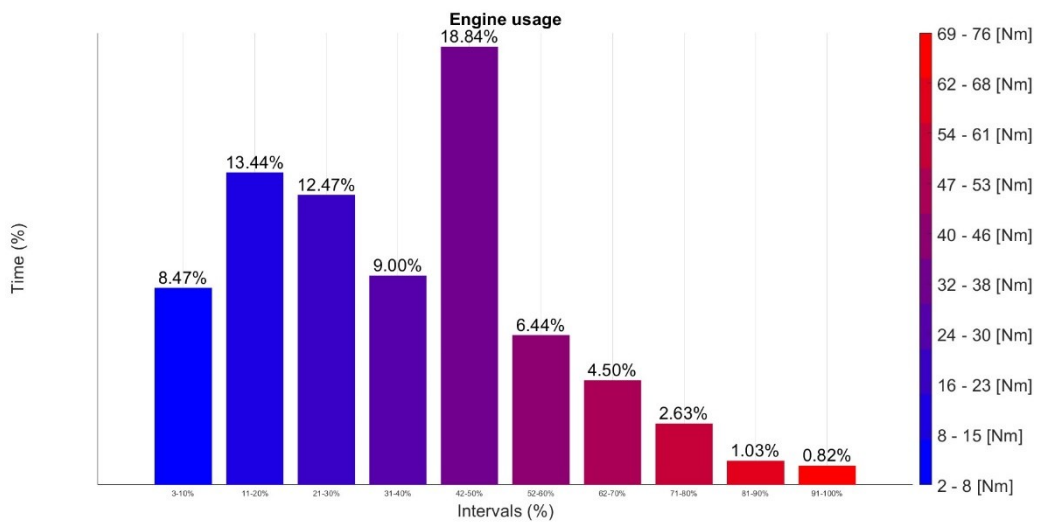


Figure 5.12: RIDER_3 Torque over time

The engine torque usage is emphasizing the extensive usage of the TOUR and SPORT maps. The maximum value of the engine torque sticks out because it reaches the highest value among the four riders at 76 Nm.

5.4 RIDER_4

Rider_4 had a higher level of training compared to the other participants, while exhibiting a skill level similar to Rider_1. This combination of advanced fitness and moderate MTB skills allowed for a relatively quick and efficient ascent.

- TIME: 1h 19min 50s

Rider_4 completed the climb in an good time of 1 hour, 19 minutes, and 50 seconds, making it the second fastest times recorded during the tests, almost without using BOOST engine map.

- Leftover bike battery: 36%

At the conclusion of the climb, Rider_4 had 36% of the bike’s battery remaining, the highest among all the riders. This demonstrates their excellent management of the motor assistance and their ability to rely more on their physical strength.

- Average Cyclist Torque: 23,1
- Average Total Torque: 32,8

5.4.1 RIDER_4 map selection

ENGINE MAP	Time (s)	%
Off	160	3
Eco	940	19
Tour	1715	35
Sport	2064	42
Boost	37	1
TOTAL TIME		4916

Table 5.6: RIDER_4 maps duty cycle

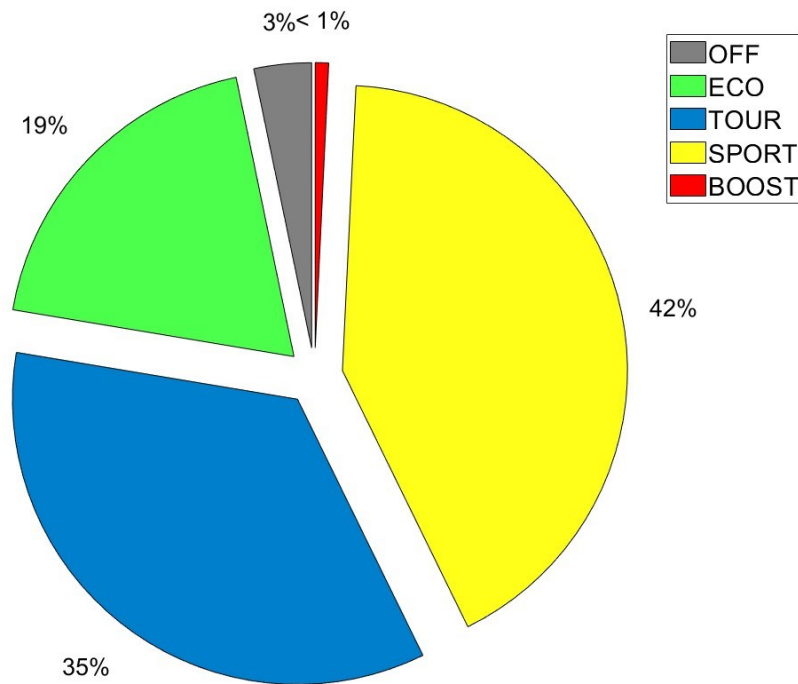


Figure 5.13: RIDER_4 maps duty cycle

There is a remarkable reduction in time spend in BOOST, in fact it is less than 1% of the time. As for Rider_3 TOUR and SPORT maps are the dominant ones, reaching in this case more of the 75% of time spend. There is also an increase of time spent in ECO that shows a better usage with the battery management in mind. It was shown by the highest level of leftover battery. This map usage also remark a higher level of training of Rider_4, that completed the ride relatively fast with the use of lower-assistance maps.

5.4.2 RIDER_4 gear

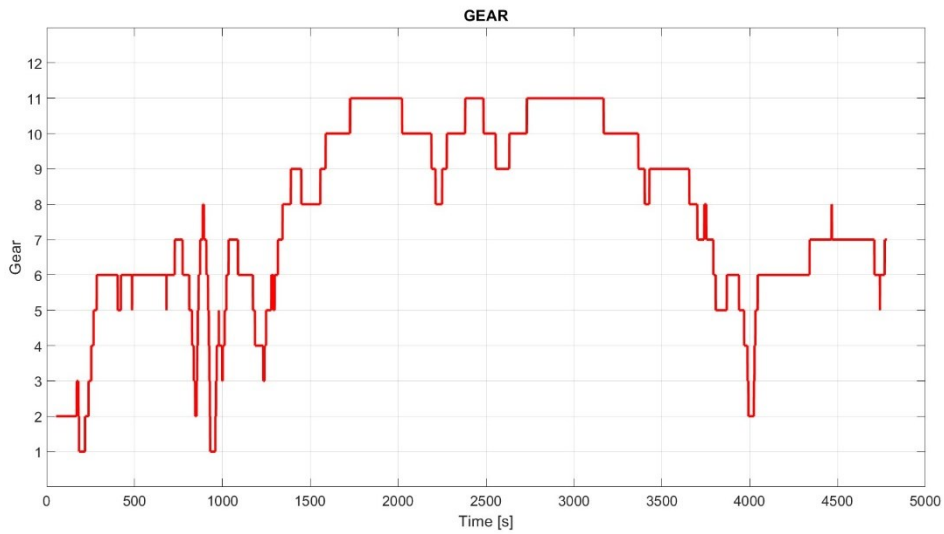


Figure 5.14: RIDER_4 gear in function of time

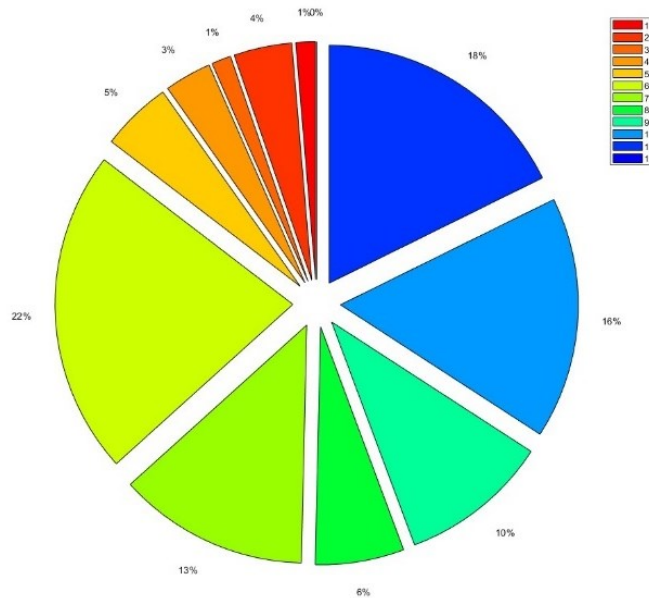


Figure 5.15: RIDER_4 gear usage

Despite the reduce time spent on BOOST map, not even reaching the 1% of the total time, Rider_4 was able to avoid using gear 12. It shows, as expected, that a higher training level let the rider keep a harder gear even when climbing while ensuring a good cadence too. All this combined increases the travelling speed resulting in a faster ascent as the total riding time confirms.

5.4.3 RIDER_4 torque usage

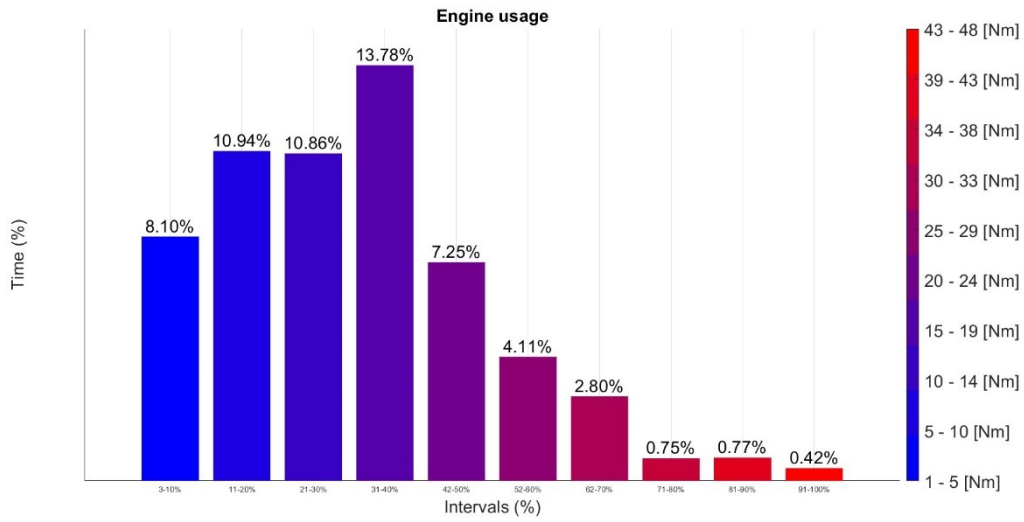


Figure 5.16: RIDER_4 Torque over time

The graph highlights that the engine usage for RIDER_4 was much lower than the other riders. The maximum value was of 48 Nm, whereas the other rider's maximum engine torque was ranging from 64 Nm to 76 Nm. This, in combination with the torque distribution shifted to the left side of the graph, shows the higher level of training of RIDER_4.

5.5 Long climb results

The long climb testing conducted with four different riders revealed a variety of interesting results, useful to understand the impact of prior experience, training and rider's skills on the performance and usage of pedal-assisted mountain bikes. Several key factors, such as engine map management, gear selection, and engine torque distribution, provide valuable insights into the riders' strategies and adaptation to the test conditions.

Starting with the engine maps, a clear distinction can be made between Rider_1 and Rider_2, which both didn't have any previous experience with pedal-assisted mountain bikes, and Rider_3 and Rider_4, who had already used this type of bikes in the past. Rider_1 and Rider_2, as expected, spent more time in higher assistance levels, while Rider_3 and Rider_4 showed a more strategic use of lower assistance levels. As their training and strength levels increased, they were able to decrease the time spent on higher assistance maps. This illustrates the impact of prior experience and physical conditioning on optimizing bike performance and managing energy efficiently.

In terms of gear selection, the differences between the riders are also noteworthy. Rider_2, Rider_3, and Rider_4 were able to utilize the entire range of gears available on the bikes, or at least most of them, although with some variations in how they distributed their time across the gears. This indicates that these riders were able to find the optimal gearing for different stages of the climb, balancing power output and pedalling cadence to maximize efficiency. However, what stands out the most is Rider_1's gear usage. Despite having access to all 12 gears as the other riders, Rider_1 only used 9 of them. This choice was only possible because of her reliance on the bike's BOOST engine map. By frequently engaging the highest assistance level, she was able to maintain a reasonable cadence and power output without needing to shift through the full range of gears.

When it comes to engine torque usage, it becomes clear that there is a direct relationship between the engine map selection and the torque distribution. As expected, when riders used higher assistance maps, such as the BOOST mode, the torque values were shifted toward the higher end of the spectrum. Similarly, when riders chose lower assistance levels, the torque distribution shifted to lower values.

5. LONG CLIMB TESTS

To further understand the map selection for the different levels of skills and different levels of training a graph summarizing this information was created (Figure 5.17): the horizontal axis represents the level of training, ranging from low to high, whereas the vertical one represents the level of skill, still ranging from low to high.

For each of the combination of these two parameters created by the four riders, the engine map duty cycle chart was placed on the grid created by these two axis.

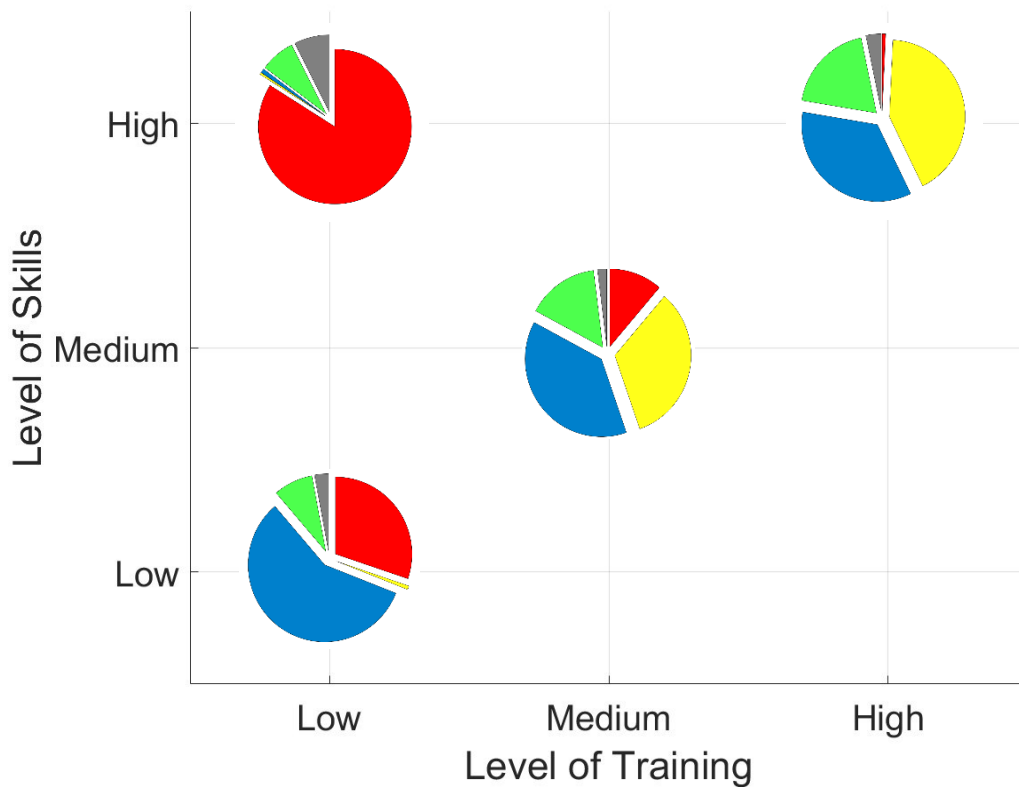


Figure 5.17: Engine map duty cycle chart

The graph allows to immediately see the engine map distribution in function of the rider's characteristics.

