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Brake load characterization of heavy-duty vehicles

Final report

TME180 Automotive Engineering Project

Sayid Achmad Munthahar
Bhumika Dhamane
David Randby
Nandu Suresh
Jakob Wurzinger

DEPARTMENT OF MECHANICS AND MARITIME SCIENCES

CHALMERS UNIVERSITY OF TECHNOLOGY
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www.chalmers.se

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Brake load characterization of heavy-duty vehicles

An estimation of brake dust emissions from heavy-duty vehicles

Department of Mechanics and Maritime Sciences
Chalmers University of Technology
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Abstract

In the fast-changing automotive world, more vehicles have zero tail-pipe emissions due to electrification. Global and local air quality has increased in recent times due to the implementation of legislation regarding tail-pipe emissions. Regulators are now looking at other sources of emissions, like particulate matter from brakes and tires, which have severe health effects. The particulate matter can enter the airways and if it is small enough, it can travel down to the lungs and even further into the bloodstream. The particle sizes can be divided into PM10, PM2.5, and Ultra-fine particles. Legislation for PM10 will be implemented regarding brake wear in the new Euro 7 legislation for light-duty vehicles in 2025 and something similar to this is expected for heavy-duty vehicles. The stakeholder for this project is Volvo Group, which has been involved during the whole project. This project mainly focuses on the emissions caused by disc brakes on Volvo's Internal Combustion Engine (ICE) and Battery Electric Vehicle (BEV) heavy-duty vehicles. Field-test datasets from several ICE and BEV trucks, along with Volvo's brake test rig data are used to estimate brake wear based on brake temperature and braking energy. Data analysis was performed on the dataset and brake wear estimation was done to characterize the braking behaviors of ICE and BEV trucks and determine which affects the brake wear the most.

An in-depth analysis was performed by doing a multivariate analysis. The in-depth analysis resulted in the identification of four different clusters that were characterized by their unique driving behavior. From this exploration, it becomes evident that several factors influence brake wear, with temperature emerging as a prominent indicator linked to driving behavior.

Acknowledgements

We would like to express our gratitude to our supervisor, Jonas Sjöblom, who has guided us through this project, pushed us to investigate further, and helped us reach our goals.

We also want to thank Volvo Group for giving us the opportunity to do this project. We are especially thankful to Suraj Srivastava and Martin Petersson for their exceptional commitment of time, expertise, and guidance.

List of Acronyms

Below is the list of acronyms that have been used throughout this report listed in alphabetical order:

AQG	Air Quality Guideline
BEV	Battery Electric Vehicle
BWP	Brake Wear Particles
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
NOx	Nitrogen Oxides
PM	Particulate Matter
PNC	Particle Number Concentration
UFP	Ultrafine Particles
PCA	Principle Component Analysis

List of Variables

Below is the list of acronyms that have been used throughout this report:

T_{brake}	Disc brake torque (Nm)
p_{brake}	Disc brake pressure (kPa)
P_b	Disc brake power (w)
E_b	Disc brake energy (j)
ω	Wheel angular speed (rad/s)
dt	Measurement period (s)
P_{engb}	Engine braking power (w)
T_{engb}	Engine braking torque (Nm)
ω_{eng}	Engine speed (rad/s)
P_{ret}	Retarder power (w)
T_{ret}	Retarder torque (Nm)
$\omega_{propshaft}$	Propshaft angular speed (rad/s)
P_{regen_i}	Regenerative power of electric motor i (w)
n_{motor}	Number of electric motor in the truck
T_{m_i}	Torque of electric motor i (nm)
ω_{m_i}	Angular speed of electric motor i (rad/s)
$P_{traction_i}$	Traction power of electric motor i (w)
E	Disc braking energy on test rig (j)
N	Number of brakings on test rig
I	Rotating inertia of the wheel on the test rig (kgm^2)
R	Wheel radius (m)
V_1	Test rig starting speed (km/h)
V_2	Test rig end speed (km/h)

Contents

1 Introduction

The sector with heavy-duty transportation needs to become more energy efficient and minimize the use of fossil fuels. A way to do this is to use electrified powertrains that offer a higher propulsion efficiency than regular combustion engines and the ability to regenerate some of that energy during braking events. The need for traditional brakes is still there so there is a challenge to achieve optimal utilization of both regenerative braking and traditional braking.

The downside with traditional braking systems is that they generate wear particles, which can have severe health effects on humans including lung cancer, inflammatory illnesses, and cardiovascular conditions [1]. The particle size influences how far into the body the particles can travel [1]. Since 2013, the wear emissions from brakes, tires, and roads have been the primary contributor to transportation-related PM2.5, due to the implementation of tail-pipe regulations that have led to the use of particulate filters. Legislation for wear particles will be introduced with Euro 7. The legislation will be applied for both light-duty and heavy-duty vehicles, but there is no set value for heavy-duty vehicles as of now. This is a concern since emissions from transportation with heavy-duty vehicles continue to contribute to thousands of premature deaths in Europe. Because of this, a deeper understanding of minimizing particle emissions is needed.

Particles of various sizes originate from various sources, including combustion processes and sandstorms, construction sites, and agriculture. However, this project specifically narrows its focus to address particles released during braking activities. During braking, particles form due to friction between the pads and the disc and also to the increasing temperature. This is the reason for vehicle manufacturers wanting vehicles to use auxiliary brakes as much as possible during travel, to be able to save the mechanical brakes and at the same time lower the possible emissions.

This project aims to contribute to reducing the negative health effects associated with particle emissions from PM10 downwards on the size scale. To do this, a MATLAB script will be developed to predict brake wear emissions based on data from Volvo's brake test rig, together with data from real-life vehicles.

1.1 Project definition

1.1.1 Goal statement

The goal of this project is to develop a MATLAB tool to aid the process of characterizing test drive data to understand the brake loads further and estimate the brake wear emissions based on brake test rig data. The characterization process will include data cleaning and identification of key events, understanding the data distribution and key statistics, as well as data visualization. Furthermore, an investigation regarding the difference in brake wear emissions between BEV trucks and ICE trucks will be performed.

1.1.2 Scope

The scope of the project is as follows:

1. For the analysis, the evaluated variables are limited to the ones related to braking performance.
2. The project is limited to the development of tools within the MATLAB environment.
3. The dataset is limited to the ones provided by the customer (Volvo Group).

1.1.3 Stakeholders and members

Parties involved in this project are defined in the following table:

Table 1.1: Stakeholder and members

Name	Role
Volvo Group	Stakeholder
Jonas Sjöblom	Supervisor
Bhumika Dhamane	Project Engineer
David Randby	Project Engineer
Jakob Wurzinger	Project Engineer
Nandu Suresh	Project Engineer
Sayid Achmad Munthahar	Project Engineer

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Background Study

2.1 Brake system

The primary function of a braking system is to decelerate or stop a vehicle in motion. They convert kinetic energy into heat energy through the friction generated when brake pads are pressed against the brake discs. After tremendous research and development in the automotive industry, braking can be achieved by various methods like regeneration, engine braking (for ICE vehicles), etc., which reduces brake emissions drastically as it does not use friction brakes for vehicle deceleration. The brake systems are of two types: Service brakes and Auxiliary brakes. The service brakes are classified into two types: disc and drum brakes, whereas the retarders and regenerative braking come under auxiliary braking.

2.1.1 Drum Brake

A drum brake comprises a housing attached to the wheel, brake shoes installed within the housing, a master cylinder linked to the brake pedal, and a spinning drum. The master cylinder creates friction between the brake shoes and the rotating drum when the brake pedal is pressed, which eventually slows down the wheel until it stops completely [2].

The main advantage of using a drum brake is the low cost. The drum brake usually has low maintenance due to good corrosion resistance since the brake unit is encapsulated. The parts are also cheap since the service parts are usually only the brake shoes and sometimes the wheel cylinders. Some drawbacks with drum brakes are overheating and grabbing. Overheating occurs because there is no outlet for the heat and it stays trapped in the drum. Grabbing occurs when the brake shoe becomes wet or rusty and when the vehicle applies brakes more than the requested value and can stay like that for a shorter period [2].

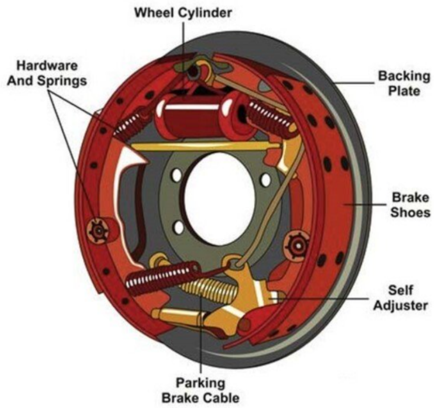

Figure 2.1: Sketch of drum brake and components [2].

2.1.2 Disc Brake

A disc brake consists of a rotor or disc, a caliper that houses the brake pads and piston, which when actuated, engages the brake pads against the rotor, which in turn slows down the vehicle or brings it to a complete stop. One of the main advantages of a disc brake over a drum brake is that it requires less force to engage the brake and produces a higher braking force. The two types of disc brakes are floating caliper and fixed caliper disc brakes.

In the floating caliper(or sliding) disc brake, the inner brake pad is pressed against the disc during the application of brakes, moving the caliper body towards the rotor and thereby engaging the outer brake pad. The fixed caliper disc brake has pistons on either side of the disc and during braking, these pistons force the brake pads against the disc[3].

The advantages of the disc brake are heat dissipation, the ability to perform well in any weather condition and the possibility to produce greater braking force. The disadvantages of disc brakes are that they are quite costly and since they are more exposed than drum brakes, they can corrode more easily [2].

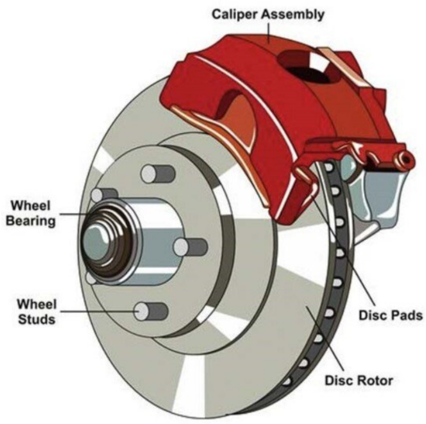

Figure 2.2: Sketch of floating caliper disc brake and components[2].

2.1.3 Auxiliary Brakes

Auxiliary brakes are the additional braking systems that are used to enhance a vehicle's braking performance. This project looks at and treats data from two different auxiliary systems which are engine braking and regenerative braking. The script is also compatible with data from retarders if some trucks would have that installed. Beyond these three, there are several more systems that will not be included here.

2.1.3.1 Engine braking

Engine braking occurs in a vehicle when the engine stops receiving fuel for combustion, typically when the accelerator pedal is not engaged. It works by closing the engine's intake valves and using the engine's compression to generate resistance, consuming the vehicle's kinetic energy to slow it down. This results in a negative torque, impeding the vehicle's propulsion. Engine braking helps to preserve the lifespan of the mechanical brakes.

2.1.3.2 Regenerative braking

Regenerative braking is a mechanism that is used in both BEVs and HEVs. In this type of braking the electric motor acts as a generator creating a negative torque. So, instead of using the disc brakes to slow down the vehicle, it converts the kinetic energy back into electrical energy. In the same way as engine braking, regenerative braking also preserves the lifespan of the disc brakes.

2.1.3.3 Retarder

Retarders are a collective name for a type of brake mechanism that some heavy-duty vehicles have to help enhance brake performance. The retarder is typically mounted on the drive line, near the transmission, where it helps to slow down the vehicle. It also helps to reduce the wear of the disc brakes by dissipating the kinetic energy, which expands the lifespan of the discs. Exactly how the retarder works depends on what type of retarder is being used.

The hydraulic retarder uses viscous fluid to generate braking force. When this type of retarder is active, the transmission directs power to an axle with fan blades placed in a chamber filled with fluid, creating resistance and producing negative torque.

Electromagnetic retarders use induction to create braking force. When electromagnetic retarders are active, they generate a magnetic field that induces currents in a rotating disc that is connected to the drive line.

2.2 Brake Emissions

Particles released from road transport activities can be categorized based on their emission sources into two main types. Firstly, exhaust traffic-related particles, which are emitted because of incomplete fuel combustion, and volatilization of the lubricant during combustion. Secondly, non-exhaust traffic-related particles are either generated by non-exhaust sources associated with traffic or are pre-existing environmental materials deposited on surfaces, later resuspended due to turbulence caused by driving[1]. In Europe, even though traffic exhaust emissions have been reduced significantly, the particle emissions caused mainly by brakes and tires are increasing with the increasing number of vehicles [4].

With the electrification of vehicles, the problem of tailpipe emissions has been solved, and this leaves other traffic emissions to deal with. A study shows the decreasing trend of tailpipe emissions and the increasing trend of non-exhaust traffic emissions across the years, especially with battery packs adding weight to the vehicle[5]. Fig 2.3 shows the trend of PM2.5 emissions, and notably, PM10 shows a similar trend as well.

