

## Measuring the Influence of Wet Pavement to Energy Consumption

Tests Conducted with Volvo Cars Battery Electric Vehicle EX90

Master's thesis in Mobility Engineering

Erik Olzon  
Gabriel Sarnacki

Department of Mechanics and Maritime Sciences



MASTER THESIS 2025

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**CHALMERS**

Department of Mechanics and Maritime Sciences  
CHALMERS UNIVERSITY OF TECHNOLOGY  
Gothenburg, Sweden 2025

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Cover: Illustration of how one of the tests looked like and where the WFT sensor was placed on the vehicle. Distances are not to scale.

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## Abstract

This report presents the outcome of this master's thesis project carried out at the Department of Mechanics and Maritime Sciences at Chalmers University of Technology during the spring of 2025.

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The automotive industry has been striving for improved energy efficiency to offer customers longer range, more sustainable means of transportation and to cut down on  $CO_2$  emissions. The introduction of electric driveline greatly improves driveline efficiencies. However, since battery electric vehicles (BEV) have such high efficiency, other factors have become more prominent in energy consumption. This includes driving on a wet road surface which can lead to significantly higher rolling resistance. Since rolling resistance is one of the two main external energy sinks in BEVs, besides aerodynamic drag, it is very important to address tire rolling resistance especially when driving on wet pavement. Some old data is available in the literature on how rain affects rolling resistance and energy consumption, but the fact that measurement technique and tires have evolved there is a need to gather new data for modern BEVs and state-of-the-art tires.

The master thesis composed of a 6 month project at Volvo Cars to research and test the impact wet surfaces have on a BEV's energy consumption. The tests were done at Hällered Proving Ground using an all wheel drive (AWD) EX90 as test vehicle driving on different amount of wet roads. The water film thickness (WFT) were measured as well as power from the inverter and vehicle dynamics parameters. The two main test categories to assess the impact were: Coast Down & Constant Speed.

The result concluded that WFT increases the rolling resistance. Often the increase in total resistance was at least 5% higher. For very wet roads, the resistance is around 6% higher at low speeds (30 km/h) and around 11% higher at high speeds (120 km/h) indicating some speed dependence at high WFT. Lastly, a proposed model was introduced where WFT was it's own variable meaning that knowing the WFT the road load can be estimated for that particular vehicle. However, the results for having WFT as it's own variable to road load are not strongly correlated.

**Keywords:** Rolling resistance, RRC, water film thickness, wet, wetness, tires, coast down, Battery Electric Vehicle, BEV, Vehicle Energy Efficiency, vehicle, efficiency,

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Mätning av våta vägbeläggningars inverkan på energiförbrukningen

Mobilitetsteknik

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## Sammanfattning

Denna rapport presenterar resultatet av detta examensarbete, som genomfördes vid Institutionen för Mekanik och Maritima Vetenskaper vid Chalmers tekniska högskola under våren 2025.

—

Bilindustrin har strävat efter att förbättra energieffektiviteten för att erbjuda kunder längre räckvidd, mer hållbara transportmedel och för att minska utsläppen av  $CO_2$ . Introduktionen av elektriska drivlinor har avsevärt förbättrat drivlinans verkningsgrad. Eftersom batterielektriska fordon (BEV) är så effektiva har andra faktorer blivit mer framträdande i energiförbrukningen. En sådan faktor är körning på våta vägbanor, vilket kan leda till betydligt högre rullmotstånd. Eftersom rullmotstånd är en av de två huvudsakliga externa energiförlusterna i BEV – utöver luftmotstånd – är det mycket viktigt att beakta däckens rullmotstånd, särskilt vid körning på vått väglag. Det finns viss äldre data i litteraturen om hur regn påverkar rullmotstånd och energiförbrukning, men eftersom mätteknik och däck har utvecklats finns det ett behov av att samla in ny data för moderna BEV och den senaste däcktekniken.

Examensarbetet bestod av ett sex månader långt projekt hos Volvo Cars där syftet var att undersöka och testa hur våta vägytor påverkar ett BEV:s energiförbrukning. Testerna genomfördes på Hällered Proving Ground med en fyrhjulsdriven (AWD) EX90 som testfordon, körandes på vägavsnitt med varierande våta. Vätskefilmens tjocklek (WFT) mättes, likaså effekt från växelriktaren och parametrar relaterade till fordonsdynamik. De två huvudsakliga testkategorierna för att utvärdera effekten var: Coast Down och Konstant Fart.