The results shows that the map usage management tends to be different mainly changing the level of training. It is clear that more trained rider can and prefer using lower assistance maps.

Chapter 6

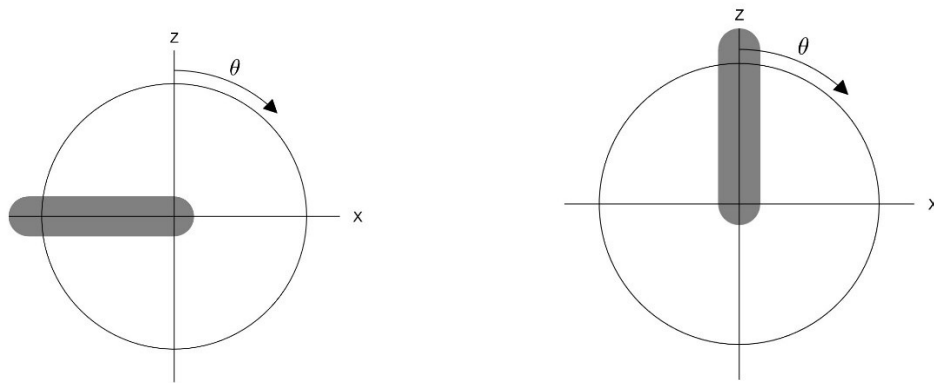
TORQUE PROFILE EVALUATION FOR DIFFERENT PEDALSTROKE

After analysing the average behaviour of some riders during a climb, where the electric motor is actually working, it is useful to explore the torque profile of riders during a pedal stroke. The system already records the torque profile by using Channel_5 and Channel_6, but it is necessary to identify the angle corresponding to the torque.

It is important to remember that the strain gauges configuration for Channel_5 and Channel_6 only measures the tangential force applied to the pedals. To measure also the radial component, it would have been necessary to apply additional strain gauges, but the biggest problem was not the add-on of the strain gauges, that would have fitted on the crankarms. An extra acquisition module would have been necessary, but it was impossible to place it on the crankarm without interfering with the rider.

In order to find the torque in function of the crankarms angle, it was necessary to integrate the data from the crank hall sensor, Channel_8. The cadence sensor records every passage of the left crankarm, so the interval between two hall effect sensor's peak was divided into 360 degrees in a linear way supposing that the rotation velocity was constant in this interval of time.

To represent the torque in a properly structured graph, where the x axis corresponds to the horizontal and the Z axis corresponds to the vertical one, an additional measurement was necessary for each one of the riders. This allows to find the offset angle, called ground offset angle, that corrects the linear interpolation between 0 and 360 degrees in order to align the left crankarm with the horizontal X axis. Because the left crankarm is facing backwards when aligned with the hall effect sensor and usually the 0-degree position corresponds to the top dead center, to the offset angle previously measured it is necessary to add 90 degrees.

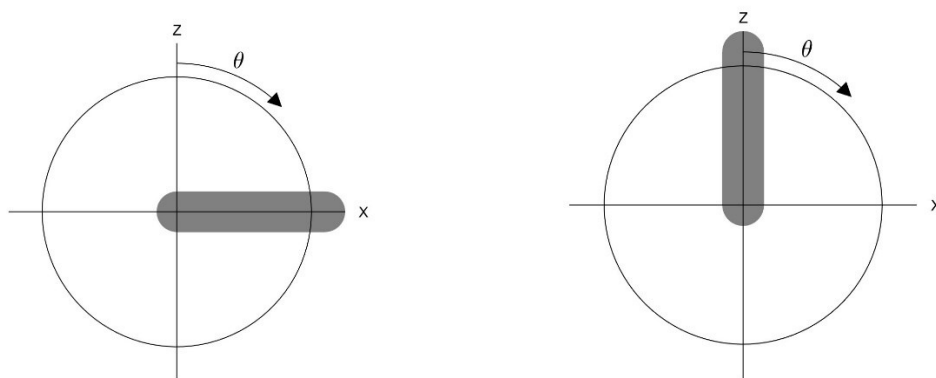


(a) Left crankarm when over hall sensor

(b) Origin

Figure 6.1: Left crankarm on the reference system

For the right crankarm a similar procedure was taken. The angle between the left and the right crankarms is obviously fixed and equal to 180 degrees. Therefore, the actual offset angle for the right crankarm is equal to the sum of the ground offset angle and 270 degrees. Part of the following graphs have an offset angle for the right crankarm set to ground offset angle plus 90 degrees: it's because in this way the two output torques, left and right are represented as in real world with a phase shift of 180 degrees.



(a) Right crankarm when over hall sensor

(b) Origin

Figure 6.2: Right crankarm on the reference system

6.1 Offset angle

The rider was asked to sit on the stationary bike while the left crankarm was perfectly placed above the hall effect sensor. An inclinometer was used to identify this angle: it was placed on the ground and set to zero, then it was placed on top of the left crankarm to measure the ground offset angle.

	GROUND OFFSET ANGLE
Without rider	3°
With rider	0°

Table 6.1: Ground offset angle

6.2 Testing procedure

The climb used for this evaluation is about 20 meters long with a slope of 5%. The bike was turned off to keep the electric motor help out of the variables to study. The rider was asked to do the climb at a constant cadence set to 80 RPM with the help of a metronome in order to keep it as constant as possible. The climb was repeated 12 times in total with different combinations of pedals, position on the bike and gear.

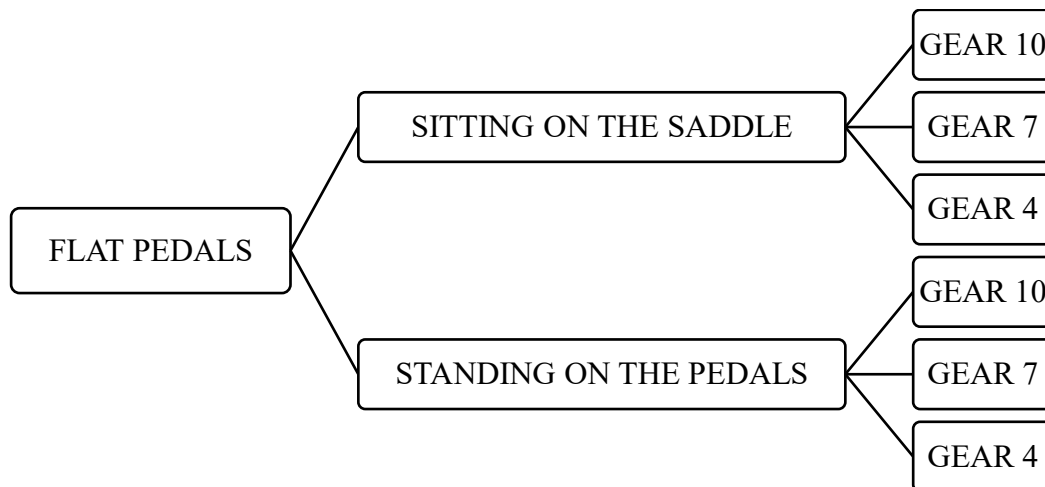


Table 6.2: Flat pedals testing

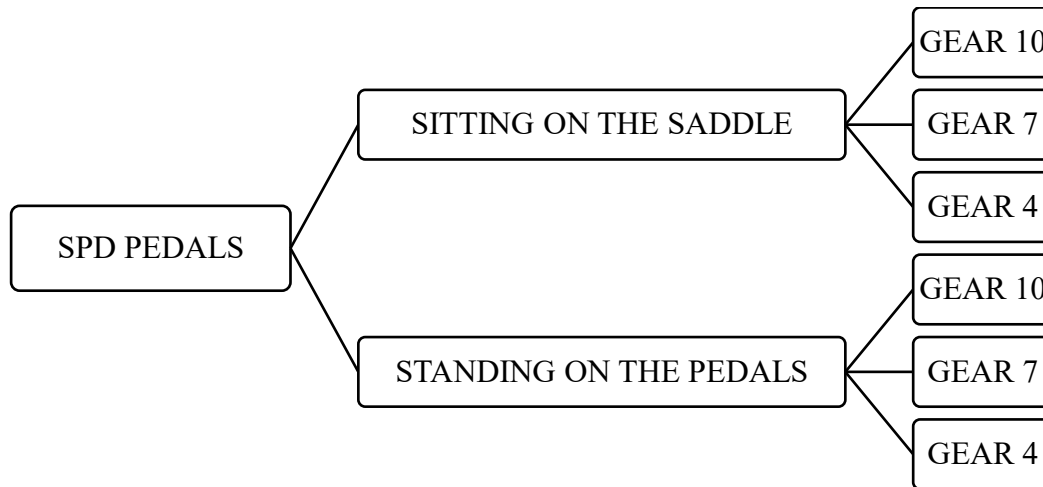


Table 6.3: SPD pedals testing

The recording procedure is the same as the one described in Chapter 2. Every sensor was turned on, even the ones not directly necessary for the specific research quest, the Mini-PC was turned on and connected to the laptop using OBS Studio. The Mandtracourt Log1000 software was launched and each channel was zeroed. Then the logging was started and the rider repeated the climb two times, one sitting and one standing, on the same recording.

Because the test was repeated with the use of two different types of pedals, a different torque profile is expected to be found depending on the type of pedal used especially on the part of the stroke that ranges from the 270 degrees position to the 360 degrees position. In this case, the fact that the shoes are fixed to the pedal allows the rider to pull the pedal rather than slightly pushing into it to keep the shoe in contact with the flat pedal.

The effort, and therefore the torque and the power, should increase while the gear decreases because the speed, at a fixed crankset RPM, increases. The result expected with different gears should show a higher torque peak with lower gears.

6.3 Torque profile and pedal efficiency

For every one of the previously described tests carried out, two important factors were evaluated: the torque profile during the pedal stroke and the pedal efficiency.

The torque profile represents the amount of torque output for left and right crankarm in function of the angle of the pedal stroke. The angle is equal to zero when the pedal is in the higher position and positive when rotating in the direction of travel.

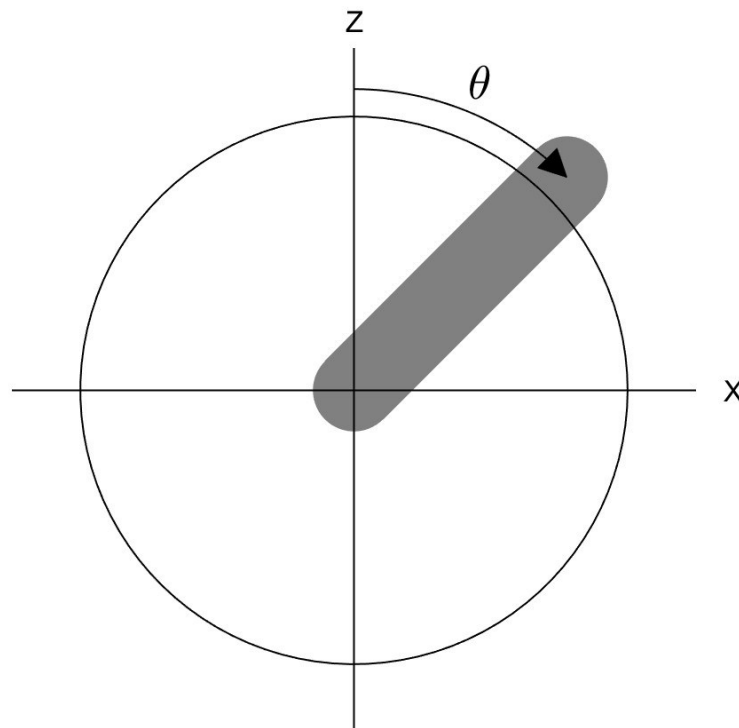


Figure 6.3: Pedal stroke angle convention

This convention represents the bike facing right with the X axis as the horizontal one and the Z axis as the vertical one. The rotation angle is θ .

Of course the torque profile is not constant throughout the pedal stroke but should have a peak ranging between 45 and 135 degrees. There is also a section where the torque has negative values. This profile should shift depending on the type of pedal used and also on the riding style.

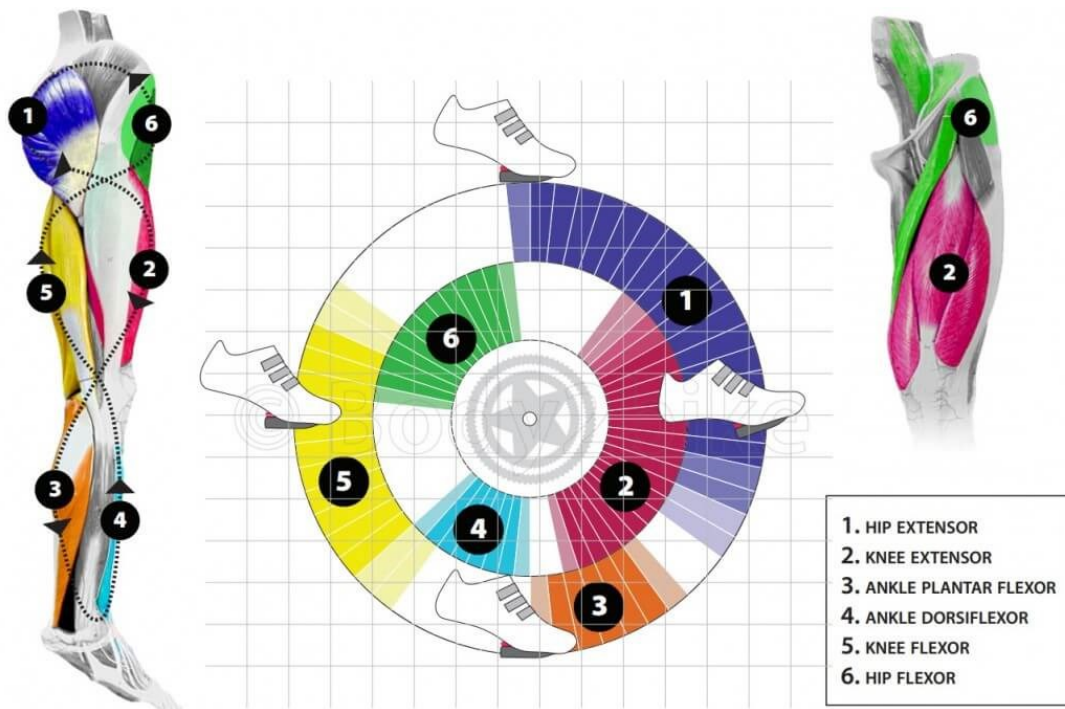


Figure 6.4: Different muscle phases during pedal stroke. Muller R. (2017).