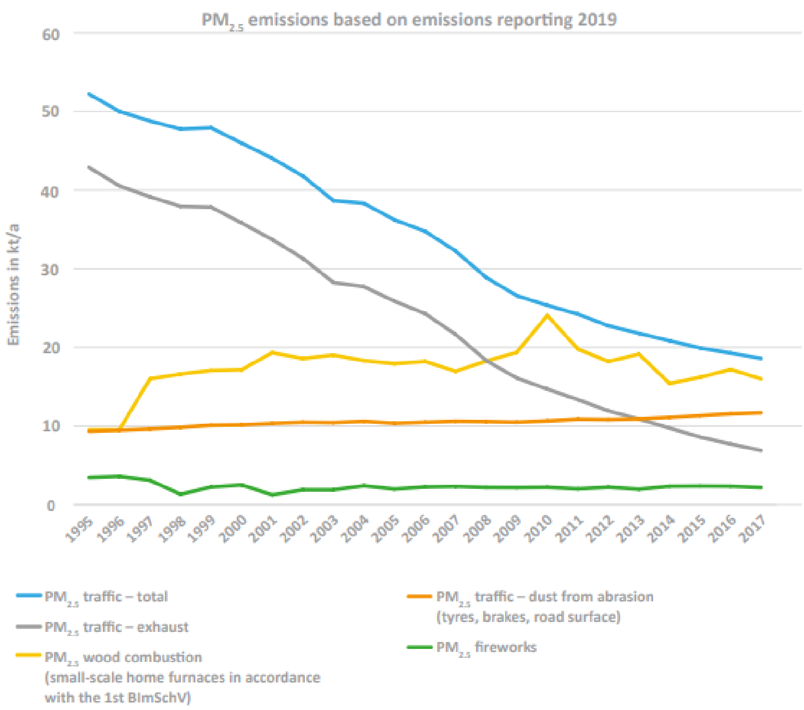

Figure 2.3: PM2.5 emissions as of 2019 [5]

Brakes are pivotal in all vehicles and serve as a vital component to help avoid a potential casualty. The main types of brakes that are being used in vehicles are disc brakes and drum brakes. Both systems have advantages and disadvantages, but the drum brake has the upper hand when it comes to brake wear emissions [6]. It was also noted that the drum brake had a significantly higher PM2.5 to PM10 ratio, indicating that the smaller particles could easily escape the enclosure and move toward the sampling point. This points to the fact that many particles are going unnoticed, which greatly threatens the ecosystem. Moreover, the same study concluded that a van brake under heavy load conditions produced the highest levels of PM2.5 and PM10, which calls for tight legislation to be brought out for heavy-duty vehicles, drastically minimizing the brake wear emissions. The objective of this project is to examine and assess braking data from both ICE and BEV trucks. The project is focusing on predicting brake wear in trucks with diverse configurations. This analysis may find areas that can be improved to mitigate emissions associated with brake wear.

2.2.1 Health effects

Air quality in metropolitan areas is a major concern worldwide, and most of the human population lives in cities that quite often do not meet air quality standards. Particulate Matter (PM) is by far the most significant air pollutant in metropolitan areas, and both short-term and long-term exposure to PM can have a variety of detrimental impacts on health, including lung cancer, inflammatory illnesses, and cardiovascular conditions. Therefore, it is essential for human health to monitor air pollution in urban areas [7].
Particle size influences particle deposition in the respiratory system, as shown by multiple studies[1] and the effect is depicted in Fig 2.4. Coarse particles get deposited in the upper respiratory tracts, whereas the ultra-fine particles can go deep into the lungs, causing serious health hazards. Other studies have shown that ultra-fine particles can get translocated to the kidneys, liver, and brain when they get infused into the bloodstream [1]. According to the World Health Organization, inhalable PM can have harmful effects on human health over short and long periods of time. These effects include even mortality from those conditions [8].

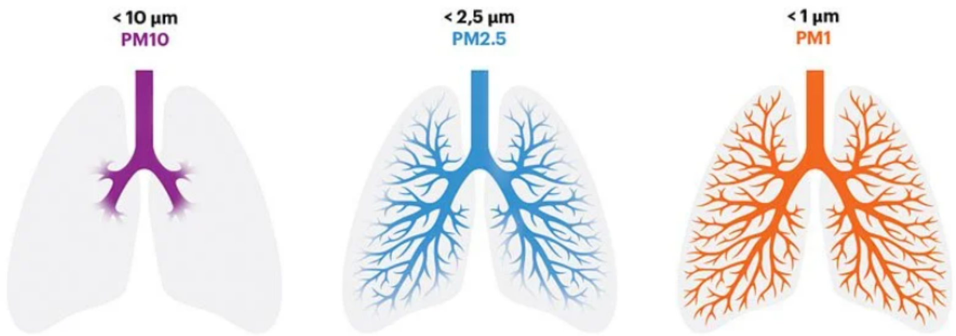

Figure 2.4: Increased risk with smaller particles [9]

2.2.2 Euro 7

The European Commission brought out the new Euro 7 standards to ensure cleaner vehicles on our roads, improved air quality, protecting the health of our citizens and the environment with road transport being the largest pollutant in cities.

The main objectives of Euro 7 legislation [10][11] are:

- To control air polluting emissions from all new vehicles better
- To update and tighten the emission limits for pollutants
- Regulate emissions from brakes and tires (First emission standard beyond tailpipe and evaporative emissions)
- To make sure that new vehicles stay clean for a long period of time i.e., 200.000 km and 10 years
- To support developments in electric vehicles (the main focus is to increase the battery durability)
- To monitor the emissions using sensors throughout the vehicle's lifetime OTA

In the EU in 2018, road transportation accounted for more than 39% of NOx emissions and 10% of main PM2.5 and PM10 emissions and these percentages are significantly greater in the cities. In the EU-28, road traffic was projected to contribute to roughly 70,000 premature deaths in 2018 [10].

As per Euro 7, by 2035, the total NOx emissions from cars and vans will be reduced by 35% compared to Euro 6 and by 56% compared to Euro VI from lorries and buses. At the same time, tailpipe emissions from cars and vans will be reduced by 13%, those from buses and trucks by 39%, and particle emissions from car brakes will be reduced by 27% [10]. According to the legislation, the permissible PM10 emissions will be 7 mg/km for M1/N1 vehicles until 31 December 2034 and 3 mg/km from 01 January 2035.

Presently, there are no upcoming legislation in place to limit PM emissions for heavy-duty vehicles. It is anticipated that such regulations will be introduced in July, 2027 [11].

2.2.3 Formation of particles due to brake wear

The formation of particles from brake wear is a complex process that is influenced by both the composition of the brake pads and under what conditions the brakes are operated. Factors due to operation that influence wear the most are temperature, pressure, and initial speed[12]. The friction between the contact zones of the pads and disc generates heat, leading to wear. Higher pressure applied to the brakes leads to higher friction, leading to a higher temperature, leading to increased wear. Particles that form at the beginning of the brake event, when the temperature is still low in the disc are often in the larger fractions, like $PM10$. And later when the temperature in the disc has increased, finer particles begin to form [12].

2.2.4 Airborne PM from brake wear

It is the particles that become airborne during braking that is harmful to humans. All the amount of mass that is lost due to wear caused by mechanical brakes is not emitted into the air. Some will end up on the road, some will be retained on the wheel, but on average, out of the total mass lost during braking, 35% is emitted into the air as smaller particles[13]. Out of these particles, $83 - 95\%$ falls within the $PM10$ fraction. Within this range, it also covers the $PM2.5$, which stands for around $5 - 17\%$.

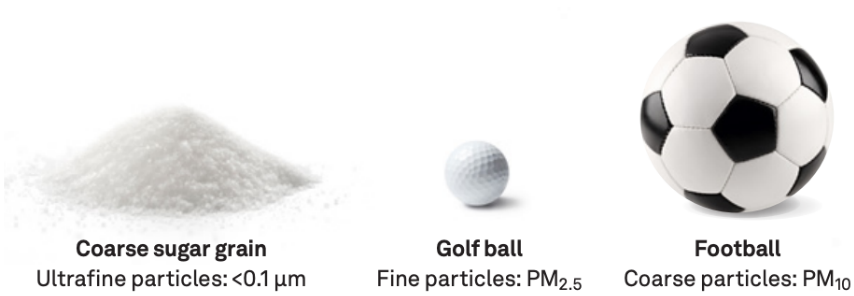

Figure 2.5: If the particles were about 30,000 times larger [14].

2.2.5 PM10

Some of the particles discussed in this project have a diameter equal to or less than 10μm, making them the larger particles under consideration. According to the WHO 2021 updated guidelines, the AQG establishes that PM10 should not exceed $45\mu g/m^3$ within a one-day timeframe [15]. This guideline is based on extensive health studies highlighting the significant impact of such particles on human health. It is important to note that each country has its own legislations. The EU sets target values for the air quality 2030 that are closer to the WHO guidelines, in order to reach the zero-pollution objective by the year 2050. The limits and target values may vary based on the conditions of each individual country, allowing for some flexibility. Each member state is required to establish air quality plans for areas where these targets are not met. These plans must be in place within three years of being measured [16].

2.2.6 PM2.5

Fine particles in the air that have a diameter less than or equal to 2.5μm. This means that if you place 40 of them in a line, they are as thick as a human hair is. Together with PM10, PM2.5 are also covered by the AQG from WHO, where the concentrations should be kept below $15\mu g/m^3$ a day. The coarser particles can travel to the lungs, while finer particles may pass through the lung barrier and end up in the blood.

2.2.7 Ultrafine particles

UFP are particles with a diameter smaller than 0.1μm, which is 100nm. They are everywhere in the ambient air. Due to the particles being so small, particle number concentration (PNC) is used to quantify the number of particles in the ambient air. But as of today, there is no AQG for the ultrafine particles as there is for both $PM10$ and $PM2.5$. In WHO's guidelines from 2021, it distinguishes between low-level concentrations as being <1000 particles/cm^3 and high-level concentrations as being >10000 particles/cm^3 in average under 24 hours or 20000 particles/cm^3 under 1 hour.[17]

2.2.8 Distribution of PM emissions

The BWPs account for 55% of non-exhaust PM by mass in urban areas and it is reported that 21% of traffic-related PM10 is generated by brake wear [18]. The mass concentrations of the total suspended particles $(PM_{total}), PM10, PM2.5, andPM1.0$ are in the range of 0.001-150 mg/m^3. A study on BWPs with realistic driving conditions determined a PM10 emission factor of around 4.6 mg/km–brake [19]. The same study found that brake drag is estimated to contribute about 34% to the total airborne particle mass emission. As discussed above under health implications, all these particles, no matter the size, pose serious threat to human health and it is important to mitigate the emission of these particles.

3 Methodology

To be able to anticipate brake wear emissions from a fleet of heavy-duty vehicles, the work from the previous year's group was studied together with the code from Volvo. This was done to get up to date with what's already been done and what the aim of this project should be. A good basic understanding of the physics involved in braking is of utmost importance for a reliable result. Therefore, the members of the group had to refresh their knowledge in this area.
The dataset also holds crucial information related to driving cycles and other factors influencing brake wear emissions. Therefore, the initial phase revolved around getting familiar with the dataset to know which parameters are relevant. The data initially received at the beginning of the project contained variables from both a BEV truck and an ICE truck, which, later on, led to the project dividing itself into two subgroups. One group focused on the BEV and the other focused on the ICE. In this way, each group could focus on the variables that were important for its specific drive line.

The methodology follows the flow chart, which can be seen in Figure 4.3. The ICE/BEV analysis was divided into separate parts since there is a difference in variables in the data due to different drive lines. An in-depth explanation of the work done can be seen below.

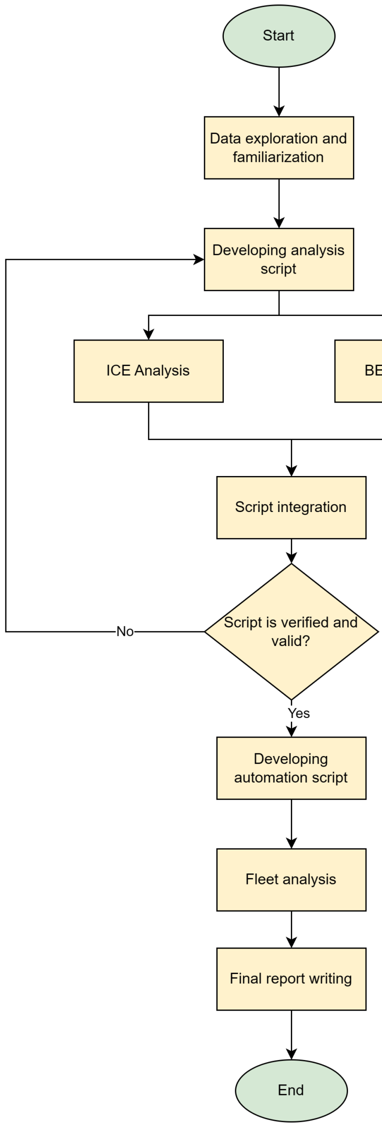

Figure 3.1: Flow chart of the methodology

3.1 Data Preprocessing

The raw data received from Volvo consists of variables that are needed for energy and braking calculations. During the recording, there are a lot of events happening and the duration varies between each event, and sometimes errors occur which causes the sensor reading to resort to a default value. Therefore, data cleaning is done to only obtain values that are valid.

Data cleaning is done by disregarding values that one can quickly assume aren't correct. The data is filtered in the following way:

- Gross combination weight < 65000kg
- wheel-based speed < 250 km/h
- front axle speed < 250 km/h

Wheel-based speed and front axle speed are two measures of vehicle longitudinal

speed that exist as variables in the dataset. The longitudinal speed variable that is considered as valid is the front axle speed. Therefore for subsequent analysis, the longitudinal speed considered is the one named front axle speed in the dataset.
Since the data is numerical, imputation is done by filling the missing data by zeros and this would not affect the analysis (i.e missing brake pressure is filled with zero such that it is considered as no brake pressure input).

3.2 Internal Combustion Engine Trucks

The first step in the script was to calculate the brake torque. This was done by using a quadratic equation from Volvo that gives the brake torque based on pressure. The torque equation is a curve fit, based on several brake tests done by Volvo, and gives a value for each wheel using the brake pressure from the dataset for that specific wheel. The equation is as follows:

$$T_{brake} = 54.9604(\frac{p_{brake}}{100})^2 + 2236.9617(\frac{p_{brake}}{100}) - 571.1999 \tag{3.1}$$

Where p_{brake} is the brake pressure and T_{brake} is the brake torque.