As the Figure 6.2 shows the different phases of the pedal stroke are carried out by different muscles. In particular, phase 5 and phase 6 are quite dependent on the type of pedal used. The standard flat pedals don't allow the knee flexor and the hip flexor to pull properly the crankarms so a zero, or lower, value is expected to be found for this type of pedals. On the other hand, SPD pedals allow these two muscle groups to pull the crankarms, therefore letting the cyclist output a higher torque value especially in these phases.

After evaluating the torque produced during a pedal stroke the subtended area of the torque in function of the degrees was measured considering both the positive component and the negative component. An example of the areas evaluated is visible in Figure 6.5, that represents these areas for left and right pedal stroke. By doing this measurement a deeper pedal stroke analysis can be conducted: it was in fact possible to evaluate the average torque that the cyclist can output and also the amount of positive and

6. TORQUE PROFILE evaluation for different pedalstroke

negative torque. These two last parameters were used to measure the efficiency in relative and absolute terms as follows (Equation 6.1 and Equation 6.2 respectively).

$$E_r = \left(1 - \frac{\text{negative area}}{\text{positive area}}\right) \cdot 100$$

Equation 6.1

$$E_a = \left(1 - \frac{\text{negative area}}{\text{total area}}\right) \cdot 100$$

Equation 6.2

Both terms are expressed as percentage value and the higher the value is the more efficient the pedal movement is. If the rider is also able to pull during phase 5 and phase 6 the efficiency, relative and absolute, should reach the 100% because the negative area is equal to zero.

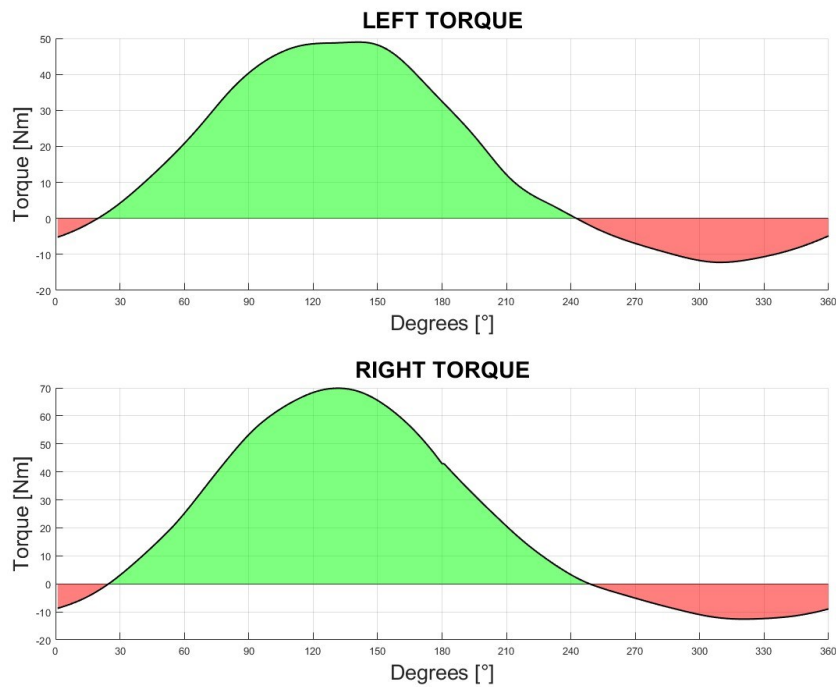


Figure 6.5: Example of torque areas

6. TORQUE PROFILE evaluation for different pedalstroke

For every one of the testing combinations described by Table 6.2 and Table 6.3 the torque profile was represented by two different types of graphs. The first type is a cartesian graph where the x-axis indicates the angle as described in Figure 6.3, between 0° and 360° , and the y-axis shows the value of the torque. There are two different lines representing the left and the right pedal stroke: left in red and right in green. The two dotted lines shows the average values of the left and right torque output.

In addition to this graph a table was used to report the maximum, the minimum and the average values of the torque.

The torque distribution and these values are extremely important to understand the amount of torque and so of stress that the engine is subjected to during a normal ride. They are necessary to build a proper test bench being able to simulate the average torque but also the maximum torque and the minimum torque, that at times can be negative.

Another type of graph was also used. It consists of the distribution of the torque in the circular reference system described by Figure 6.3. Some segments are placed in the radial direction along the circumference that represents the pedal circumference. The length of these segments is proportional to the torque applied by the cyclist and they are facing outwards when positive and facing inwards when negative. The segments are placed every 5 degrees.

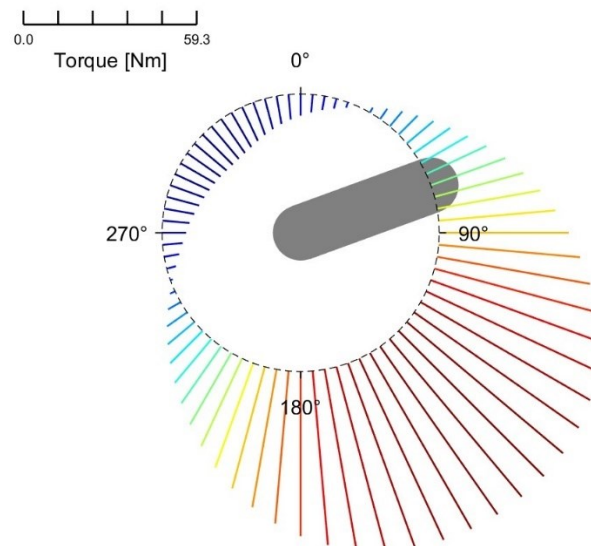


Figure 6.6: Example of torque distribution

6.4 Flat pedals sitting

As previously described the efficiency was measured for each of the 12 test rides resulting in a variation of efficiency between gears.

GEAR	AVERAGE POWER [W]	CRANK SIDE	E_r	E_a
10	146	LEFT	83%	80%
		RIGHT	87%	85%
7	216	LEFT	92%	91%
		RIGHT	96%	96%
4	356	LEFT	97%	97%
		RIGHT	99%	99%

Table 6.4: Pedal stroke efficiency for flat pedals sitting

There is a clear asymmetry between left and right that is particularly apparent at higher gears that correspond to lower speed and lower torque output as represented by the graphs in the following sections of the chapter.

It is also visible that the efficiency increases as the torque output increases. That's because the value of the negative torque remains fairly constant, at around -20 Nm, whereas the value of the positive torque increases significantly going from around 50 Nm all the way up to 140 Nm.