From this, the brake power could be calculated according to equation 3.2.

$$P_b = T_{brake} \cdot \omega \tag{3.2}$$

The next step was to define each brake event. A single braking event can be defined as a time period where the value of a braking-related variable rises from zero to a nonzero value and then goes back to zero. Each event could then be studied to see how much energy is taken up by the brakes.

The ICE truck has three variables that can be characterized as braking-related variables. These variables can be calculated into disc brake power, engine braking power, and retarder power. The disc brake power is calculated as shown in 3.1 and 3.2. Engine braking power and retarder power are calculated as shown in the equations below:

$$P_{engb} = T_{engb} \cdot \omega_{eng} \tag{3.3}$$

$$P_{ret} = T_{ret} \cdot \omega_{propshaft} \tag{3.4}$$

Where T_{engb} is the negative engine torque, given as its own variable in the data, and ω_{eng} is the engine speed. T_{ret} is the retarder torque and $\omega_{propshaft}$ is the speed of the prop shaft.

These three power calculations can then be used to detect if a braking event occurs. If any of them is larger than zero then an event starts. As shown in figure 3.2 one brake power variable can occur both simultaneously and by itself. Union is used to define one braking event if they occur simultaneously. If braking events occur with a short time apart they are regarded as one event to avoid noisy data. The resulting brake events can be seen in figure 3.3.

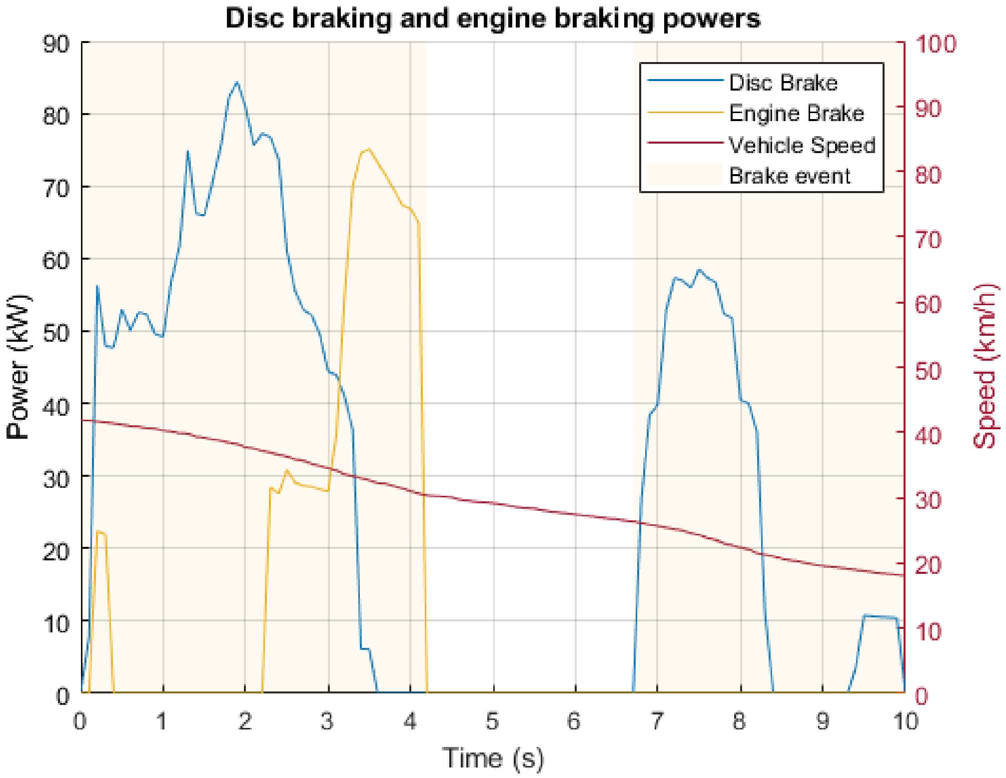

Figure 3.2: Snippet of braking power curves

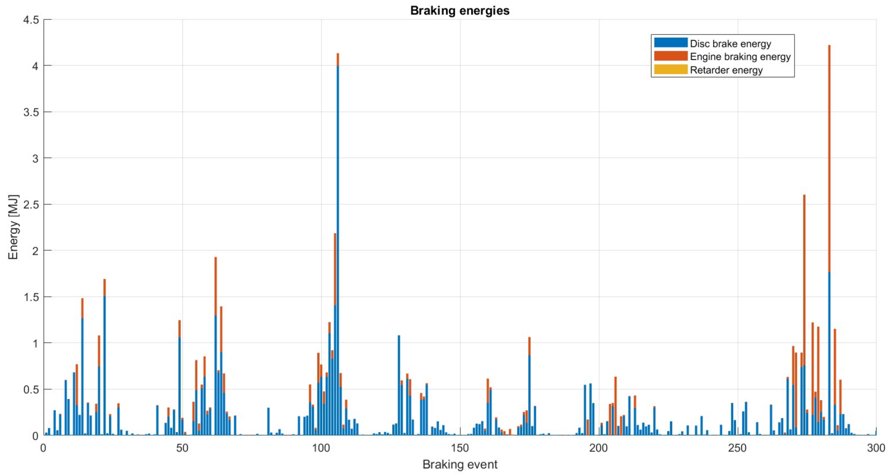

Figure 3.3: Braking energies per event ICE

3.3 Battery-Electric Trucks

Battery electric truck uses an electric motor that is capable of performing regeneration by performing negative torque. Thus, the braking means of a battery-electric truck is divided into two, disc braking and regenerative braking. The disc braking calculation is done in the same way as for ICE shown in equation 3.1 and 3.2. The regenerative power and traction power is defined in the following statements:

$$P_{regen} = \sum_{i=i}^{n_{motor}} T_{m_i}\omega_{m_i}, \text{ where } T_{m_i} < 0 \tag{3.5}$$

$$P_{traction} = \sum_{i=i}^{n_{motor}} T_{m_i}\omega_{m_i}, \text{ where } T_{m_i} \geq 0 \tag{3.6}$$

Where T_{m_i} is the torque for motor i and ω_{m_i} is the angular speed of the motor i.

A single event in this context is defined as a set of indexes where a variable deviates from the baseline and returns back to the baseline. The brake event detection for battery electric trucks uses both the braking power $P_{braking}$ and regenerative power P_{regen} as consideration. A snippet of both variables are plotted in the following figure:

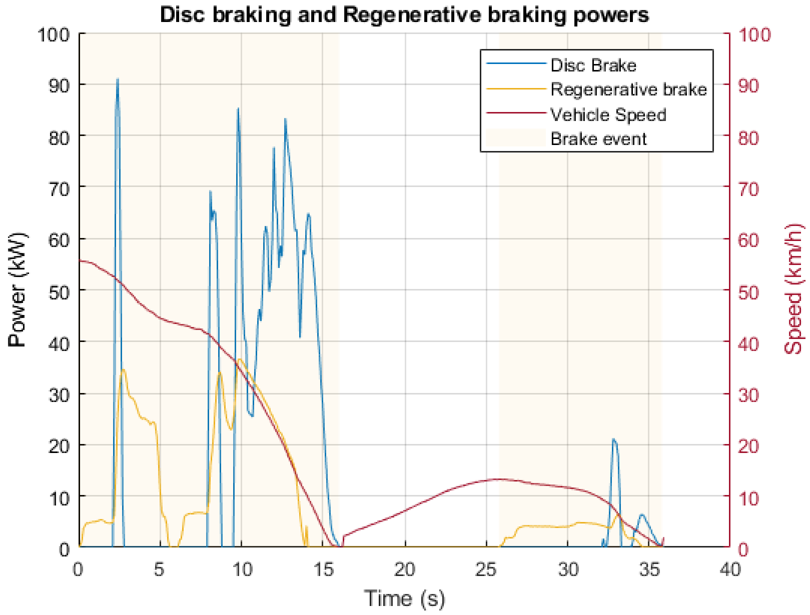

Figure 3.4: Snippet of braking power and regenerative power

Disc braking and regenerative braking do not happen at the same time at all times. Thus, to capture both disc braking and regenerative braking, a single braking event is defined as the union between a collection of event sets of both disc braking and regenerative braking. Therefore, the braking event for BEV trucks might only consist of regenerative braking, disc braking, or both. Braking events that are less than 3 seconds apart are regarded as one single event to reduce noise caused by short braking events. The result of this is shown in figure 3.5.

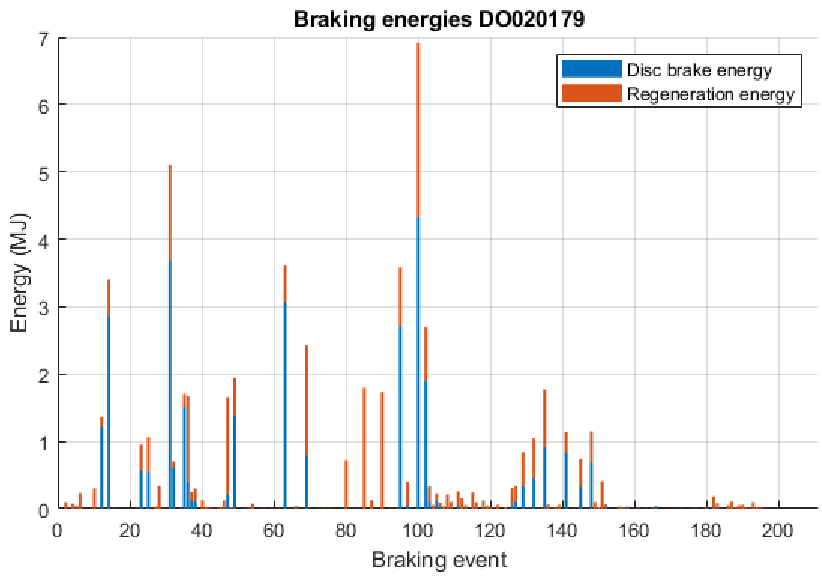

Figure 3.5: Braking energies per event BEV

3.4 Brake wear estimation

The brake wear estimation is done by using the brake test data by Volvo, which is attached in Appendix B. The test was done by performing brake tests varying the brake temperature and performing braking from 60 km/h to 0 km/h with a constant deceleration of 2 m/s^2. The pad and the disc is weighed before and after each test, which can be used, in combination with the brake energy, to calculate the wear. The brake energy for each temperature interval was calculated as followed.

$$E = \frac{N \cdot I \cdot ((V_1/3.6/R)^2 - (V_2/3.6/R)^2)}{2 \cdot 10^9} \tag{3.7}$$

Where E is the brake energy, N is the number of brakings, I is the wheel inertia, V_1 is the start speed, V_2 is the end speed and R is the wheel radius.

Normally the limits for particles in legislation's are given in mg/km hence a wear estimation in g/GJ is calculated rather than mm/GJ. Even though there are values defined for "front" and "rear" in appendix B, for both pads and disc, there is no actual difference between them and therefore one curve-fit is used for all values. The wear depends on the temperature as can be seen in figure 3.6 and 3.7 and is multiplied with the brake energy to get the wear.

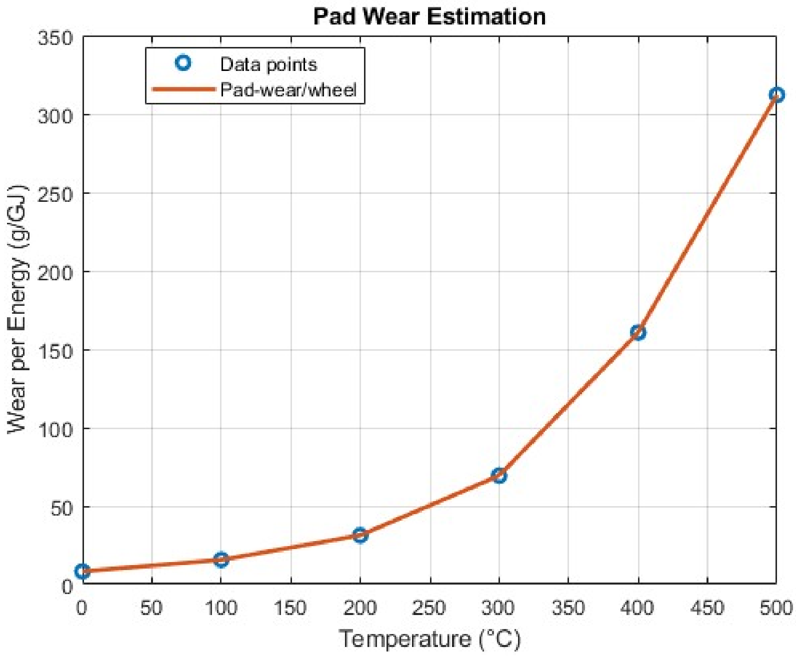

Figure 3.6: Pad wear estimation curve based on rig data (see Appendix 1).