6.4.1 GEAR 10

SIDE	MAXIMUM TORQUE	MINIMUM TORQUE	AVERAGE TORQUE
L	49	-12	14
R	70	-13	20

Table 6.5: Torque values for GEAR 10, flat pedals sitting

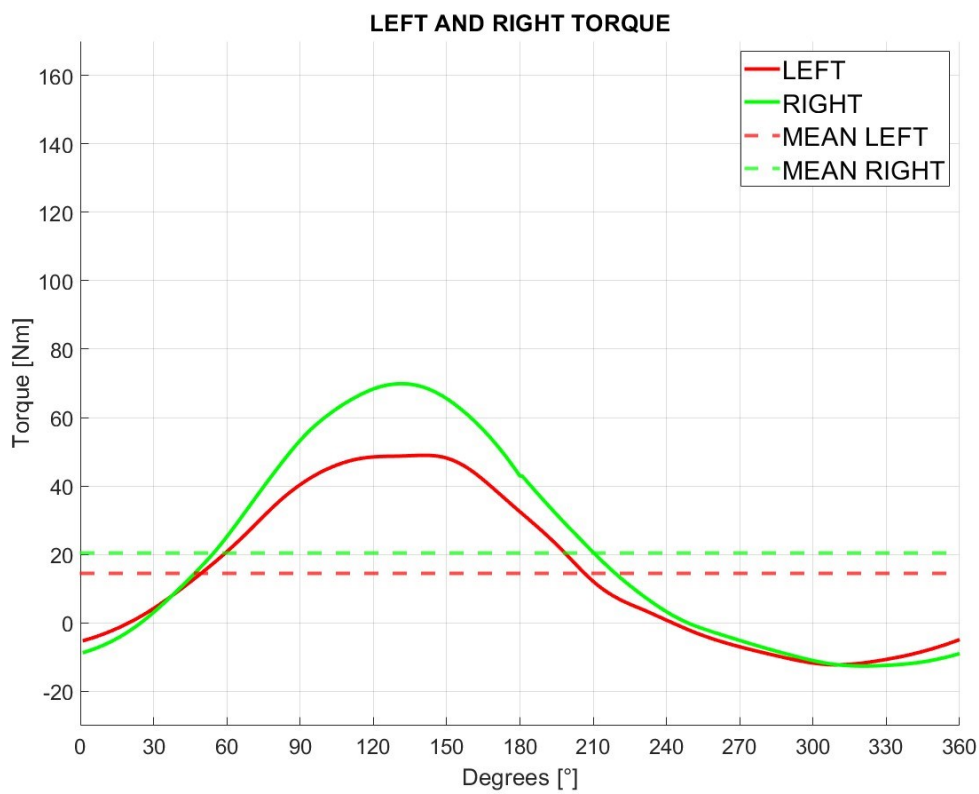


Figure 6.7: Torque profile for GEAR 10, flat pedals sitting

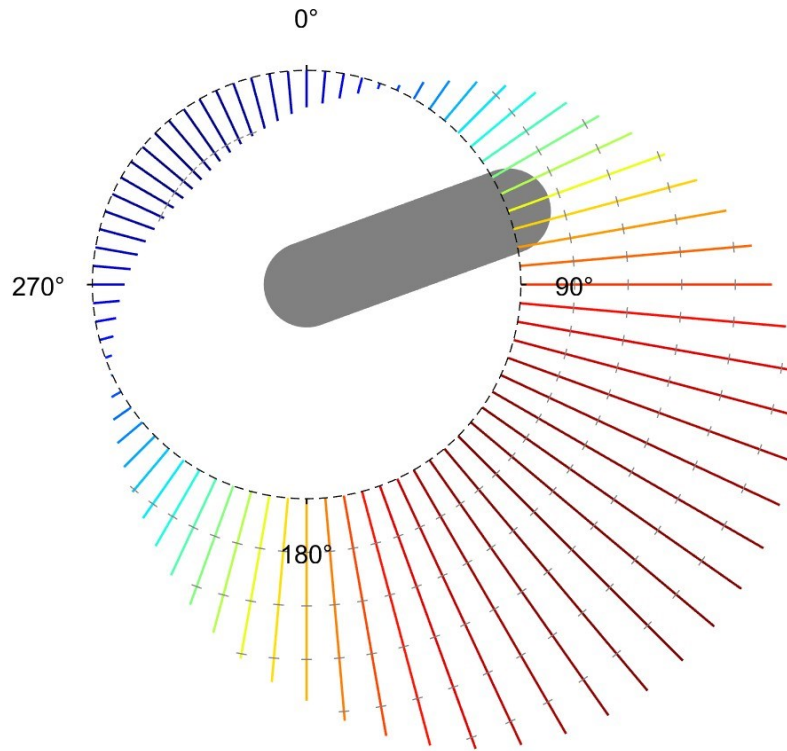


Figure 6.8: Torque distribution for GEAR 10, flat pedals sitting

6.4.2 GEAR 7

SIDE	MAXIMUM TORQUE	MINIMUM TORQUE	AVERAGE TORQUE
L	85 Nm	-9 Nm	25 Nm
R	84 Nm	-6 Nm	27 Nm

Table 6.6: Torque values for GEAR 7, flat pedals sitting

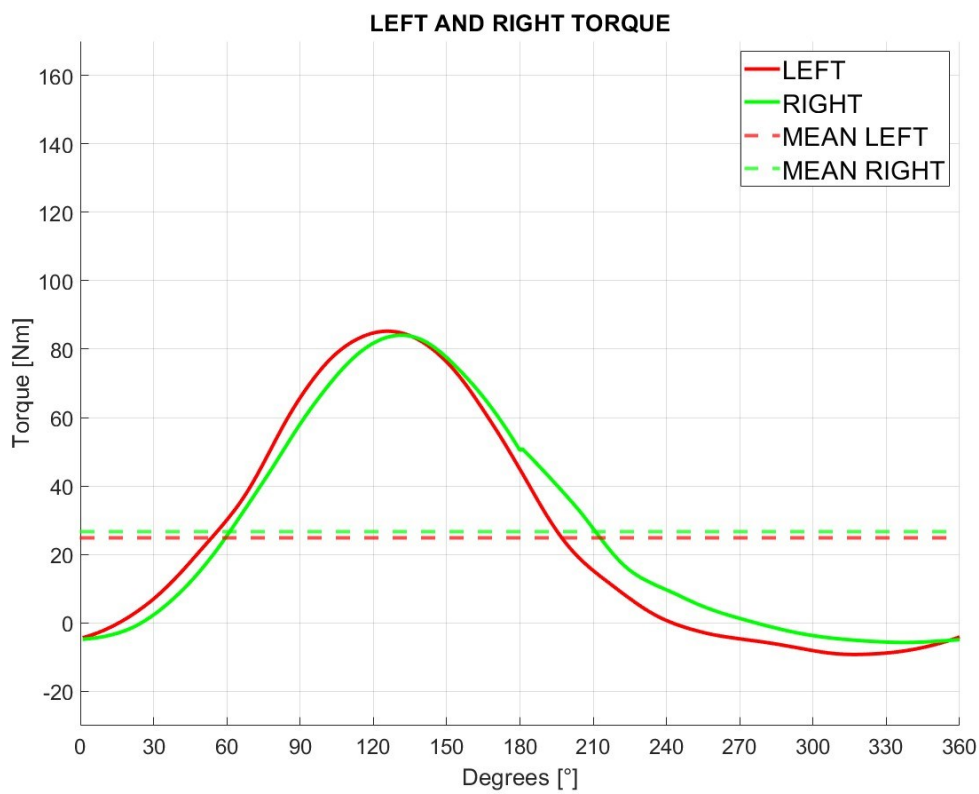


Figure 6.9: Torque profile for GEAR 7, flat pedals sitting

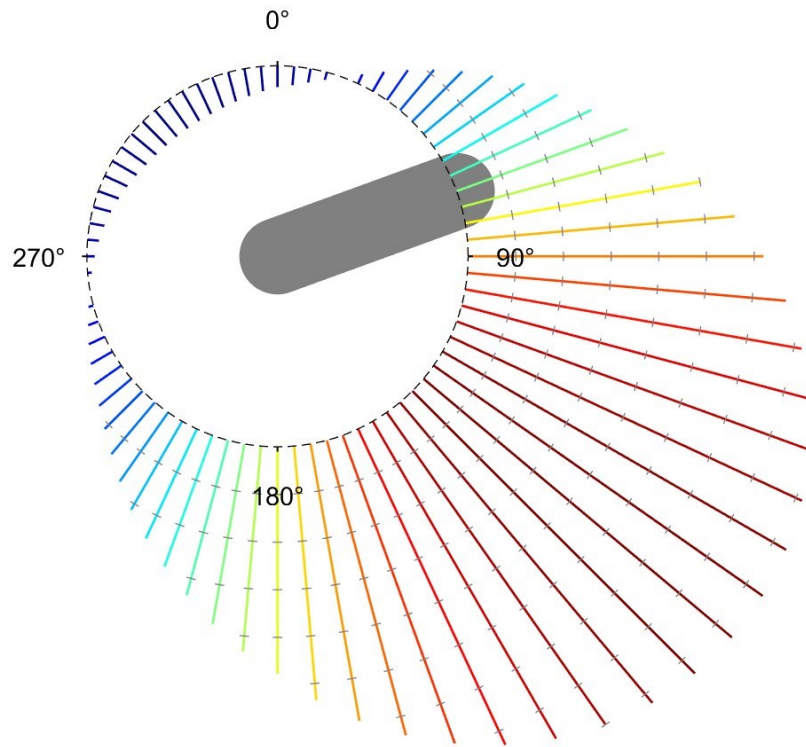


Figure 6.10: Torque distribution for GEAR 7, flat pedals sitting

6.4.3 GEAR 4

SIDE	MAXIMUM TORQUE	MINIMUM TORQUE	AVERAGE TORQUE
L	137 Nm	-5 Nm	41 Nm
R	139 Nm	-3 Nm	44 Nm

Table 6.7: Torque values for GEAR 10, flat pedals sitting

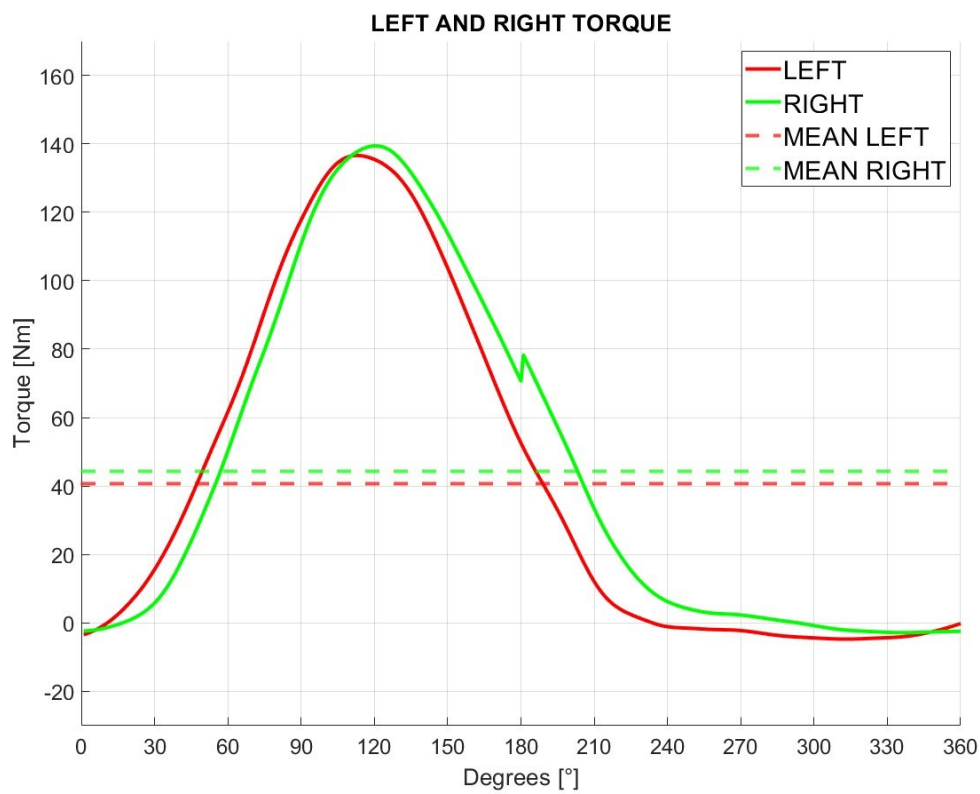


Figure 6.11: Torque profile for GEAR 4, flat pedals sitting

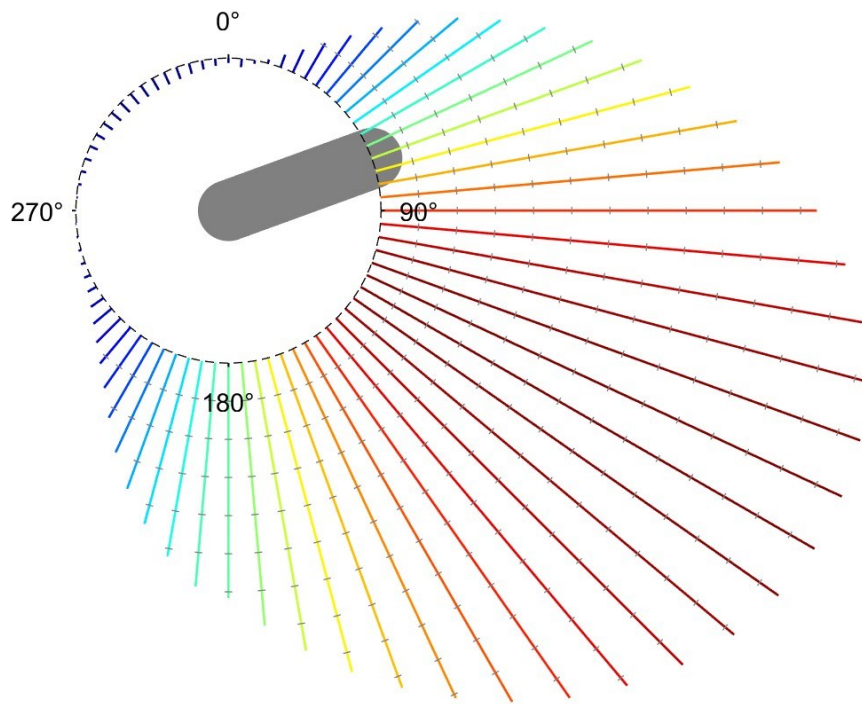


Figure 6.12: Torque distribution for GEAR 4, flat pedals sitting

6.5 Flat pedals standing

GEAR	AVERAGE POWER [W]	CRANK SIDE	E_r	E_a
10	149	LEFT	69	54%
		RIGHT	73%	62%
7	224	LEFT	87%	85%
		RIGHT	87%	85%
4	387	LEFT	96%	95%
		RIGHT	97%	97%

Table 6.8: Pedal stroke efficiency for flat pedals standing

Also standing there is a clear asymmetry between left and right that fades by increasing of the torque produced by the rider.

The efficiency is lower than the one found in the previous section. This is, as the asymmetry, bigger when the effort is lower.

6.5.1 GEAR 10

SIDE	MAXIMUM TORQUE	MINIMUM TORQUE	AVERAGE TORQUE
L	76 Nm	-25 Nm	17 Nm
R	81 Nm	-25 Nm	19 Nm

Table 6.9: Torque values for GEAR 10, flat pedals standing

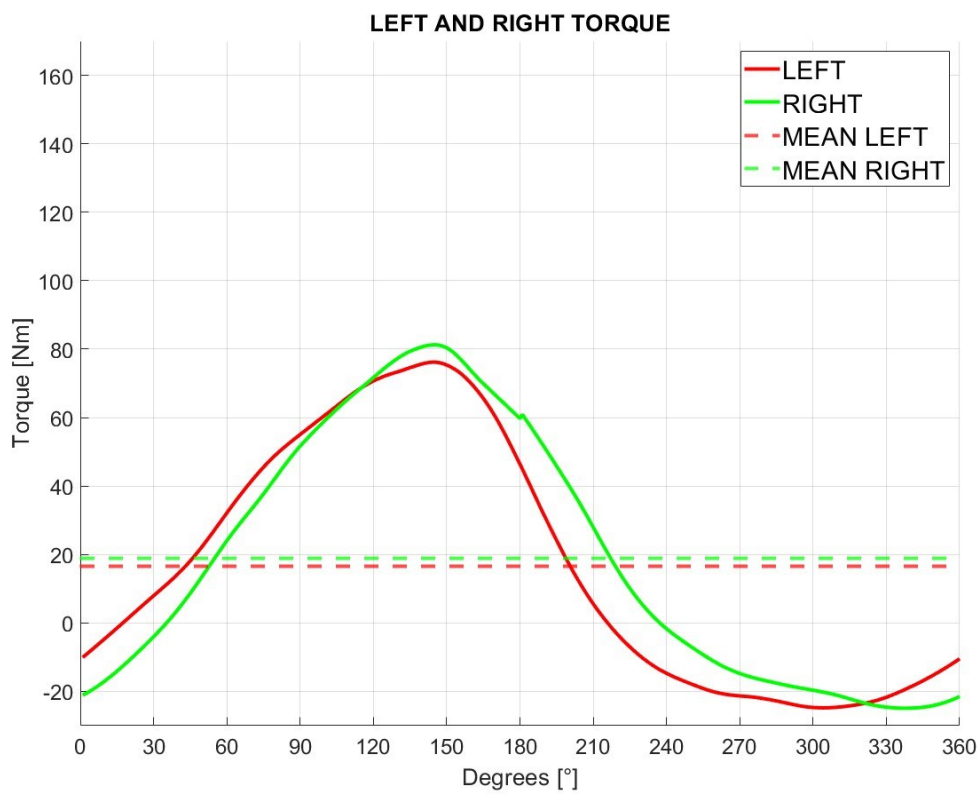


Figure 6.13: Torque profile for GEAR 10, flat pedals standing

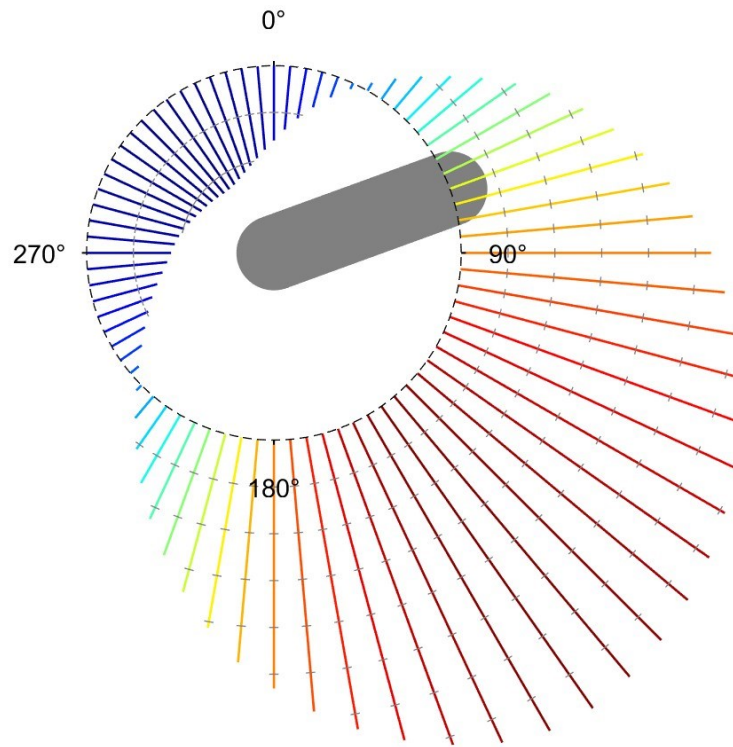


Figure 6.14: Torque distribution for GEAR 10, flat pedals standing

6.5.2 GEAR 7

SIDE	MAXIMUM TORQUE	MINIMUM TORQUE	AVERAGE TORQUE
L	92 Nm	-14 Nm	25 Nm
R	98 Nm	-17 Nm	28 Nm

Table 6.10: Torque values for GEAR 7, flat pedals standing

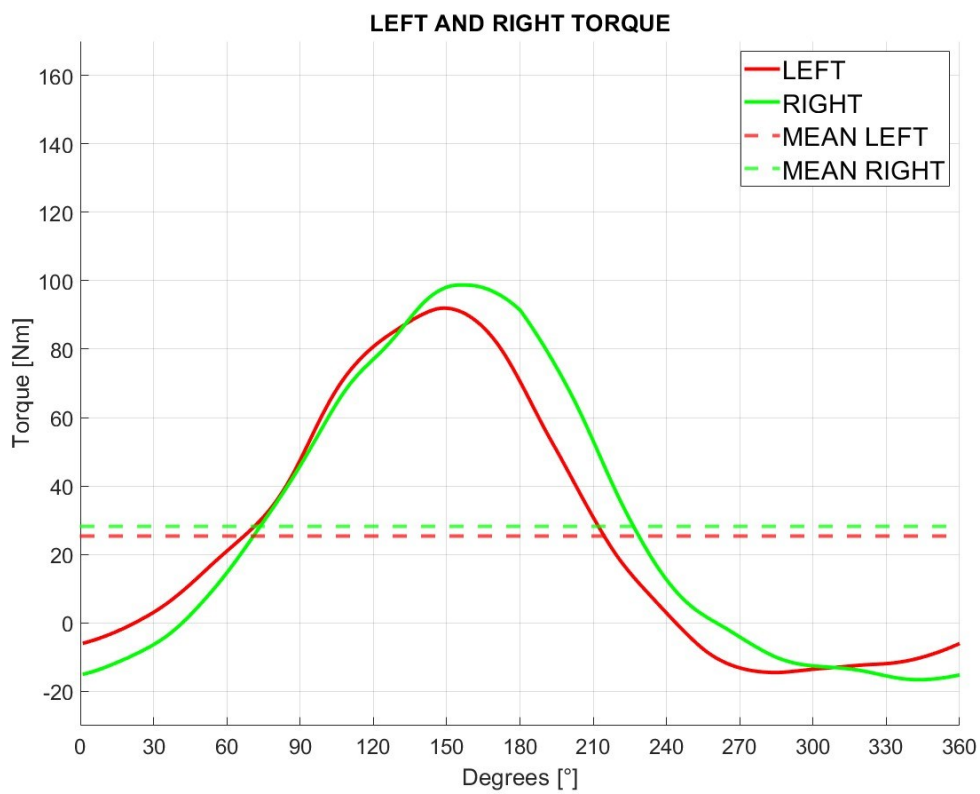


Figure 6.15: Torque profile for GEAR 7, flat pedals standing

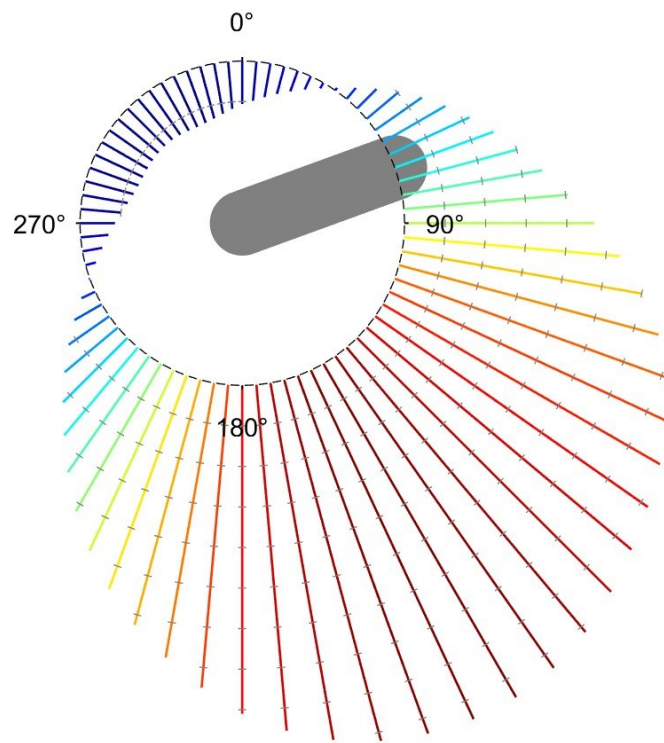


Figure 6.16: Torque distribution for GEAR 7, flat pedals standing

6.5.3 GEAR 4

SIDE	MAXIMUM TORQUE	MINIMUM TORQUE	AVERAGE TORQUE
L	159 Nm	-7 Nm	45 Nm
R	157 Nm	-9 Nm	47 Nm

Table 6.11: Torque values for GEAR 4, flat pedals standing

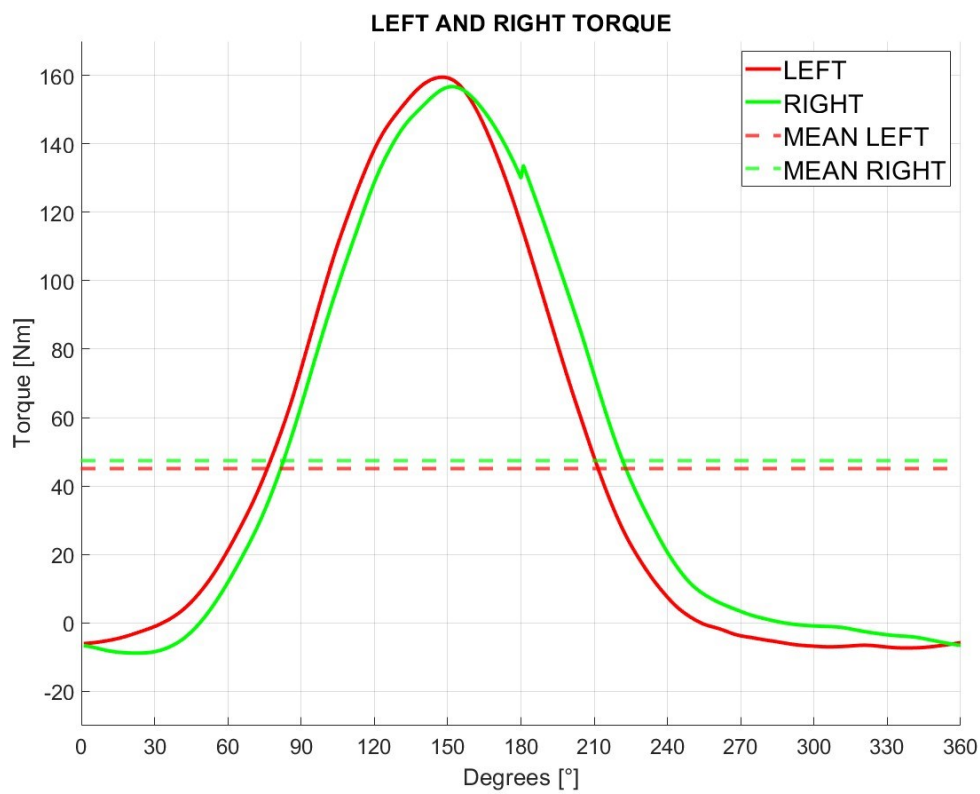


Figure 6.17: Torque profile for GEAR 4, flat pedals standing

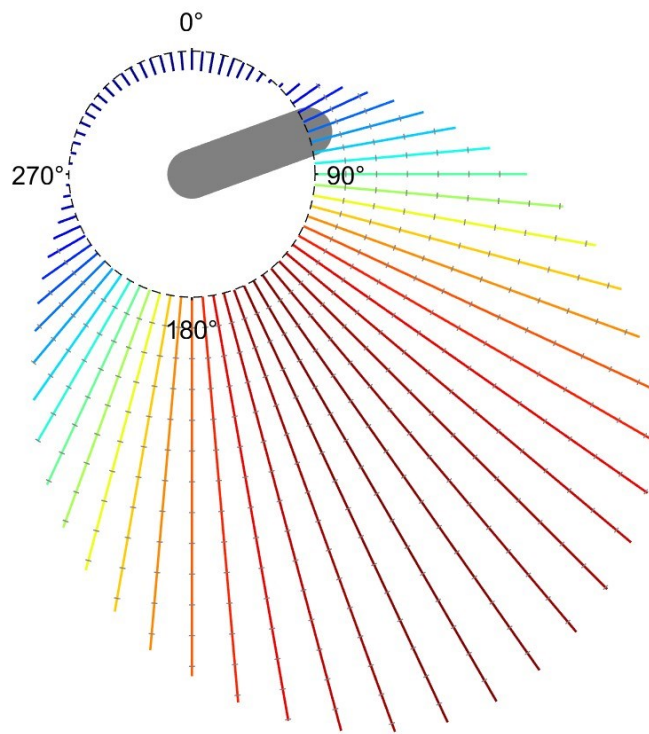


Figure 6.18: Torque distribution for GEAR 4, flat pedals standing

6.6 SPD pedals sitting

The test conducted using SPD pedals and compatible shoes produced interesting results while sitting on the saddle. Efficiency, both relative and absolute, has much higher values than what was found on the same testing but with flat pedals and normal shoes. As flat pedal showed previously, also in this case the efficiency of the pedal stroke increased by increasing the torque output. It reaches the value of 100% using GEAR 4 meaning that there's not negative torque during the full pedal stroke. It was possible only because of the firm connection between shoe and pedal.

GEAR	AVERAGE POWER [W]	CRANK SIDE	E_r	E_a
10	139	LEFT	89,7%	88,5
		RIGHT	90,9%	90%
7	200	LEFT	96,8%	96,7%
		RIGHT	97,5%	97,4%
4	351	LEFT	100%	100%
		RIGHT	100%	100%