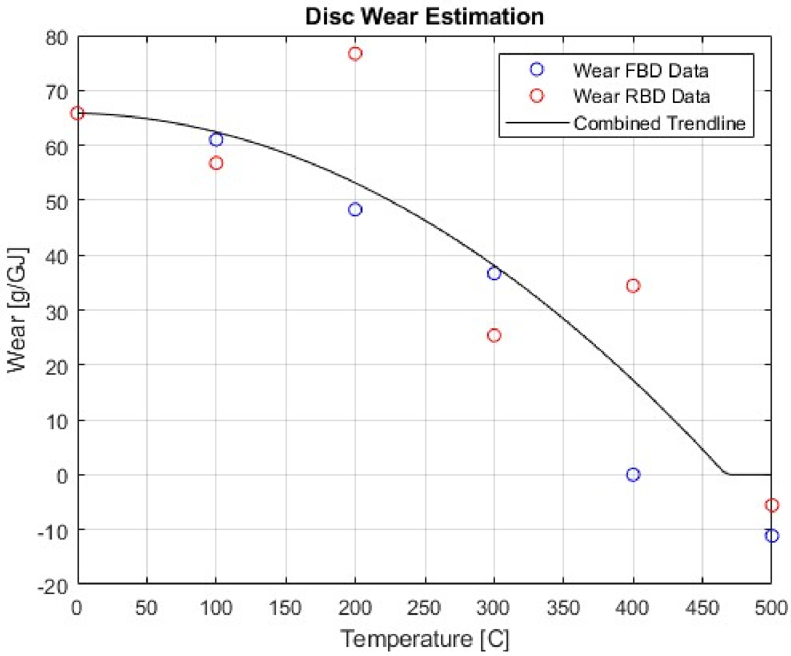

Figure 3.7: Disc wear estimation curve based on rig data (see Appendix 1).

As can be seen in the figure 3.6 and 3.7 there is a data point at $T = 0$ which is not given in appendix 1. This is estimated by doing an extrapolation for the disc, and using the same gradient as for $100 - 200°C$ for the pad. It can also be noted in figure 3.7 that there is data points which is below $0g/GJ$ for high temperatures, which would mean that material is added to the disc. This is not accurate and the curve is therefore set to 0 if the value is below 0. It can also be seen in figure 3.6 and 3.7 that the wear is higher for the disc at lower temperature then for the pads but this is due to the unit g/GJ, if the unit was mm/GJ then the pad wear would be higher then the disc wear, because the disc has a larger area then the pads.

3.5 Principal Component Analysis

Principal Component Analysis can be defined as a dimensional reduction technique that allows approximating a dataset in representative variables called principal components [20]. This component is a linear combination of the original variables that points in the direction which gives the most variability and each component are orthogonal to each other. Given a mean-centered matrix X, using PCA, it can be written as:

$$X = TP' + E \tag{3.8}$$

Where T is the matrix of scores, P' is the matrix of loadings. E contains the error from the approximation process. The columns of P represent the principal components. The first principal component will contain the most variability, followed by the second principal component, and so on. Basically, loadings are the "weight" of each variable in the principal components and scores are the original dataset that are projected to the principal components. Biplot is a plot that contains both the loadings and scores in the same figure. The direction in which the loading points are "pointing" can explain how each original variables correlate with each other within the principal components space. The position of the scores explains to which principal component an observation tends to be.

Within the context of this project, PCA is used to process all the relevant variables to better see the difference between ICE and BEV trucks.

4
Results

4.1 Data overview

The data that we use consists of field test trucks of 11 BEV trucks and 10 ICE trucks. The summary of the data is as follows:

Table 4.1: BEV (Max and Min values)

	Max	Min
Distance Travelled [km]	6394.95	722.85
Average speed [km/h]	63.7	42.85
Total pad wear per km [mg/km]	18.34	1.79
Total disc wear per km [mg/km]	26.09	7.65

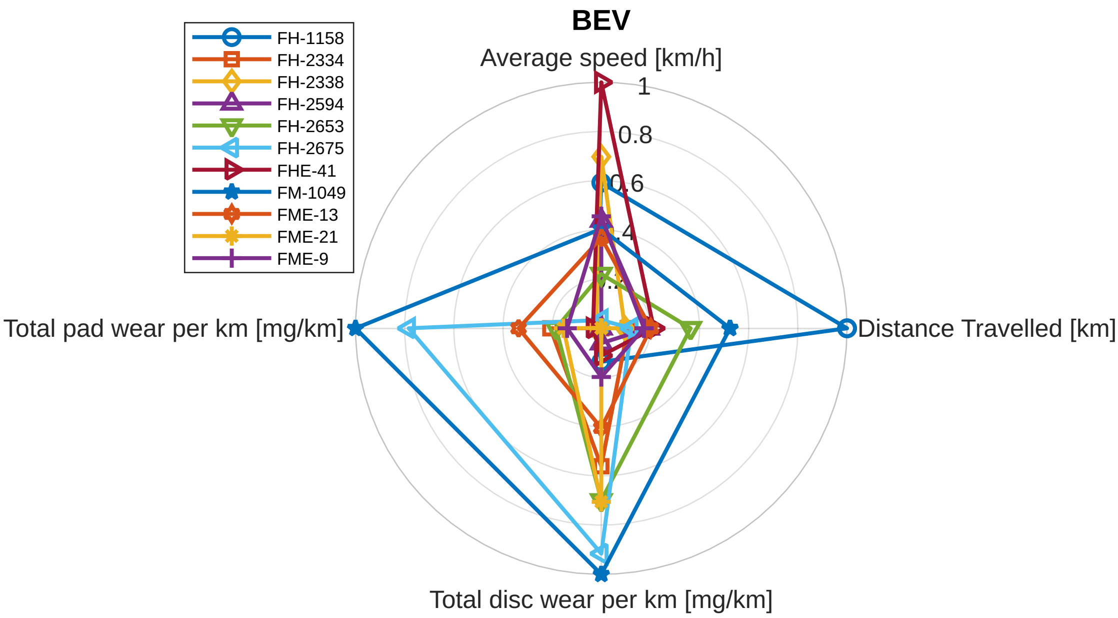

Figure 4.1: Radar chart of the 11 BEV trucks. Each category in the radar chart is normalized, with a value of 1 corresponding to the maximum value within that category.

Table 4.2: ICE (Max and Min Values)

	Max	Min
Distance Travelled [km]	48974.04	4224.14
Average speed [km/h]	79.67	32.48
Total pad wear per km [mg/km]	26.91	2.55
Total disc wear per km [mg/km]	57.9	7.85

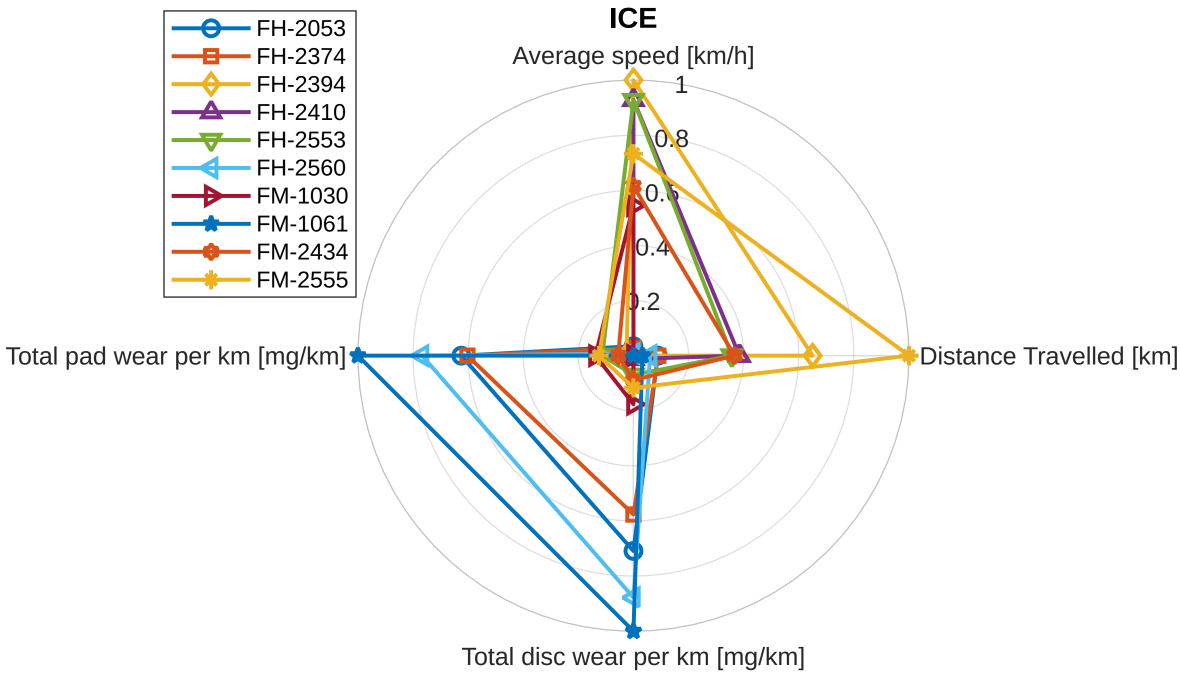

Figure 4.2: Radar chart of the 10 ICE trucks. Each category in the radar chart is normalized, with a value of 1 corresponding to the maximum value within that category.

Both figures above, 4.1 and 4.2 use four normalized axes to compare the difference between the studied trucks in the project. This normalization ensures that the data for each category is scaled, allowing for a more meaningful comparison on the radar chart. Each category is normalized independently of the others, resulting in a radar chart where each axis has a different scale based on the original range of values in that category. The radar chart indicates how certain categories are affecting the wear more than others. To normalize a value on the axis, the scale is first shifted to begin at zero and end at one. Then, the normalization is achieved by subtracting the minimum value of the category from the value in question and then dividing it by the range, which is the difference between the maximum and minimum values of that category.

$$Normalized\_value = ((Value\_in\_question) - (min\_value))/((max\_value) - (min\_value))$$

Percentage disc braking is defined as the percentage of disc braking energy with respect to the total braking energy. Percentage auxiliary braking is the complement of percentage of disc braking. The pad and disc wear in mg per km plotted against the percentage of disc braking is as follow:

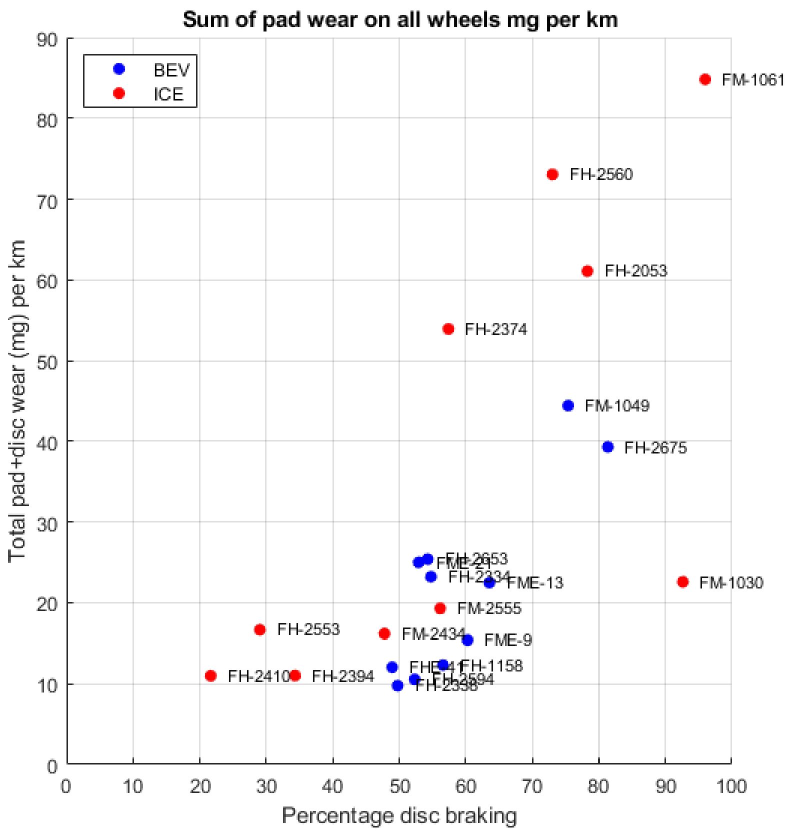

Figure 4.3: Pad+disc wear in mg per km

It is quite obvious that higher percentage of disc braking tends to make the vehicle shed more wear per km. However, there is no clear separation between BEV and ICE trucks. Therefore in the subsequent analysis, we perform PCA analysis to better differentiate the braking characteristics.

4.2 Fleet analysis

The fleet analysis was done using Principal Component Analysis (PCA). The dataset that is used is the braking events dataset. Each row or datapoints correspond to a single braking event. PCA was performed on the following variables as the columns: average gross combination weight, average speed, pad wear per km, disc wear per km, pad wear per gj of braking energy, disc wear per gj of braking energy, pad wear per number of braking events, disc wear per number of braking events, percentage of disc braking with respect to total braking energy, and percentage of auxiliary braking with respect to total braking energy.

This set of normalized wear is chosen to minimize the effect of the difference in the amount of data between each trucks and between each propulsion category as well as higher interpretability of the principal components. After the PCA is done, Scree plot is then plotted to see the explained variance.