Table 6.12: Pedal stroke efficiency for SPD pedals sitting

6.6.1 GEAR 10

SIDE	MAXIMUM TORQUE	MINIMUM TORQUE	AVERAGE TORQUE
L	52 Nm	-8 Nm	16 Nm
R	53 Nm	-8 Nm	17 Nm

Table 6.13: Torque values for GEAR 10, SPD pedals sitting

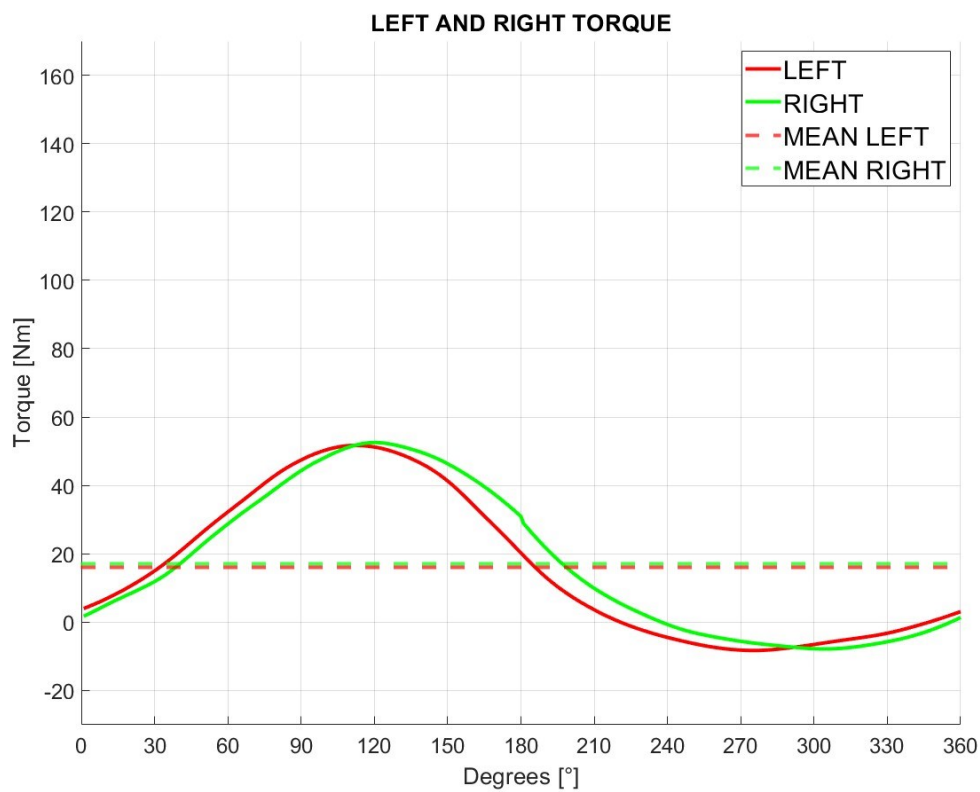


Figure 6.19: Torque profile for GEAR 10, SPD pedals sitting

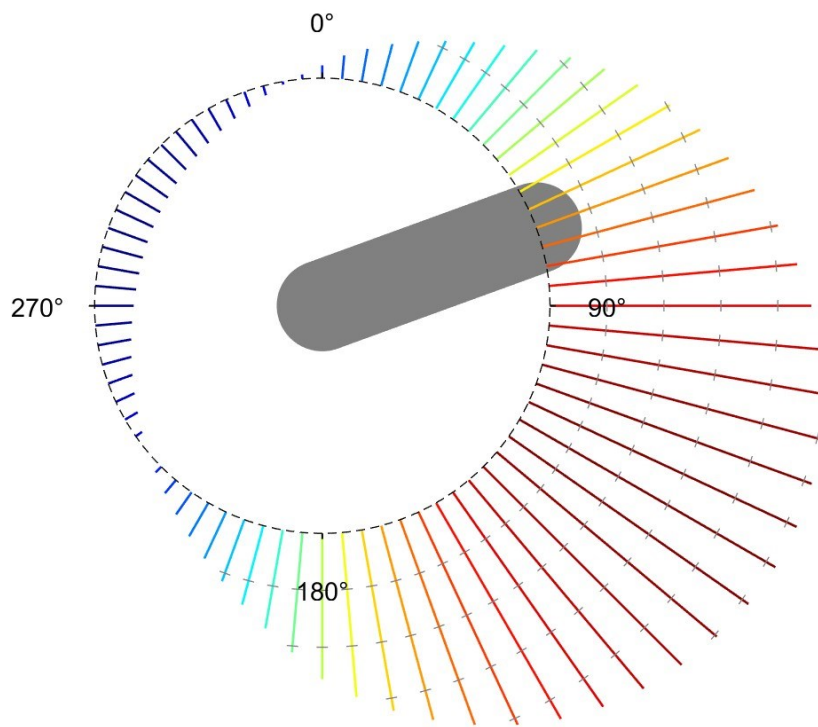


Figure 6.20: Torque distribution for GEAR 10, SPD pedals sitting

6.6.2 GEAR 7

SIDE	MAXIMUM TORQUE	MINIMUM TORQUE	AVERAGE TORQUE
L	73 Nm	-4 Nm	23 Nm
R	79 Nm	-4 Nm	25 Nm

Table 6.14: Torque values for GEAR 7, SPD pedals sitting

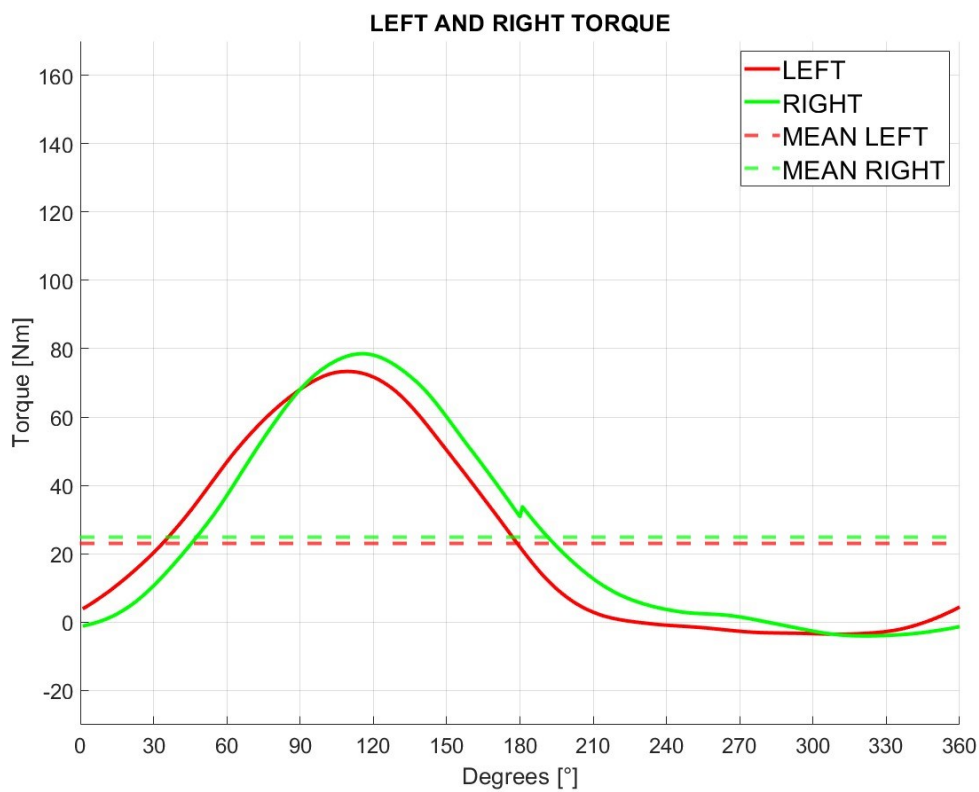


Figure 6.21: Torque profile for GEAR 7, SPD pedals sitting

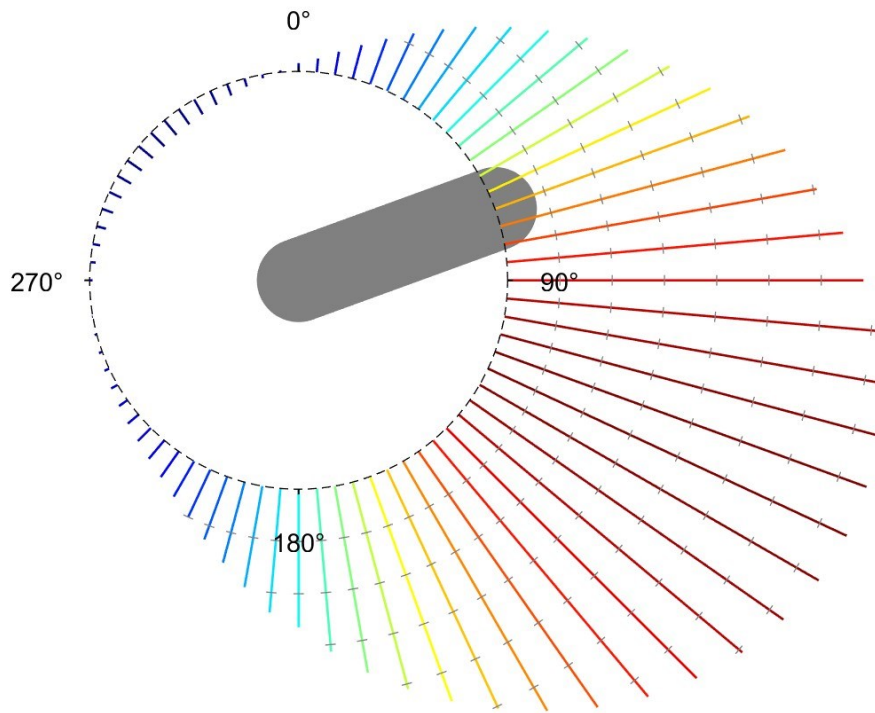


Figure 6.22: Torque distribution for GEAR 7, SPD pedals sitting

6.6.3 GEAR 4

SIDE	MAXIMUM TORQUE	MINIMUM TORQUE	AVERAGE TORQUE
L	116 Nm	6 Nm	41 Nm
R	119 Nm	5 Nm	43 Nm

Table 6.15: Torque values for GEAR 4, SPD pedals sitting

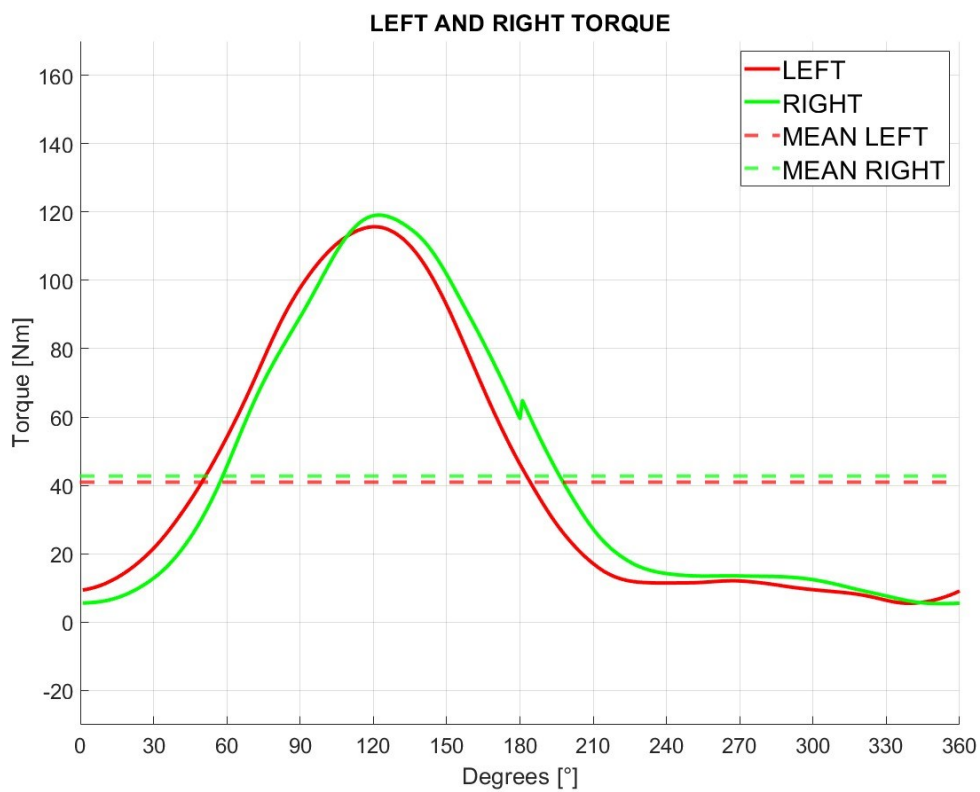


Figure 6.23: Torque profile for GEAR 4, SPD pedals sitting

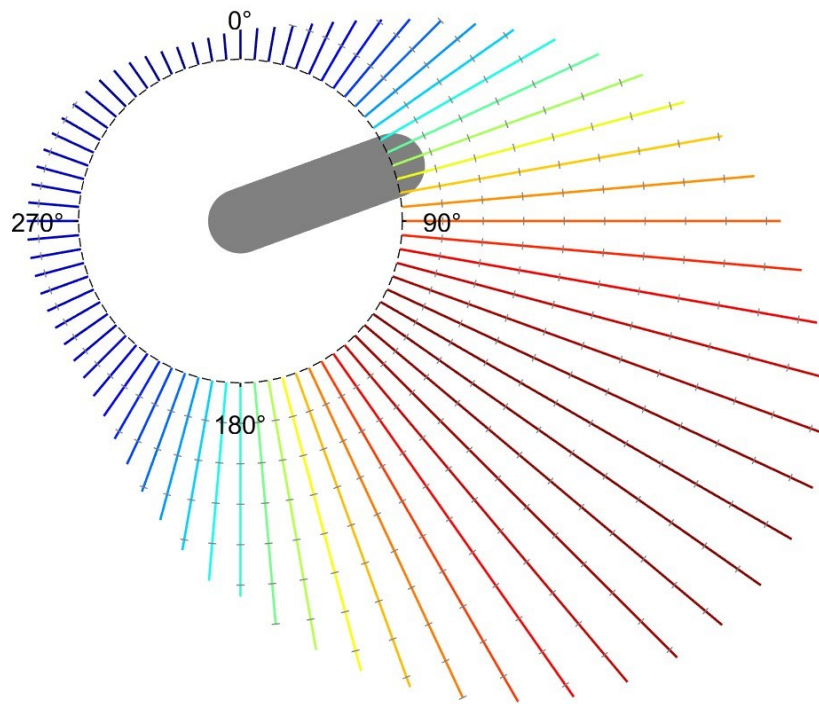


Figure 6.24: Torque distibution for GEAR 4, SPD pedals sitting

6.7 SPD pedals standing

For the SPD pedals standing results show a lower efficiency than what was found for the same type of pedals but sitting. Same differences between standing and sitting have been found also using flat pedal. There is still a higher overall efficiency compared to the other pedals.

GEAR	AVERAGE POWER [W]	CRANK SIDE	E_r	E_a
10	155	LEFT	77,7%	71,3%
		RIGHT	74,7%	66,1%
7	211	LEFT	84,6%	81,8%
		RIGHT	84,2%	81,2%
4	337	LEFT	98%	97,9%
		RIGHT	99,7%	99,7%

Table 6.16: Pedal stroke efficiency for SPD pedals standing

6.7.1 GEAR 10

SIDE	MAXIMUM TORQUE	MINIMUM TORQUE	AVERAGE TORQUE
L	79 Nm	-16 Nm	19 Nm
R	75 Nm	-20 Nm	18 Nm

Table 6.17: Torque values for GEAR 10, SPD pedals standing

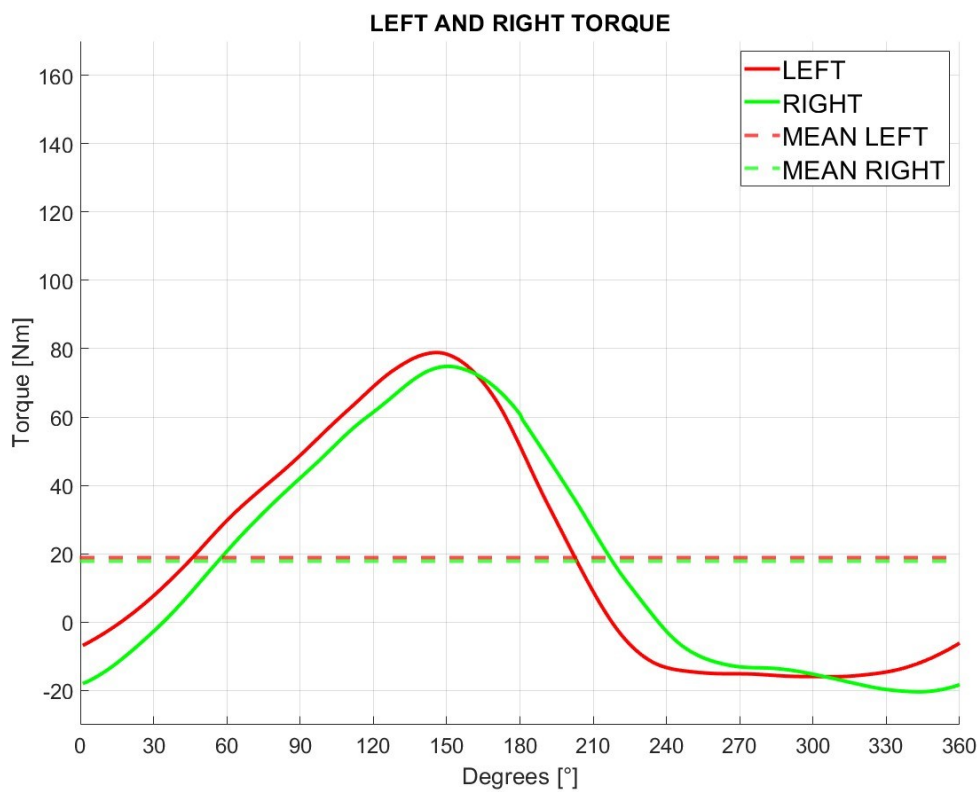


Figure 6.25: Torque profile for GEAR 10, SPD pedals standing

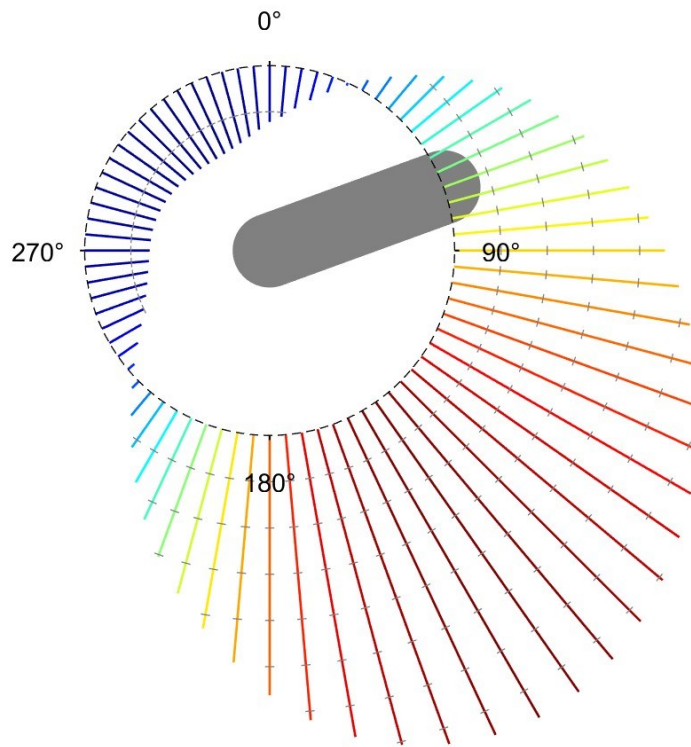


Figure 6.26: Torque distibution for GEAR 10, SPD pedals standing

6.7.2 GEAR 7

SIDE	MAXIMUM TORQUE	MINIMUM TORQUE	AVERAGE TORQUE
L	106 Nm	-14 Nm	26 Nm
R	99 Nm	-16 Nm	25 Nm

Table 6.18: Torque values for GEAR 7, SPD pedals standing

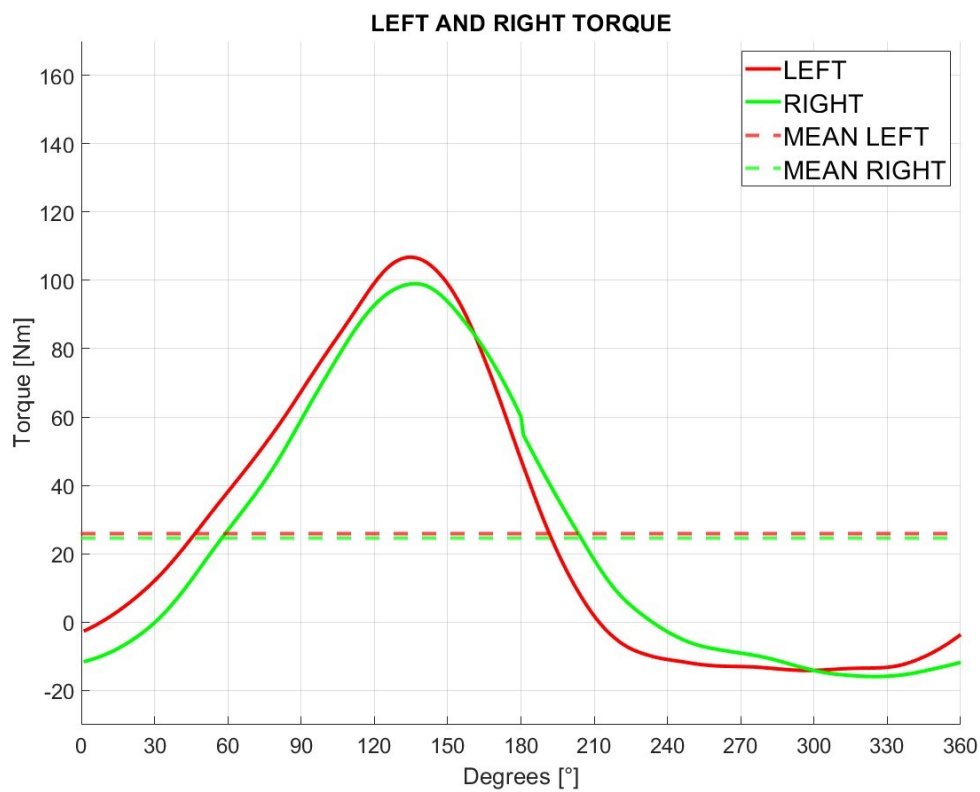


Figure 6.27: Torque profile for GEAR 7, SPD pedals standing

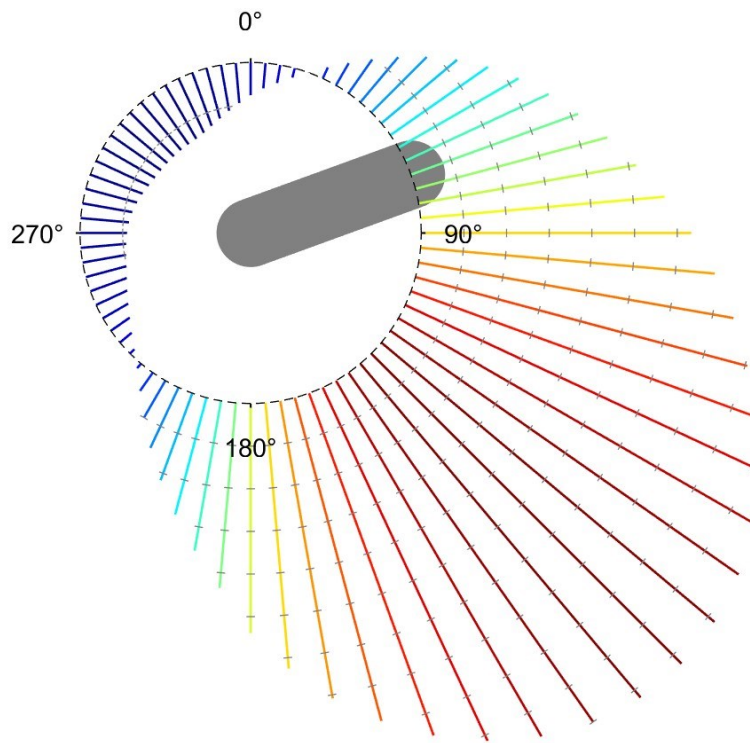


Figure 6.28: Torque distribution for GEAR 7, SPD pedals standing

6.7.3 GEAR 4

SIDE	MAXIMUM TORQUE	MINIMUM TORQUE	AVERAGE TORQUE
L	131 Nm	-4 Nm	39 Nm
R	124 Nm	-1 Nm	41 Nm

Table 6.19: Torque values for GEAR 4, SPD pedals standing

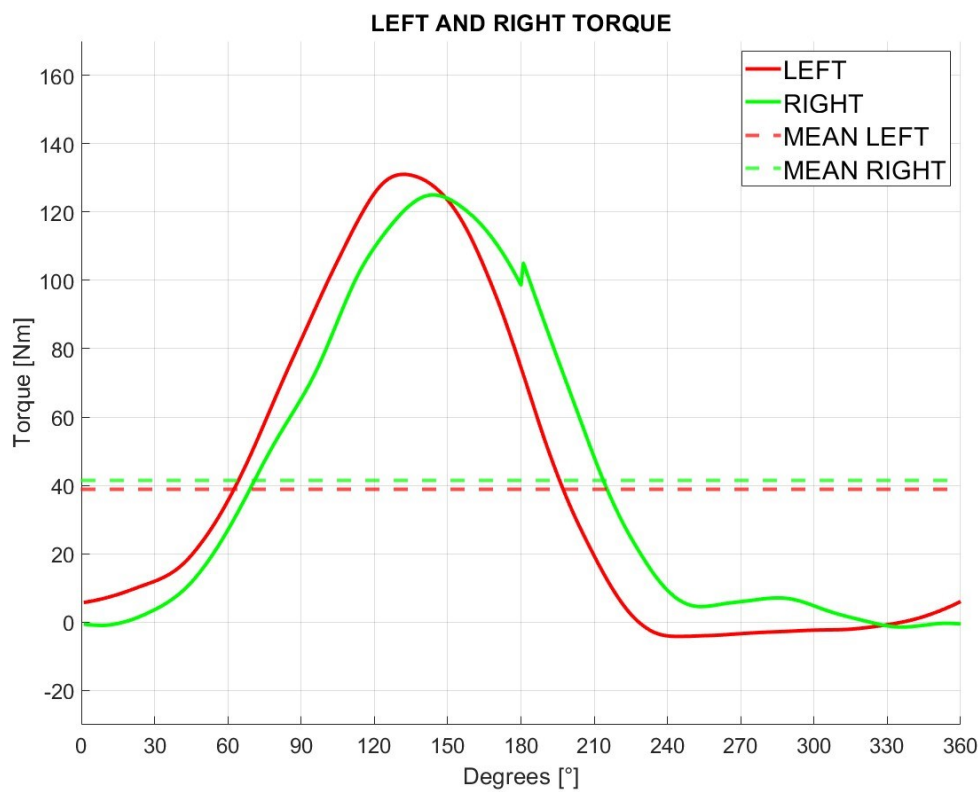


Figure 6.29: Torque profile for GEAR 4, SPD pedals standing

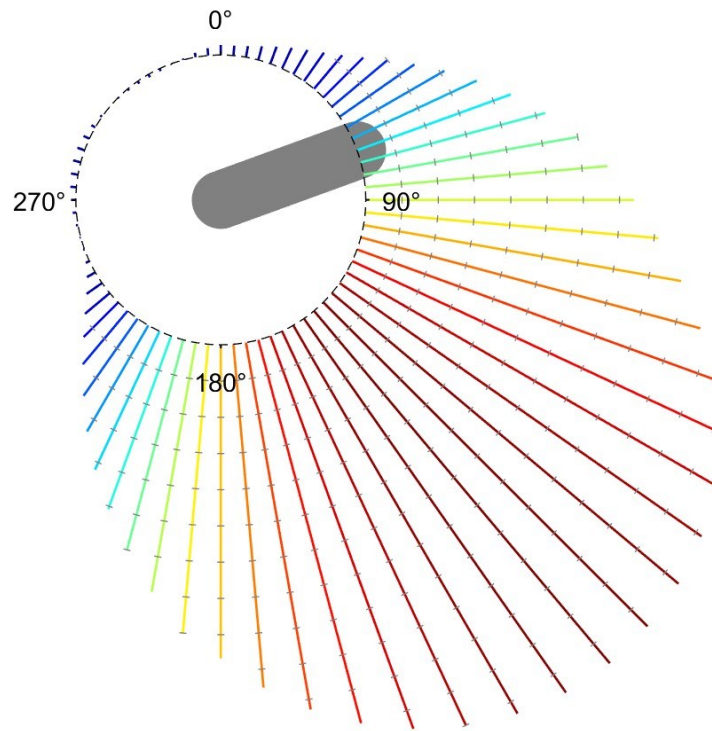


Figure 6.30: Torque distribution for GEAR 4, SPD pedals standing

6.8 Torque profile results

The torque profile analysis showed quite interesting results.

The first one is that the torque profile efficiency increases directly with the increase of power output of the rider reaching levels around 100% for power output between 350 W and 400 W, which is the highest value tested. For the lower values of power the efficiency drops down, reaching its minimum when the rider is pedalling standing on the pedals.

The comparison between the two types of pedals highlighted how the efficiency increases by using SPD pedals, that allowed in some situations to reach an efficiency of 100%.

The main focus of this torque profile analysis was to find a way to properly test the engine indoor and in-vitro. Results showed that the torque profile has a clear spike of positive torque in the main phase of the pedal stroke. Not only there is a spike, but the torque also reaches negative values, most of the times, in the phase ranging from 270° and 360°, considering the angle convention previously described.

There are two ways to simulate this torque profile. The first one is to directly connect two electric motors where the two crankarms are connected. This choice is simple and very effective to apply the average torque load on the motor, but it is not very easy to reproduce the real torque profile.

The other way to simulate this torque profile is to create two motor-actuated mock legs connected to the pedals. This system is much more complicated than the one previously described but offers a finer tuning of the torque profile load. It also allows to reproduce on the motor the other loads that the rider produce, such as radial force and YZ plane torque on the crankarms.

That being said, the outdoor and in-vivo testing still offer a wider field of view of real scenarios loads that the engine have to support.

For the GEAR 7, which correspond to values of power ranging from 200 W to 251 W, the various torque profile where overlapped to see better the difference between them, as Figure 6.31 shows. It is interesting that flat pedal induced the rider to output a higher peak torque and these peaks are shifted to the right compared to the SPD pedals ones. For both types of pedals the peak torque while standing is higher and shifted to the right compared to the curve that corresponds to the sitting ride.

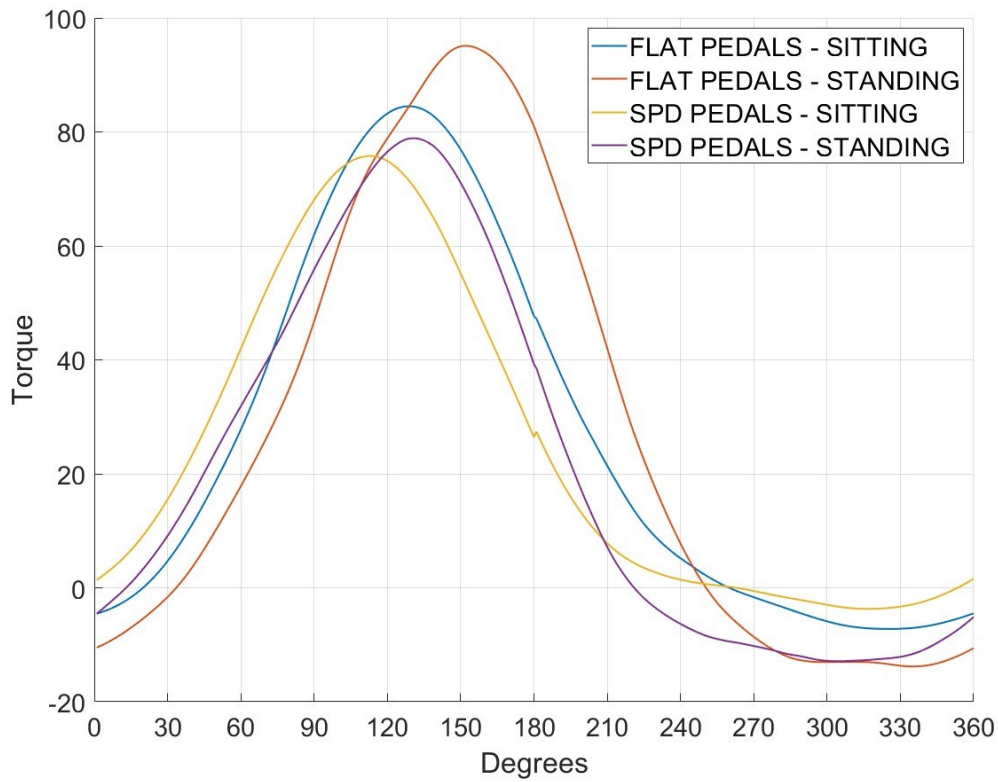


Figure 6.31: Overlapped torque for GEAR 7

As shown in the graph, for both types of pedals while standing on the pedal the torque reaches a lower value than while sitting on the saddle, reducing the overall efficiency as previous results showed.

In Figure 6.32 are represented the same combinations of Figure 6.31 but using the radial representation of the cyclist effective average torque. These graphs highlight once again the same results of Figure 6.31.

6. TORQUE PROFILE evaluation for different pedalstroke

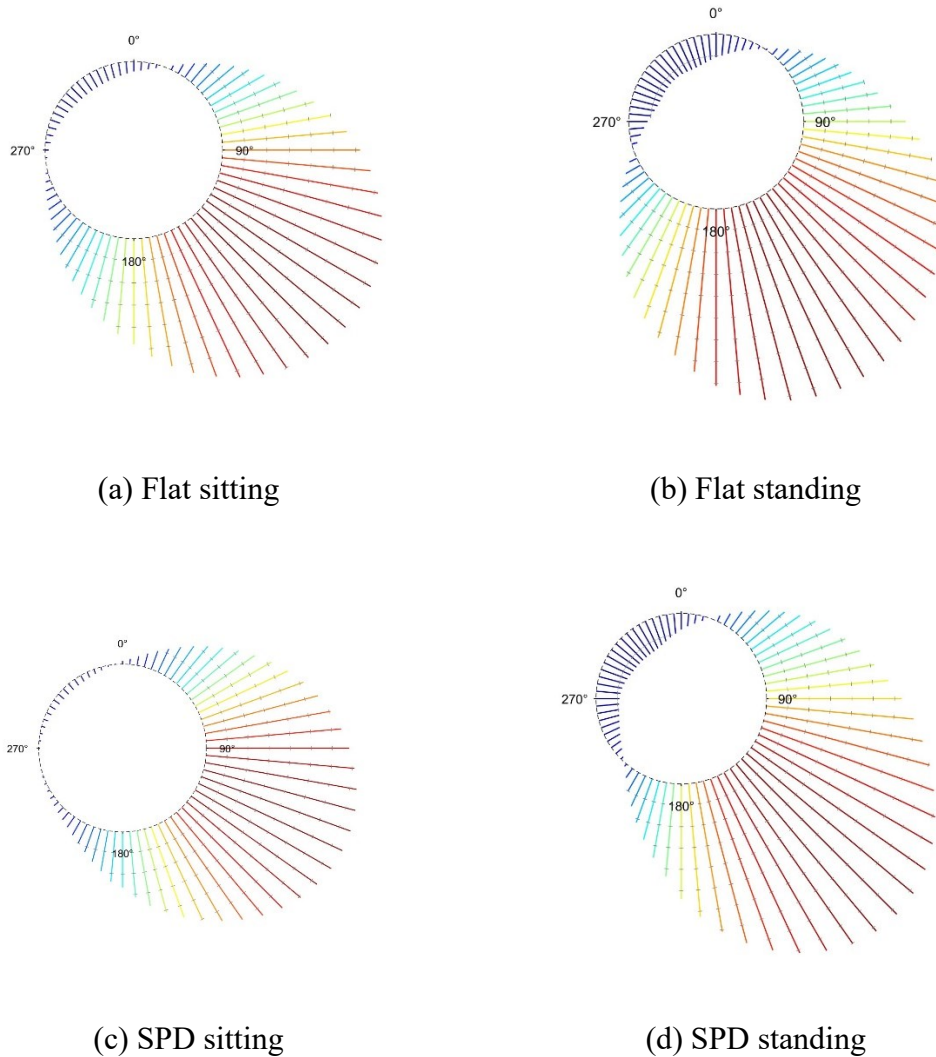


Figure 6.32: Radial representation of torque – GEAR 7

The following graphs, Fig. 6.33, Fig. 6.34, Fig. 6.35, Fig. 6.36, represents the torque profile for different gears, and therefore power outputs, given the type of pedals used and the position on the bike. It is clear that the increase of power output of the rider shifts the curves up, both on the positive part and the negative one, meaning that the efficiency increases not only for the higher value of the maximum torque but also because of a reduction of the negative torque.