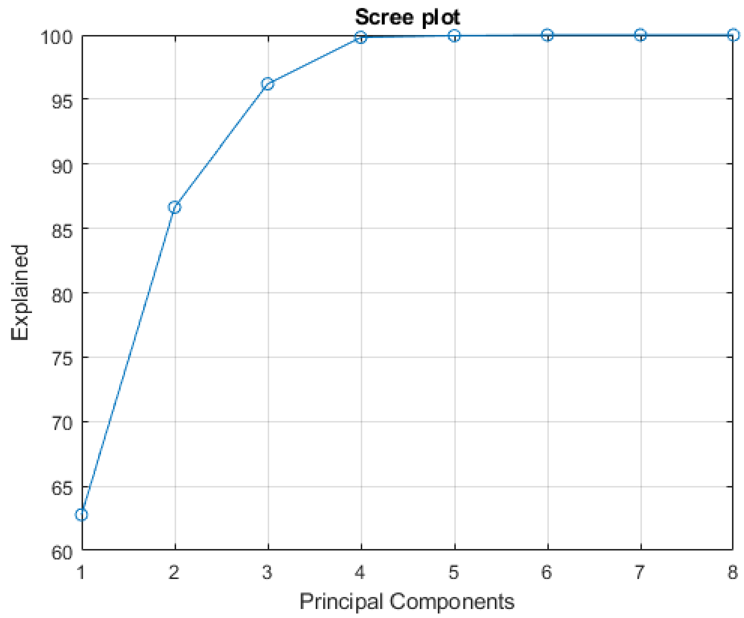

Figure 4.4: PCA scree plot

Based on the scree plot above, it can be seen that the first and second principal components contains nearly 87% of variability in the dataset. Therefore, we can proceed by using the first and second principal components. The loading's of both of the principal components are as follows:

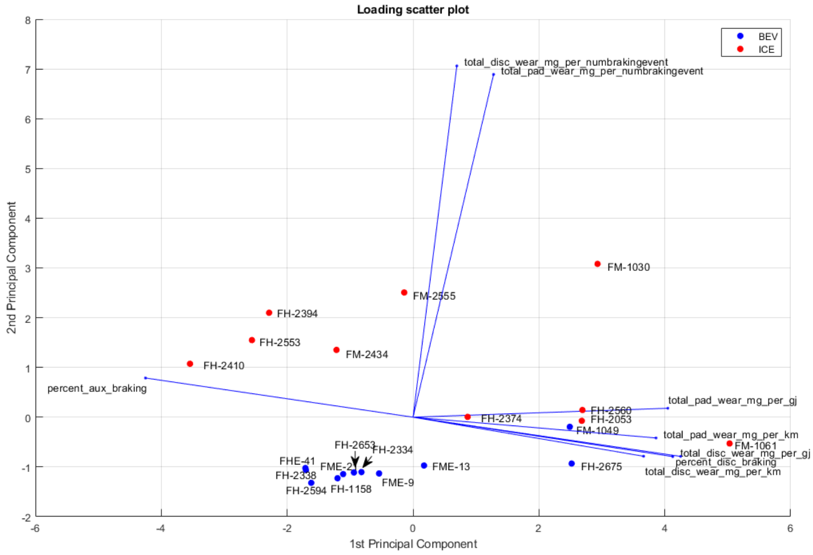

Figure 4.5: PCA Biplot

It is clear that higher disc wear correlates with higher pad wear. Higher value of principal component 1 can be interpreted as less efficient brakings in terms of the amount of wear. The amount of normalized wear increases when principal component 1 increases. This also correlates with higher percentage of disc braking while having lower percentage of auxiliary braking. Principal component 2 can be interpreted as the measure of braking emissions per number of braking event. Variances in principal component 2 might indicate high variability in terms of braking characteristics per event which may cause high wear per number of braking event. By visual, we can observe that there are clusters. BEV and ICE trucks tends to agglomerate together, while there are a mix of BEV and ICE trucks on the cluster with higher PC1 located on the right hand side of figure 4.5.
With this result, the analysis then will be done based on the clusters to simplify the process. K-means clustering was then done to determine the clusters based on the sum of distance squared to the centroid. The number of the clusters is calculated by utilizing elbow method.

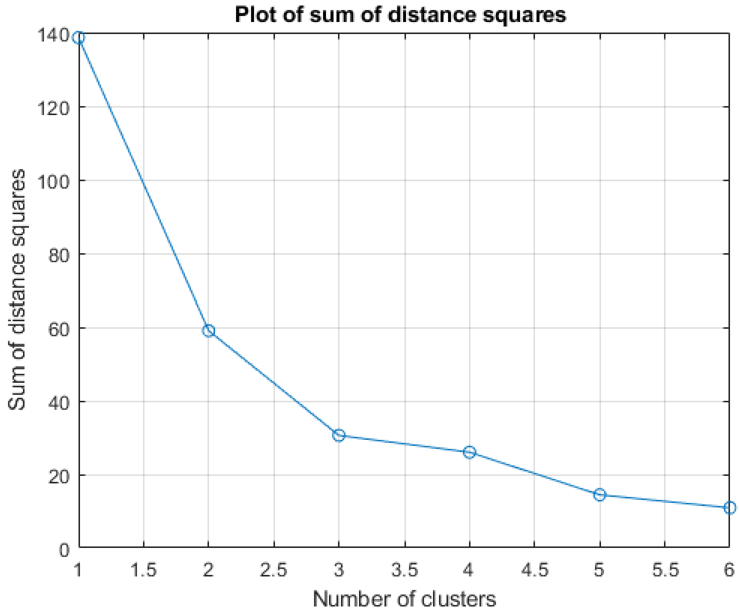

Figure 4.6: PCA loadings scatterplot

Based on the figure above, choosing 3 as the number of clusters is reasonable. The result of the k-means clustering is as follows:

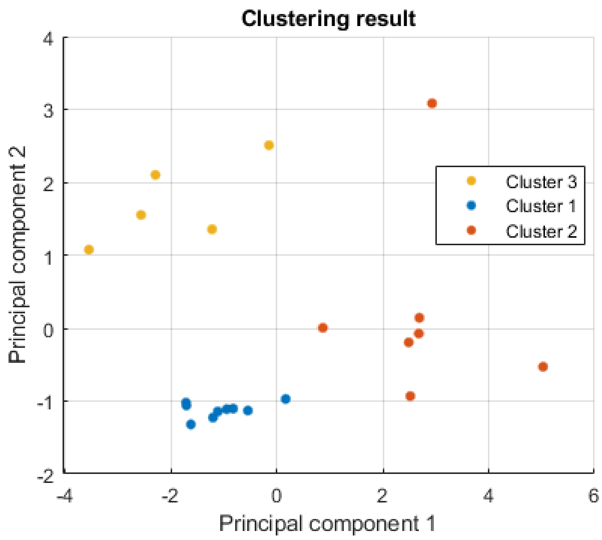

Figure 4.7: Clusters based on principal components 1 and 2

It is clear that cluster 1 and cluster 3 consists of only BEV and ICE trucks respectively. However, cluster 2 contains both BEV and ICE trucks. This might indicate that the clusters does not discriminate between BEV and ICE only, but also in terms of the driving behavior or the driving cycle. That is, there are two different sub-clusters within BEV and ICE clusters. Therefore, it was decided to define a cluster 4 which consists of BEV trucks from cluster 2. This is done to better differentiate BEV and ICE characteristics. The PCA loadings scatter plot is now as in figure 4.8:

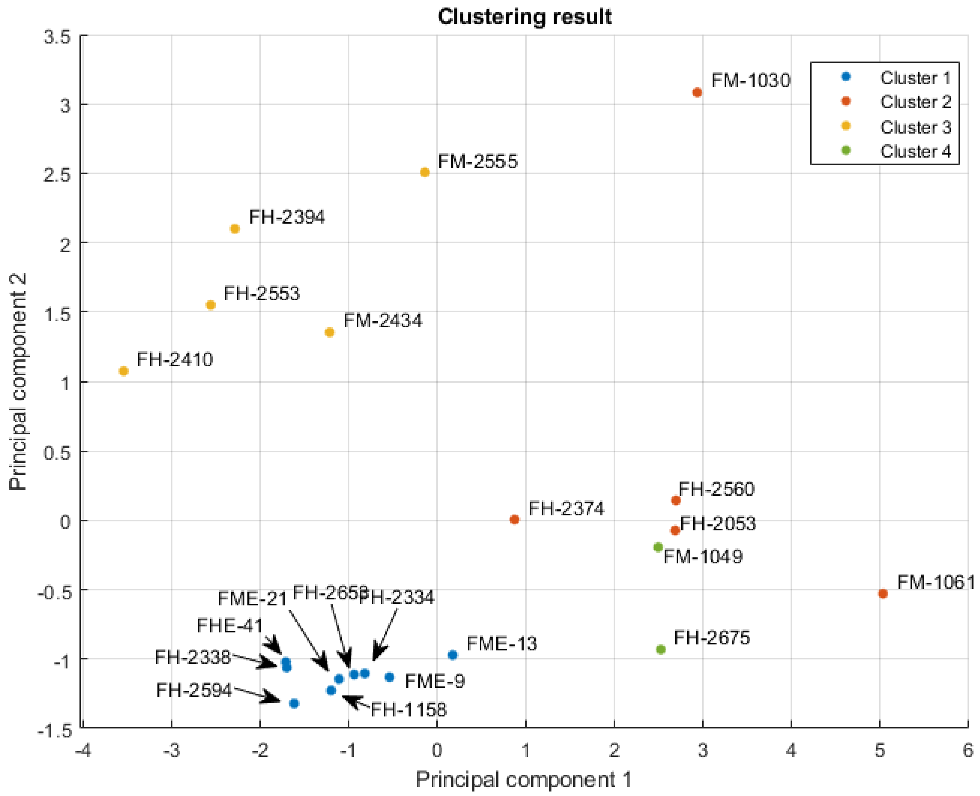

Figure 4.8: PCA loadings scatterplot with cluster 4

The average starting and ending speed, distance, duration, and percentage of disc and auxiliary braking usage of the braking events of the clusters are as follow:

Table 4.3: Driving characteristics per cluster

Variable	Cluster 1	Cluster 2	Cluster 3	Cluster 4
Average driving speed (km/h)	51.59	38.28	72.16	47.42
Average braking start speed (km/h)	44.58	29.29	49.59	43.23
Average braking end speed (km/h)	35.81	16.74	38.53	34.25
Average braking distance (m)	79.25	41.51	136.02	84.54
Average braking duration (s)	7.68	5.46	8.78	8.03
Average percent disc braking usage (%)	24.07	87.93	64.95	28.55
Average percent aux braking usage (%)	75.93	12.07	35.05	71.45
Number of braking events per km	2.67	2.57	0.44	3.04
Braking energy per event (MJ/event)	0.154	0.455	1.200	0.204

We can see that cluster 1 and 4 are relatively similar. However, cluster 2 and 3 are different with the other clusters. To further investigate, The histograms of the clusters are plotted and shown in the appendix. At a glance, there are differences in the histogram of each clusters that explain the differences in the braking behavior of each clusters. This will be discussed further in the next chapter.

4.3 Brake Pads Wear patterns

The dataset included information on both inner and outer brake pads, and upon analysis, we observed distinct wear patterns for each type. In the case of outer brake pads, we noted a higher degree of wear on the outer diameter. This can be attributed to the fact that the outer diameter covers more distance during operation than the inner diameter. On the other hand, the inner brake pads exhibited a different wear trend. The wear was more pronounced towards the front part of the brake, aligning with the direction in which the vehicle moves. This strategic wear pattern suggests that the inner brake pads are designed to be more effective in braking, as the wear is concentrated in the area that plays a crucial role in stopping the vehicle. When doing the estimation curve for the pads this was not used. Instead, the average values were used.

Figure 4.9: Brake pad measurement positions

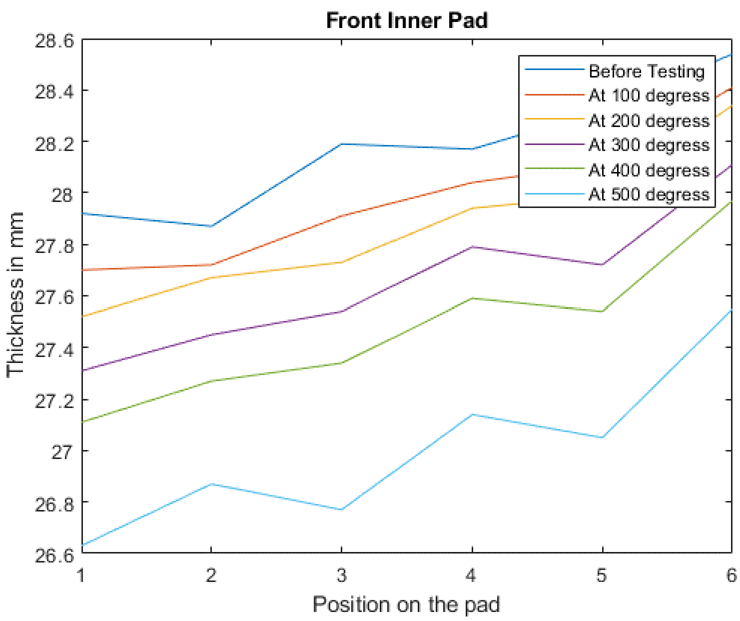

Figure 4.10: Inner Pad - Wear at measurement points

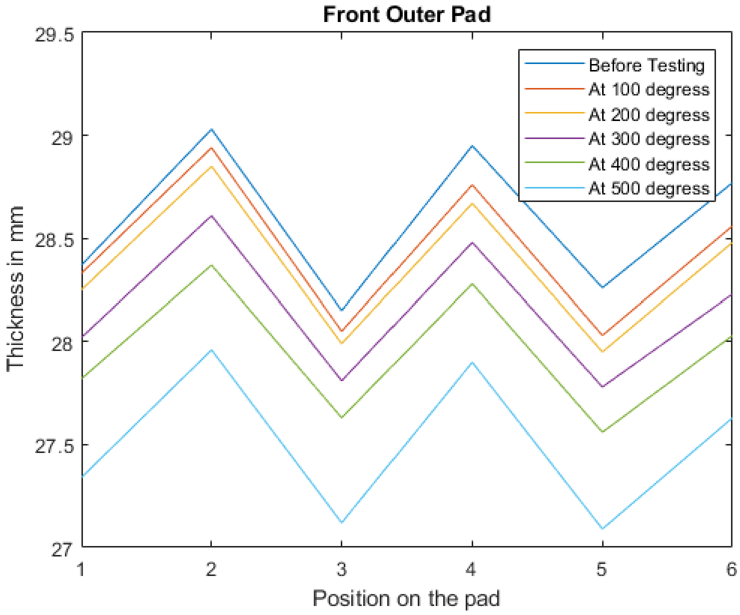

Figure 4.11: Outer Pad - Wear at measurement points

5 Discussion and Conclusion

Throughout this project, our estimation codes were developed based on data provided by Volvo, sourced from their brake test rig in Lundby. This dataset aligns with the information utilized by the previous year's project team. Volvo's brake test rig employs a standardized procedure, involving braking from 60 km/h with a deceleration of 2 m/s^2 to a complete stop. This process is repeated multiple times, covering a temperature range of 100 to 500 degrees in 100-degree intervals.