6. TORQUE PROFILE evaluation for different pedalstroke

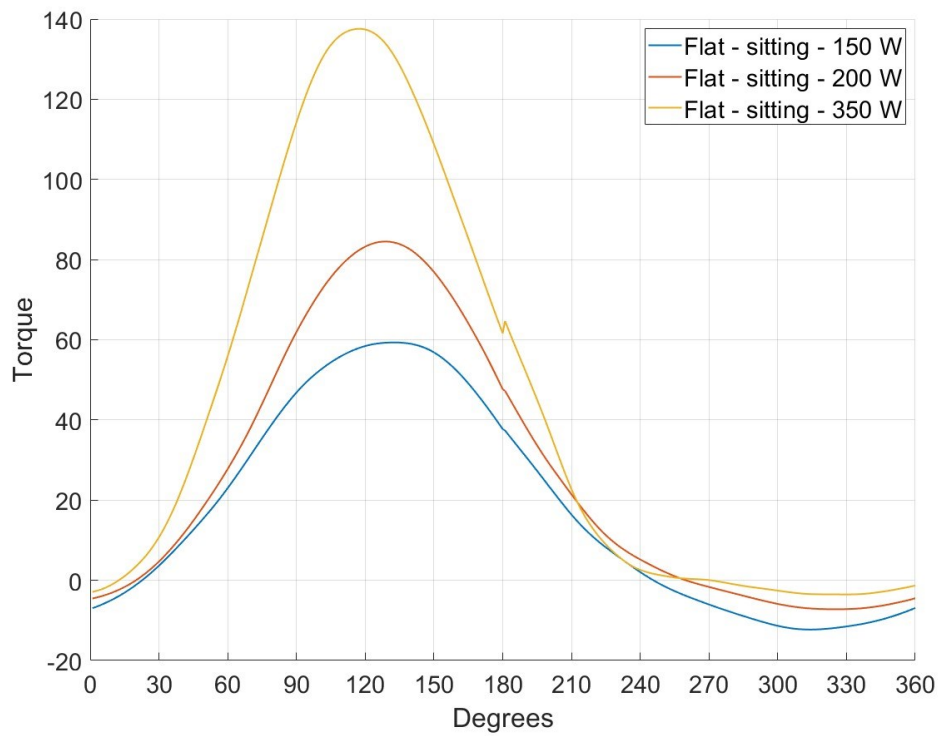


Figure 6.33: Torque profiles for flat pedals sitting

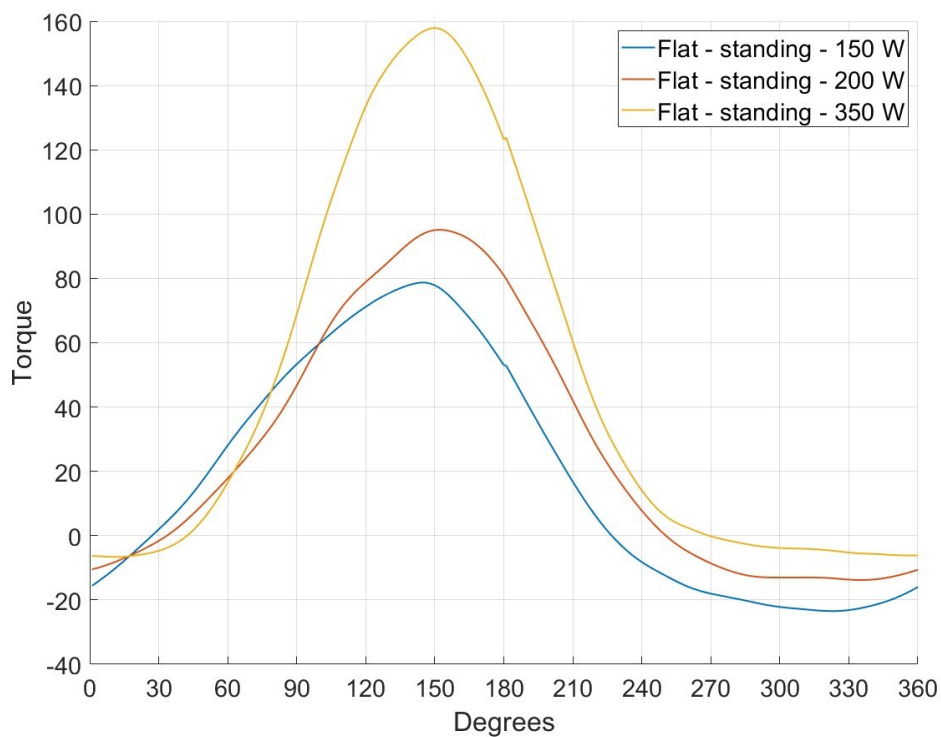


Figure 6.34: Torque profiles for flat pedals standing

6. TORQUE PROFILE evaluation for different pedalstroke

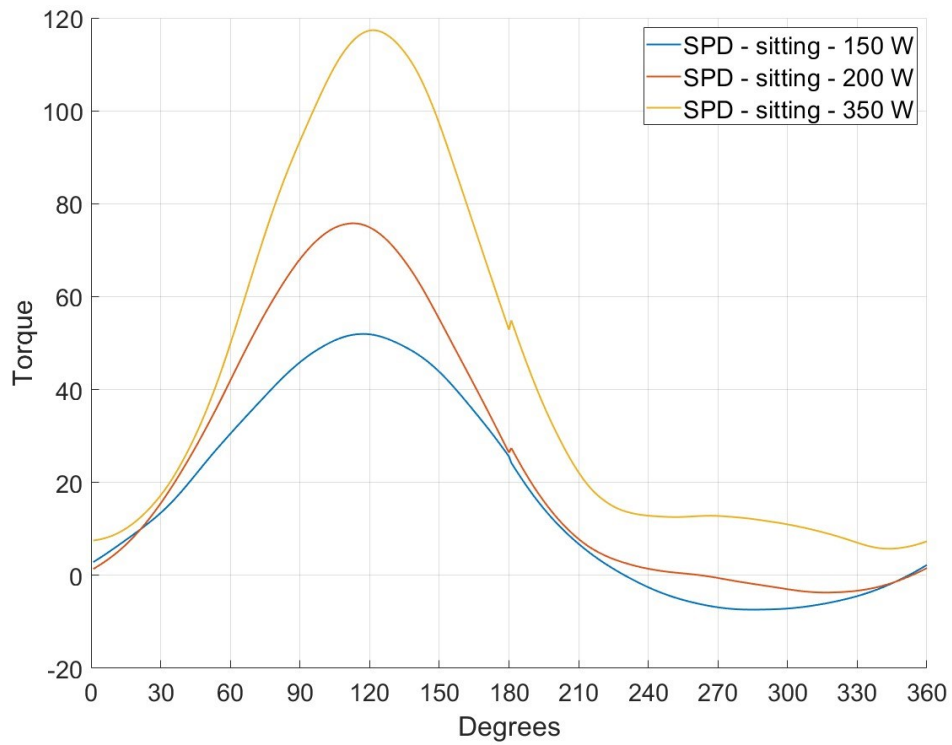


Figure 6.35: Torque profiles for SPD pedals sitting

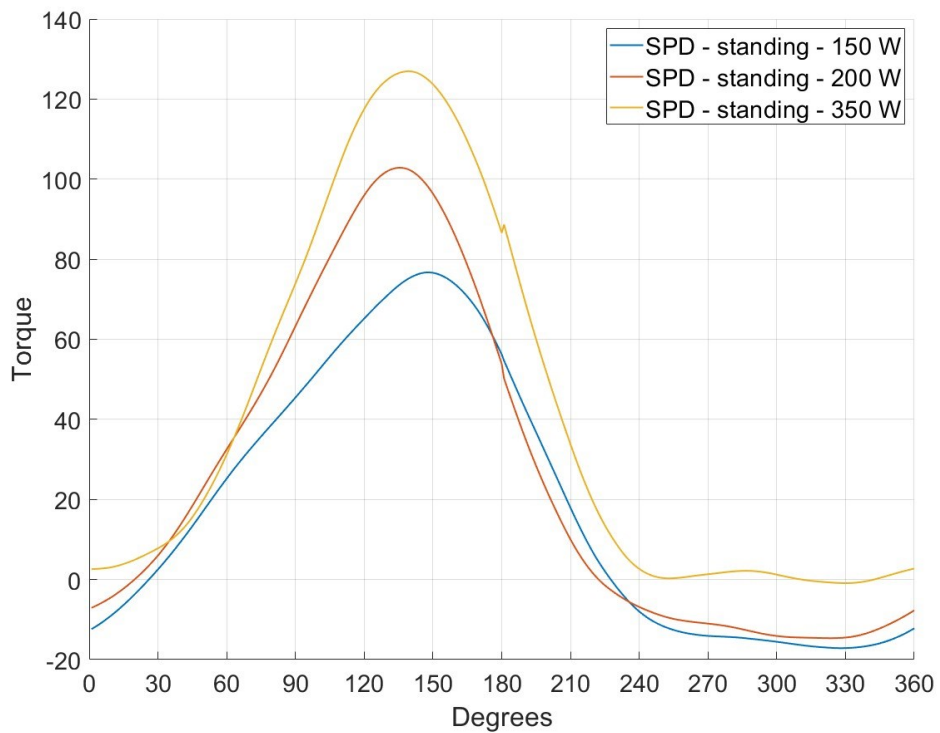


Figure 6.36: Torque profiles for SPD pedals standing

Chapter 7

CONCLUSIONS

The work carried out allowed to deeply understand how pedal-assisted mountain bikes behave and how different levels riders use them.

A significant difference in assistance during a constant load have been found between various maps available, apart from the SPORT and BOOST maps. The difference in assistance level between ECO and TOUR is comparable to the one between TOUR and sport, resulting in a linear increase in engine torque output. Also the maximum assistance level declare by the manufacturer is reached only under specific conditions and not for a constant load. The values found of assistance, defined as Engine Torque over Cyclist Torque are:

- 25% for the ECO map
- 70% for the TOUR map
- 125% for the SPORT map
- 130% for the BOOST map

Whereas the values for the absolute assistance, defined as Engine Torque over Total Torque, are:

- 20% for the ECO map
- 35% for the TOUR map
- 60% for the SPORT map
- 55% for the BOOST map

The duty cycle of these maps, analysed for four different riders in a long climb, was different for different levels of training and skills. In particular, the time spent on more aggressive engine maps decreased with the increase of rider level of training. The skills were less important for the choice of the assistance level. All the riders limited the time in the ECO map, which seemed quite hard even for more trained athletes in this type of terrains and slopes. The gear usage where quite similar between all the riders, meaning that the help of the electric motor smoothed out the difference in skills and training. There

was an out layer test run that still represents one of the possible scenarios in which a bike of this kind can potentially be used.

To open the possibility of doing this type of testing in-vitro the torque profile of a rider was analysed highlighting the complexity of trying to replicate it. The torque profile in fact depends on various factors such as rider's position on the bike, average power output and type of pedals used. Results showed that all these parameters modify the torque profile significantly, in particular the efficiency of the pedalstroke.

Further studies can be carried out by trying to find how different engine maps deliver torque and power under non-static conditions, in particular evaluating the difference between SPORT and BOOST which had similar results when under a constant load.

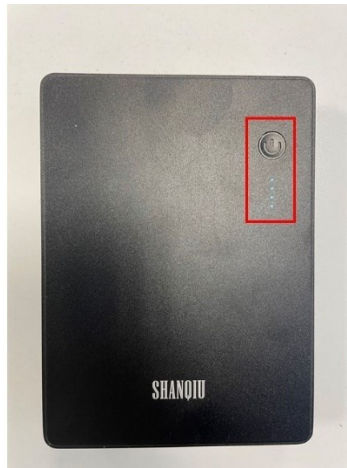
It would also be interesting to repeat the long climb testing with a wider field of riders with different combinations of levels of training and skill, in order to understand deeply how the engine map duty cycle for every combination of these characteristics is.

Some problems were found during the various testing in terms of consistency of the acquisition of data by the telemetry system such as interruption of signal by one of the various sensors available. The system resulted also a bit fragile because it is quite exposed, especially the sensors placed on the crankarms.

Appendix A

PRELIMINARY SETTINGS E-BIKE TEST

- Check battery voltage with tester (3V is ideal, replace below 2.4 to avoid risking battery safe mode);
- Check UPS module battery status;



- Turn on the UPS module, connect the type-c cable to the mini-PC and turn it on (the light turns from red to blue).



- Turn on all the acquisition units by switching from OFF to ON every battery case.

- Connect mini-PC with laptop and stream video through OBS Studio application. USB is required which converts the signal;



- Open “Mantracourt T24 100log” program on the mini PC;

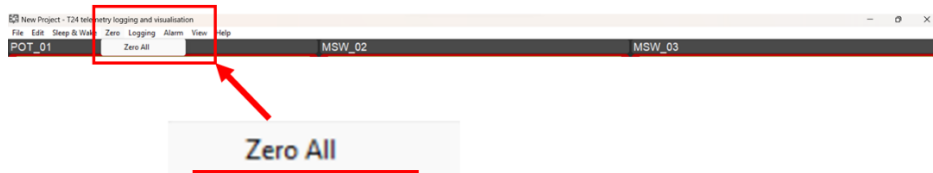


- Turn on the e-bike handle control and set it to “OFF”;
- Check that the left crank magnet does not touch the rear triangle. It is advisable to position the pedal with the pedal forward;

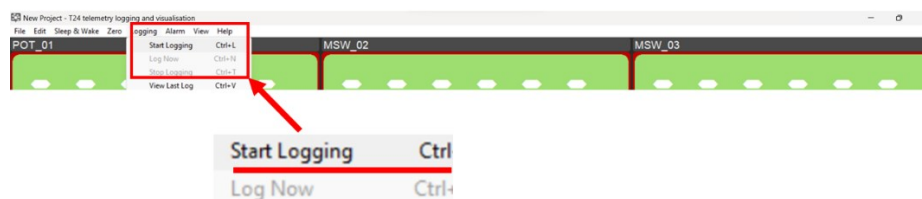
- Verify that all units are connected to the acquisition system;



- Zero all channels using Mantracourt's "Zero all" function in the tool bar;



- Start acquisition via Mantracourt's "Start Logging" function in the tool bar;



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