The collected data is crucial for constructing a curve-fit, which serves as a foundation for estimating wear in real-life trucks. To enhance the accuracy of our curve-fit table, we initially aimed to conduct additional brake tests using Volvo's rig. Our plan included varying key parameters such as applied pressure and testing at temperatures below 100 degrees. This diversified approach would have provided a more comprehensive data set for refining the estimations for future works. Furthermore, increasing the number of trucks for code validation would not only enhance the validity of our results but also allow for a better examination of trends in the pattern. This step is crucial for ensuring the robustness and reliability of our methodology.

Referring to the PCA results with the four clusters, We can see that Cluster 1 consists completely of BEV trucks, Cluster 2 consists completely of ICE trucks, Cluster 3 also consists of ICE trucks and Cluster 4 consists of BEV trucks that have different characteristics with cluster 1. By these results only, we can see that there are differences in the braking characteristics between BEV and ICE. Looking at cluster 1 and 3, there is significant difference in terms of the second principal component. With respect to the first principal components, there are no considerable differences between cluster 1 and cluster 3. Cluster 2 and cluster 4 on the other hand, tends to have more wear per braking energy and distance compared to both cluster 1 and 3. To further investigate this, the histogram of the percentage of disc braking usage is plotted in figure B.9.
From the percentage of disc brake usage histogram, we can see that cluster 1 and cluster 4, which consist of BEV trucks have similar characteristics noted by relatively low usage of disc brake. On the other hand, cluster 2 and cluster 3 which consist of ICE trucks has higher disc brake usage. However, all clusters can be considered as having bimodal distribution since two modes can be seen on lower and higher percentage of disc brake usage. This implies that there are inherently two underlying characteristics within the data. Therefore, for the subsequent analysis, the histograms will be plotted where the data is filtered based on percentage of disc or auxiliary braking.

The speed where the braking starts and ends is plotted in figure B.10 and B.11 to investigate the brakings with a **high percentage of disc braking** (more than 90% of braking energy is dissipated by disc brake) usage. Based on the plots, we can see that brake events that have high usage of disc braking tend to happen at the lower range of speeds and mostly for full-stop braking for all clusters. Furthermore, there are no considerable differences between the clusters. This indicates that there is no difference in the characteristics of the disc braking usage between BEV and ICE trucks.
The next investigation is for braking events with **high usage of auxiliary brakings** (more than 90% of braking energy is dissipated by auxiliary brake). The histogram of the braking start and end speed are plotted in figure B.12 and B.13.
By inspecting the histograms, we can see that cluster 1 and 4 which consists of all BEV tends to have no significant difference. Brake events with high auxiliary braking usage tend to happen at all ranges of speeds. This is not the case for the other two clusters. Cluster 2 and 3 have a significant difference in the characteristics. Cluster 2 tends to use auxiliary braking at speeds lower than Cluster 3, which tends to have a significantly high starting speed for braking with a high auxiliary braking percentage. With this plot, the difference between regenerative braking and engine braking is also visible. Regenerative braking is able to perform until full-stop while engine braking does not. This is due to the fact that engine braking is using the rotation of the wheels to run the engine, if the wheels stop rotating then the engine will stop.

Two questions arise. First, why the braking speed characteristics between cluster 1 and 4 are the same while having different wear characteristics shown by higher magnitude of principal component 1 and 2 for cluster 4? second, why cluster 2 and 3, which consists of all ICE trucks, have such stark differences in the braking speed characteristics and also different magnitude of the principal components?

The answer to the first question lies in the difference of the brake temperature of cluster 1 and cluster 4 which can be seen in B.3 The values are shown in this following table:

Table 5.1: Table of the mean and median brake temperature for cluster 1 and 4.

Cluster	Mean brake temperature (degC)	Median brake temperature (degC)
Cluster 1	66.92	55.00
Cluster 4	94.40	66.00

Even though there are no significant difference in the driving profile as shown by 4.3, cluster 4 has a significantly higher brake temperature. This effect alone increases the normalized wear as shown in the PCA plots. High brake temperature might be caused by the fact that cluster 4 has a relatively higher braking events per km and braking energy per event compared to cluster 1 as shown in table 4.3 which indicates higher intensity brakings. Further investigation on the brake temperature

Table 5.2: Interpretation of each cluster

Cluster	Comments	Remark
Cluster 1	BEV trucks that drive in highway	Lowest normalized brake wear
Cluster 2	ICE trucks that drive in cities	Highest brake wear per km and per braking energy but lower brake wear per event compared to cluster 3
Cluster 3	ICE trucks that drive in highway	Highest brake wear per brake event but comparable normalized brake wear to cluster 1
Cluster 4	BEV trucks that drive in highway but with hotter brake temperature	Higher normalized brake wear compared to cluster 1

dynamics is outside the scope of this project.

Question two can be answered by investigating the histogram of the end braking speed where the **start braking speed is more than 60 km/h** (brake events that start from high speed). The histogram of the end speed is plotted in figure B.14.
From figure B.14, it can be seen that cluster 3 rarely brakes from more than 60 km/h to low speeds where cluster 2 has considerable amount of events where it brakes to low speeds. This indicates that cluster 2 is driven in different mission profile compared to cluster 3. We can also see that cluster 1 and 4 have a comparably similar characteristics except that there are higher occurences of braking to low speed (to 20-30 km/h) in cluster 4.
Therefore, we can infer that cluster 1,3, and 4 are driven in scenario where the speed is relatively higher with low occurence of full-stop braking from high speed while cluster 2 is driven in scenario where there are considerable amount of braking events where it goes full-stop from more than 60 km/h of driving. We can consider them as *highway-driving* and *city driving* respectively. The interpretation is summarized in the table 5.2.

Therefore, conclusion can be made regarding this analysis is that driving scenario or mission profile affects the normalized brake wear. Scenarios with mostly highway driving that is characterized with higher speed and lower occurence of full-stop braking tends to have lower normalized brake wear per km and per braking energy. However it can produce high amount of wear per braking events due to the fact that the events mostly occurs at high speed.

The specific operational use of each truck may significantly influence brake wear. Differences in driving conditions and individual driving styles among truck operators can result in variations in braking frequency, duration, and intensity. These factors influence the rate of wear and how much wear is generated. An operator who is more frequent and aggressive on the brake pedal may contribute to a rise in wear compared to one who is trying to use the auxiliary brakes or using a more conservative braking method instead.

The fact that brake temperature may affect the normalized wear by a considerable amount might indicate that environmental condition may have played a non-negligible role in the brake wear.

Moreover, referring to figure B.10 and figure B.11, for brake events with high disc brake usage, there is no clear characteristic difference between BEV and ICE trucks as well as within highway driving and city driving. Therefore, the differentiating factor between BEV and ICE trucks lies in the auxiliary braking. The comparison of auxiliary braking characteristics between the clusters are shown in table 5.3.

Table 5.3: Auxiliary braking characteristics

Variable	Cluster 1	Cluster 2	Cluster 3	Cluster 4
Percentage of braking events with more than 90% auxiliary braking usage (%)	62.59	4.92	20.02	62.96
Average auxiliary braking power in events with more than 90% auxiliary braking usage (kW)	5.20	72.17	109.05	4.21
Maximum auxiliary braking power in events with more than 90% auxiliary braking usage (kW)	60.22	345.10	204.06	57.54

BEV trucks which are represented by cluster 1 and 4 tend to have a significant amount of brake events with more than 90% of its braking energy being absorbed by regenerative braking. ICE trucks, on the other hand, tend to have considerably lower percentages both in highway driving and city driving situations. However, engine braking has a significantly higher capability for braking shown by substantially higher average and maximum auxiliary braking power in table 5.3. The difference might lie in the fundamentals of engine braking and regenerative braking. Engine braking is more plausible to perform at higher speeds with high power shedding capability but the capability will be very limited in low speed while regenerative braking can be performed at any speed with limited power. The limitation of regenerative power however, will increase the disc brake usage if the truck is in situations where it has to shed high amount of kinetic energy per unit of time (i.e long downhill slope). However, driver's behavior might play a role in this since the amount of regenerative braking power can be set.

Therefore we can conclude that from the perspective of brake wear, BEV trucks are generally better than ICE trucks for driving scenarios which requires high number of brakings and lower speed (i.e city driving). ICE trucks are better for high speed scenarios with low number of brakings (i.e highway driving) since the auxiliary brakes at higher speeds are more effective than BEV's regenerative braking. This conclusion however, is based on the dataset that we have.

Concerning the temperature data from the real-life trucks, there is uncertainty due to being calculated and not being a measured value. The temperature used for estimating brake wear may exhibit a range of ±50 degrees, introducing a variation between the upper and lower bounds of the estimate. This temperature uncertainty introduces a range of potential variations to the results. The temperature is one of the key variables in the process that generates wear and is therefore a priority to fix for future projects.

One critical aspect that has been discussed is how payload capacity and vehicle weight could influence the profit and losses when comparing BEVs to ICE vehicles. Without any trailer, the BEV vehicles weigh significantly more than similar ICE vehicles. This weight of the batteries can limit the amount of goods a BEV can carry compared to ICE vehicles. This limitation could be a problem for the overall efficiency when it comes to transporting large volumes or heavy loads.

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A

Appendix 1

WEAR TEST 100°C								
8	Wear test		2		60	0	100	1000
9	Efficiency test	1, 2, 3, 4, 6, 8, 10			60	0	100	7
Stop for inspection and wear measurement								
WEAR TEST 200°C								
10	Wear test		2		60	0	200	500
11	Efficiency test	1, 2, 3, 4, 6, 8, 10			60	0	100	7
Stop for inspection and wear measurement								
WEAR TEST 300°C								
12	Wear test		2		60	0	300	500
13	Efficiency test	1, 2, 3, 4, 6, 8, 10			60	0	100	7
Stop for inspection and wear measurement								
WEAR TEST 400°C								
14	Wear test		2		60	0	400	250
15	Efficiency test	1, 2, 3, 4, 6, 8, 10			60	0	100	7
Stop for inspection and wear measurement								
WEAR TEST 500°C								
16	Wear test		2		60	0	500	250
17	Efficiency test	1, 2, 3, 4, 6, 8, 10			60	0	100	7
Stop for final inspection and wear measurement								

Figure A.1: Wear test information used for curve fits.

6.1 Pad wear

Test no	Temp (°C)	Speed (km/h)	Wear (mm/GJ) Front brake (A)	Rear brake (B)
8	100	60	**0,23**	**0,22**
10	200	60	**0,28**	**0,27**
12	300	60	**0,59**	**0,55**
14	400	60	**1,10**	**1,09**
16	500	60	**2,56**	**2,23**

(See appendix 12 and 13).

6.2 Disc wear

Test no	Temp (°C)	Speed (km/h)	Weight loss Front (A) (g)	Weight loss Rear (B) (g)
8	100	60	**43**	**40**
10	200	60	**17**	**27**
12	300	60	**13**	**9**
14	400	60	**0**	**6**
16	500	60	**-2**	**-1**
8-16	100-500	60	**71**	**81**

(See appendix 13)

Figure A.2: pad and disc wear used for curve fits.

Front (A)

Inner pad	Weight change (Kg)	Points of measuring 1	2	3	4	5	6	Mean thickness (mm)
Before	2,645	27,92	27,87	28,19	28,17	28,32	28,54	28,17
After 100°C wear	2,639	27,70	27,72	27,91	28,04	28,11	28,41	27,98
	0,006	**0,22**	**0,15**	**0,28**	**0,13**	**0,21**	**0,13**	**0,19**
After 200°C wear	2,633	27,52	27,67	27,73	27,94	27,99	28,34	27,87
	0,006	**0,18**	**0,05**	**0,18**	**0,10**	**0,12**	**0,07**	**0,12**
After 300°C wear	2,620	27,31	27,45	27,54	27,79	27,72	28,11	27,65
	0,013	**0,21**	**0,22**	**0,19**	**0,15**	**0,27**	**0,23**	**0,21**
After 400°C wear	2,604	27,11	27,27	27,34	27,59	27,54	27,97	27,47
	0,016	**0,20**	**0,18**	**0,20**	**0,20**	**0,18**	**0,14**	**0,18**
After 500°C wear	2,573	26,63	26,87	26,77	27,14	27,05	27,55	27,00
	0,031	**0,48**	**0,40**	**0,57**	**0,45**	**0,49**	**0,42**	**0,47**
Sum wear	**0,072**	**1,29**	**1,00**	**1,42**	**1,03**	**1,27**	**0,99**	**1,17**

Front (A)

Outer pad	Weight change (Kg)	Points of measuring 1	2	3	4	5	6	Mean thickness (mm)
Before	2,660	28,37	29,03	28,15	28,95	28,26	28,77	28,59
After 100°C wear	2,655	28,33	28,94	28,05	28,76	28,03	28,56	28,45
	0,005	**0,04**	**0,09**	**0,10**	**0,19**	**0,23**	**0,21**	**0,14**
After 200°C wear	2,650	28,25	28,85	27,99	28,67	27,95	28,48	28,37
	0,005	**0,08**	**0,09**	**0,06**	**0,09**	**0,08**	**0,08**	**0,08**
After 300°C wear	2,637	28,02	28,61	27,81	28,48	27,78	28,23	28,16
	0,013	**0,23**	**0,24**	**0,18**	**0,19**	**0,17**	**0,25**	**0,21**
After 400°C wear	2,624	27,82	28,37	27,63	28,28	27,56	28,03	27,95
	0,013	**0,20**	**0,24**	**0,18**	**0,20**	**0,22**	**0,20**	**0,21**
After 500°C wear	2,596	27,34	27,96	27,12	27,90	27,09	27,63	27,51
	0,028	**0,48**	**0,41**	**0,51**	**0,38**	**0,47**	**0,40**	**0,44**
Sum wear	**0,064**	**1,03**	**1,07**	**1,03**	**1,05**	**1,17**	**1,14**	**1,08**

	100°C	200°C	300°C	400°C	500°C
Mean wear (kg)	**0,006**	**0,005**	**0,013**	**0,015**	**0,030**
Mean wear (mm)	**0,17**	**0,10**	**0,21**	**0,20**	**0,46**

Points of measuring

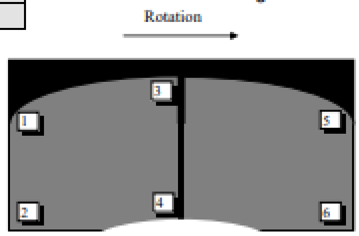

Figure A.3: Front brake pad wear used for the exponential fit

Rear (B)

Inner pad	Weight change (Kg)	Points of measuring 1	2	3	4	5	6	Mean thickness (mm)
Before	2,652	27,97	28,11	28,33	28,47	28,40	28,72	28,33
After 100°C wear	2,645	27,74	28,07	28,03	28,32	28,21	28,65	28,17
	0,007	**0,23**	**0,04**	**0,30**	**0,15**	**0,19**	**0,07**	**0,16**
After 200°C wear	2,639	27,59	27,95	27,87	28,22	28,09	28,57	28,05
	0,006	**0,15**	**0,12**	**0,16**	**0,10**	**0,12**	**0,08**	**0,12**
After 300°C wear	2,628	27,37	27,79	27,66	28,05	27,92	28,36	27,86
	0,011	**0,22**	**0,16**	**0,21**	**0,17**	**0,17**	**0,21**	**0,19**
After 400°C wear	2,613	27,18	27,58	27,44	27,87	27,69	28,17	27,66
	0,015	**0,19**	**0,21**	**0,22**	**0,18**	**0,23**	**0,19**	**0,20**
After 500°C wear	2,585	26,85	27,24	26,97	27,47	27,23	27,80	27,26
	0,028	**0,33**	**0,34**	**0,47**	**0,40**	**0,46**	**0,37**	**0,40**
Sum wear	**0,067**	**1,12**	**0,87**	**1,36**	**1,00**	**1,17**	**0,92**	**1,07**

Rear (B)

Outer pad	Weight change (Kg)	Points of measuring 1	2	3	4	5	6	Mean thickness (mm)
Before	2,653	28,32	28,69	28,14	28,63	28,08	28,50	28,39
After 100°C wear	2,649	28,17	28,58	27,98	28,45	27,92	28,38	28,25
	0,004	**0,15**	**0,11**	**0,16**	**0,18**	**0,16**	**0,12**	**0,15**
After 200°C wear	2,644	28,13	28,49	27,91	28,37	27,86	28,29	28,18
	0,005	**0,04**	**0,09**	**0,07**	**0,08**	**0,06**	**0,09**	**0,07**
After 300°C wear	2,632	27,90	28,27	27,72	28,20	27,68	28,09	27,98
	0,012	**0,23**	**0,22**	**0,19**	**0,17**	**0,18**	**0,20**	**0,20**
After 400°C wear	2,620	27,72	28,10	27,53	28,00	27,49	27,91	27,79
	0,012	**0,18**	**0,17**	**0,19**	**0,20**	**0,19**	**0,18**	**0,18**
After 500°C wear	2,595	27,16	27,67	27,08	27,67	27,13	27,64	27,39
	0,025	**0,56**	**0,43**	**0,45**	**0,33**	**0,36**	**0,27**	**0,40**
Sum wear	**0,058**	**1,16**	**1,02**	**1,06**	**0,96**	**0,95**	**0,86**	**1,00**

	100°C	200°C	300°C	400°C	500°C
Mean wear (kg)	**0,006**	**0,006**	**0,011**	**0,014**	**0,027**
Mean wear (mm)	**0,15**	**0,10**	**0,19**	**0,19**	**0,40**

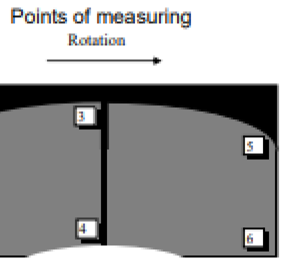

Figure A.4: Rear brake pad wear used for the exponential fit

B

Appendix 2

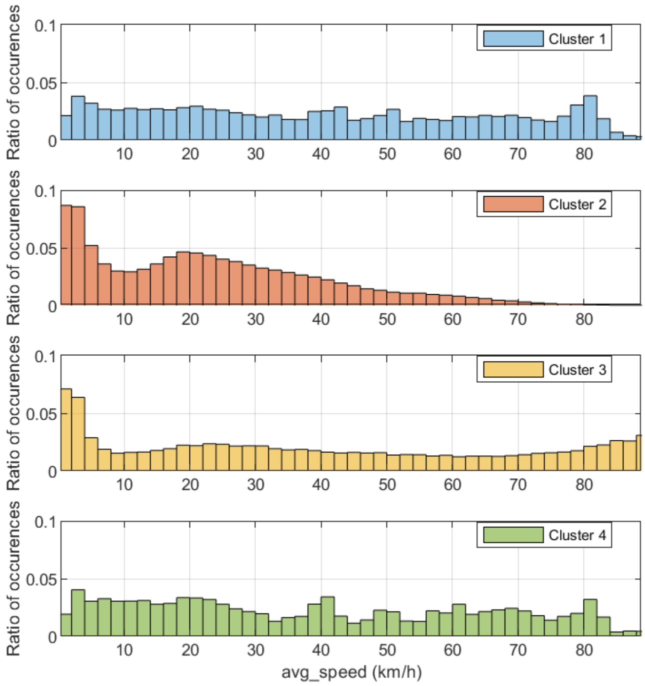

Figure B.1: Histogram of the average speed for the 4 clusters.

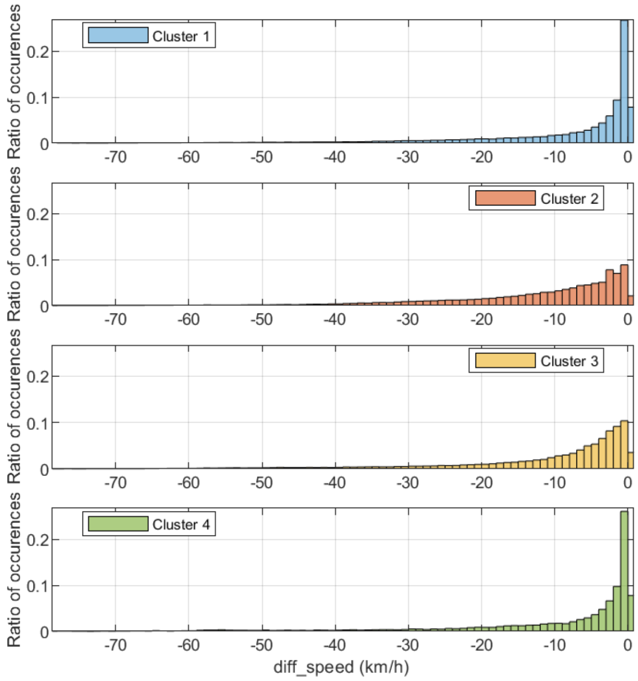

Figure B.2: Histogram of the change in speed during braking for the 4 clusters.

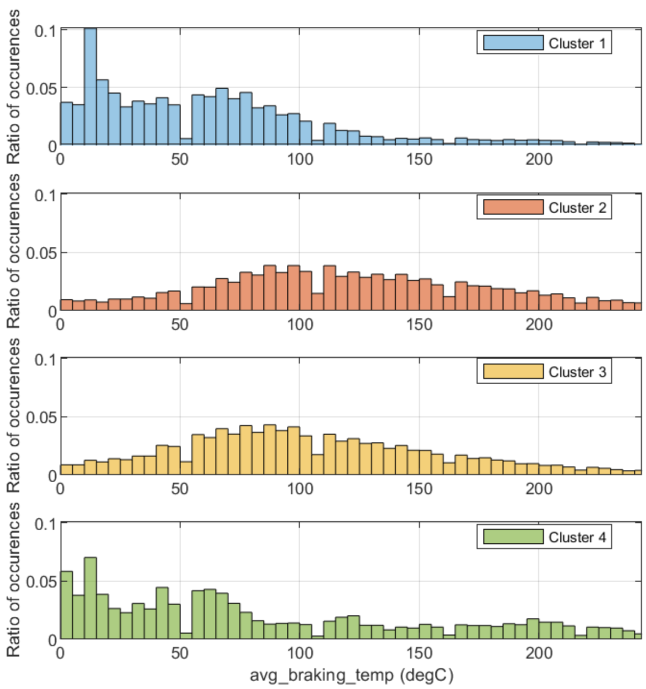

Figure B.3: Histogram of the average brake temperature in °C for the 4 clusters.

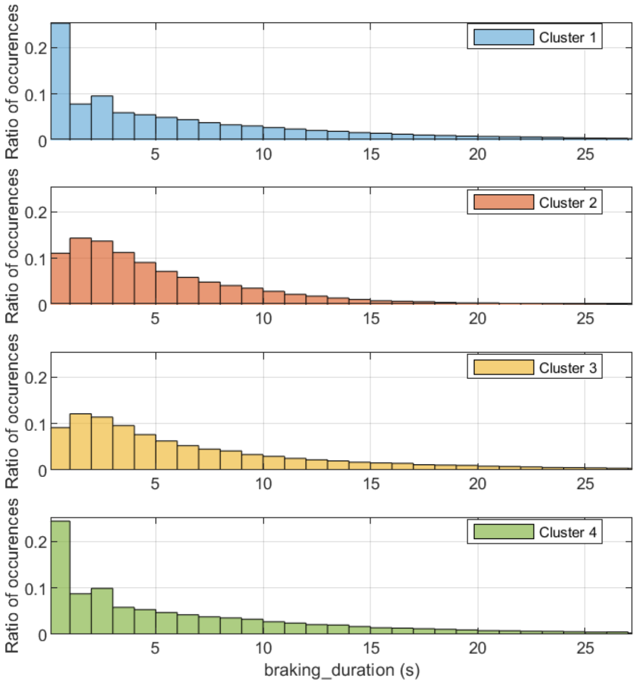

Figure B.4: Histogram of the braking duration in seconds for the 4 clusters.

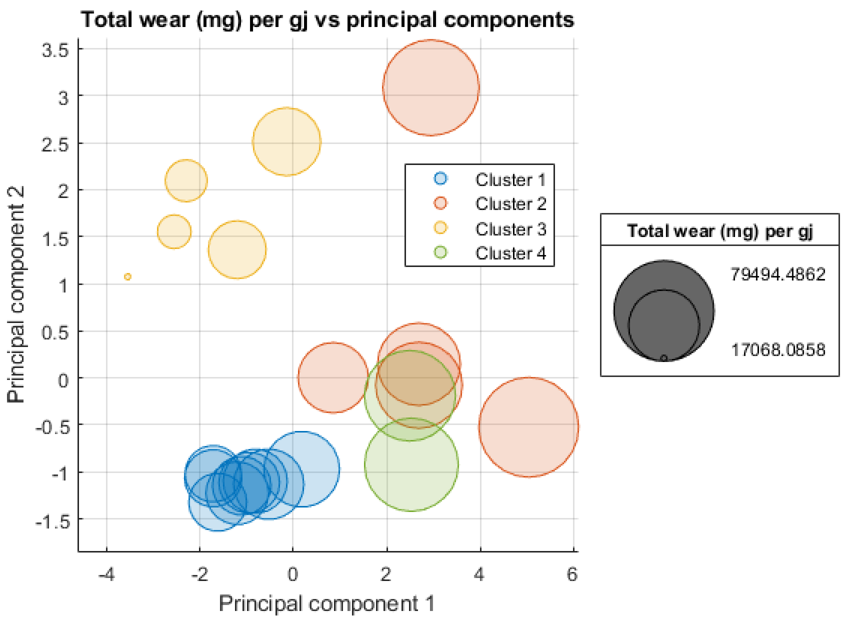

Figure B.5: Bubble plot of each clusters with respect to principal components and wear per braking energy.

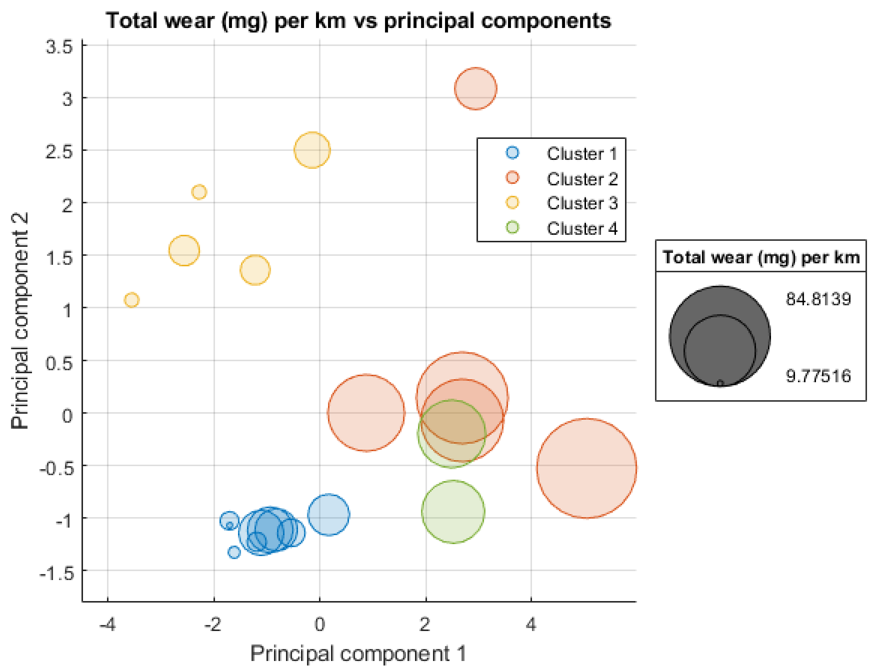

Figure B.6: Bubble plot of each clusters with respect to principal components and wear per km driving distance.

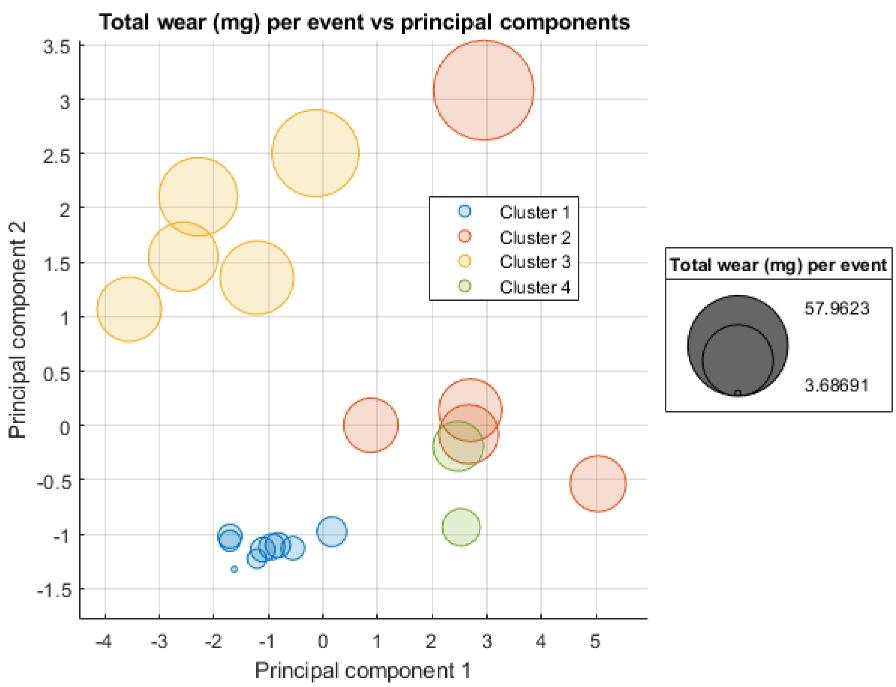

Figure B.7: Bubble plot of each clusters with respect to principal components and wear per number of braking event

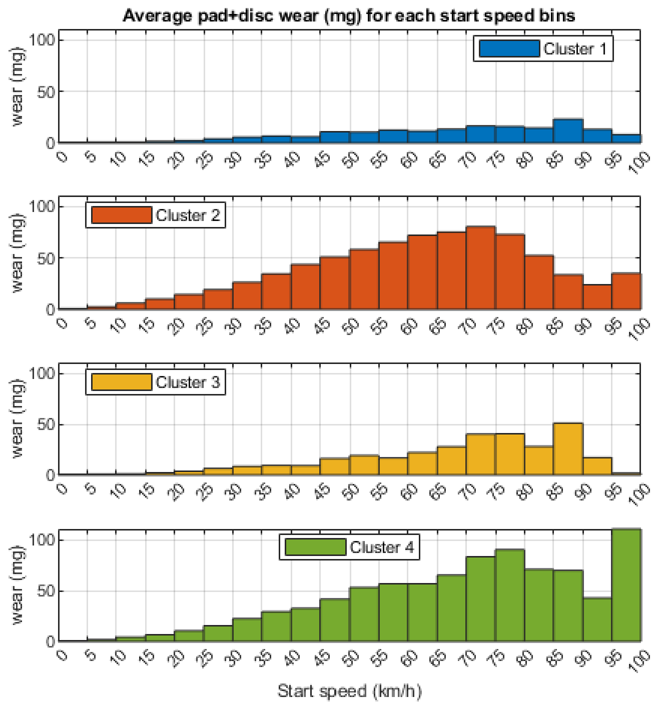

Figure B.8: Pad and disc wear average with respect to braking start speed.

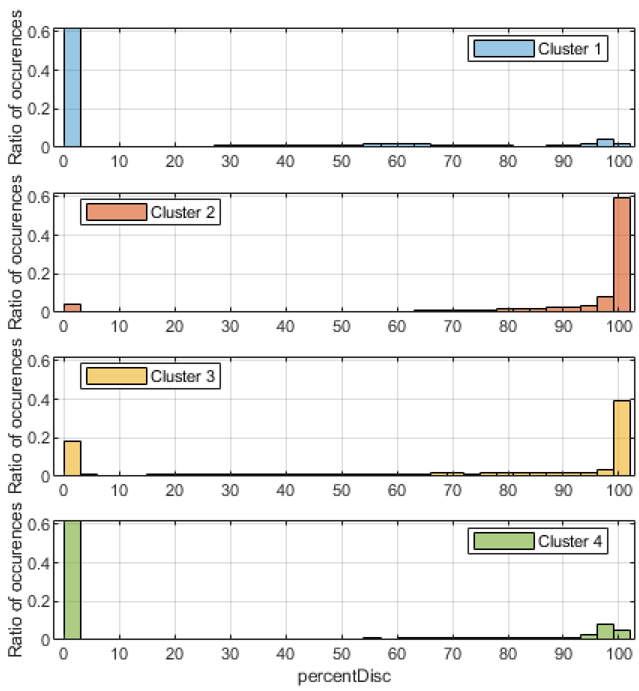

Figure B.9: Histogram of the percentage of disc usage during braking.

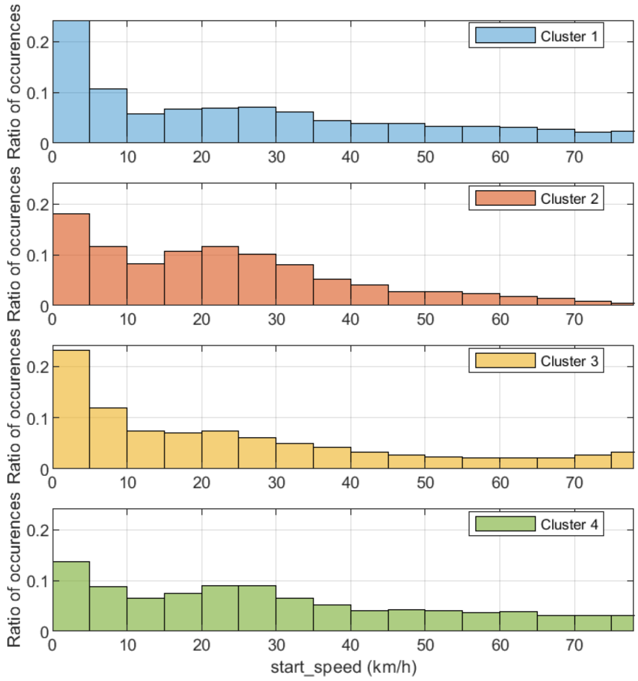

Figure B.10: Histogram of the speed at the start of a braking event with high disc usage.

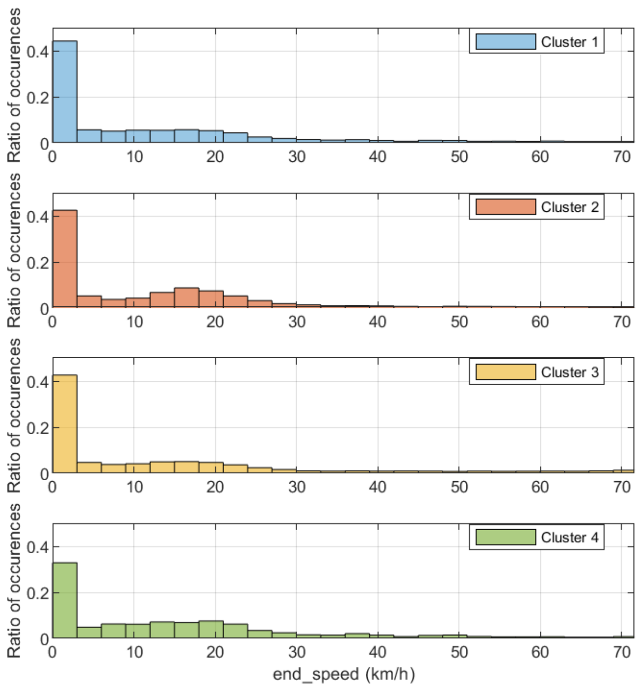

Figure B.11: Histogram of the speed at the end of a braking event with high disc brake usage.

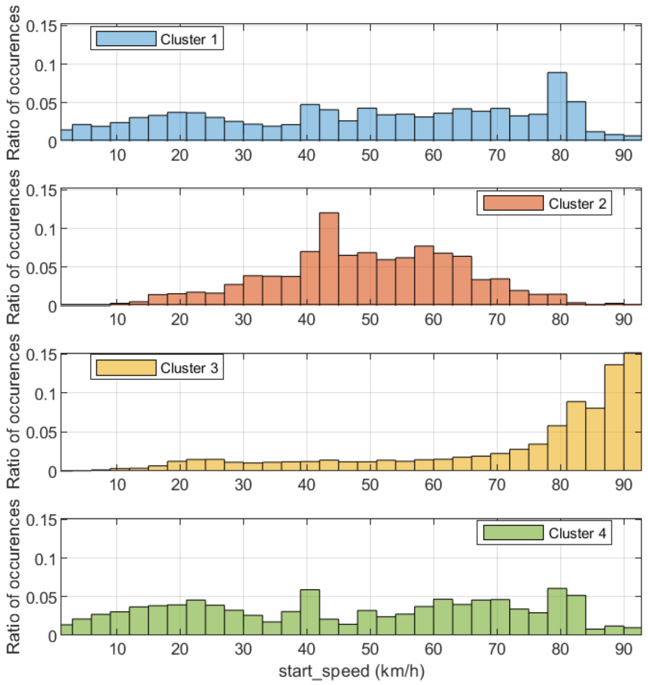

Figure B.12: Histogram of the speed at the start of a braking event with high auxiliary usage.

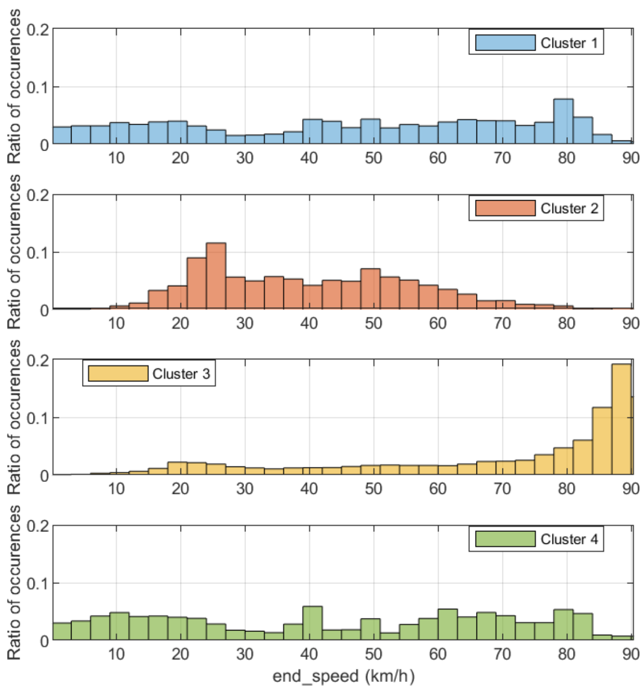

Figure B.13: Histogram the speed at the end of a braking event with high auxiliary usage.

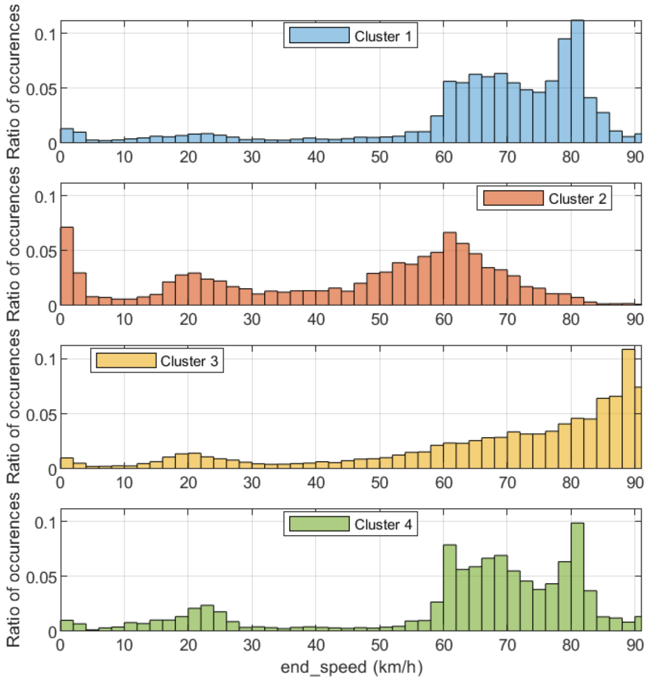

Figure B.14: Histogram of the speed at the end of braking events where the start speed is above 60 km/h.

DEPARTMENT OF MECHANICS AND MARITIME SCIENCES
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden
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