Resultaten visade att ökad vattenfilmstjocklek leder till högre rullmotstånd. Ofta var ökningen av det totala motståndet minst 5%. Vid mycket våta vägar var motståndet cirka 6% högre vid låga hastigheter (30 km/h) och cirka 11% högre vid höga hastigheter (120 km/h), vilket indikerar ett visst hastighetsberoende vid höga WFT-nivåer. Slutligen presenterades en föreslagen modell där WFT användes som en egen variabel, vilket innebär att om vattenfilmstjocklek är känd kan vägmotståndet uppskattas för det aktuella fordonet. Dock visade resultaten att sambandet mellan vattenfilmstjocklek och vägmotstånd inte är starkt korrelerat.

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**Nyckelord:** Rullmotstånd, RRC, vattenfilm, tjocklek, vått, blött, däck, utrullning, batterielektriskt fordon, elbil, fordonsenergieffektivitet, fordon, effektivitet

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# List of Acronyms

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

ADAS	Advanced Driver Assistance Systems
AWD	All Wheel Drive
BEV	Battery Electric Vehicle
CD	Coast Down
CS	Constant Speed
IR	Infrared
RRC	Rolling Resistance Coefficient
WFT	Water Film Thickness
VEE	Vehicle Energy Efficiency (department)



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# 1

## Background

The automotive industry has always been striving for improved energy efficiency to offer customers longer range and higher power output. Sustainability has also become a factor to increase the morale among customers and achieve the Global Agenda by 2030 by reducing  $CO_2$  emissions [5]. The introduction of BEV's has greatly improved drive-line efficiencies, which means that other factors have become more prominent in energy consumption. Factors include driving style, weather, and the use of auxiliary accessories such as heating and cooling. Driving in rainy conditions or on a road surface covered by rainwater can lead to significantly higher tire rolling resistance [1]. Since tire rolling resistance is one of the two main external energy sinks in BEVs, besides aerodynamic drag, it is very important to address tire rolling resistance, more specifically rolling resistance and tire dynamics on wet pavement. Outdated data is available in literature on how rain affects rolling resistance and energy consumption, but since the data is relatively old and the fact that there are new measurement tools and more modern tires, there is a need to gather new data for modern BEVs and state-of-the-art tires. A better understanding of how BEV energy consumption is affected by driving in rainy conditions and on wet roads is important to accurately predict the remaining driving range, time of arrival at the destination, as well as planning of charging stops, in real-world customer conditions.

There is currently a gap between ideal certification conditions and real-world scenarios in BEVs when it comes to expected range, battery consumption and RRC.

### 1.1 Purpose

This project was conducted by two students doing their master thesis at Volvo Cars AB. Their background is in Mobility Engineering (Mechanical engineering) at Chalmers University of Gothenburg, Sweden.

The thesis was associated with Volvo Cars Vehicle Energy Efficiency's department ongoing research to increase the knowledge of how rain-covered road surfaces, affect tire rolling resistance and thus BEV energy consumption and range. To gain a better understanding of this phenomena, physical testing was performed at Volvo Cars testing facilities using a Volvo EX90 data acquisition vehicle with the capability to measure thousands of internal signals.

"How does wet pavement contribute toward overall energy consumption on passenger vehicles?" is the question this thesis project hopes to answer using a real world driving environment and quantifiable test results. Focusing on rolling resistance on wet surfaces contributing towards energy consumption this thesis aims help Volvo Cars narrow the gap and increase customer satisfaction.

## 1.2 Objectives

The objectives of this thesis:

- Understand how a post-rain covered surface water film thickness (WFT) affects the energy consumption using real world testing scenarios. This includes:
  - Perform a literature study of previous relevant research and apply knowledge to develop a suitable test environment.
  - Prepare and set-up vehicle testing on a test track using dry and wet conditions.
  - Analyze the test results to quantify the effect of rain on wet roads regarding EV energy consumption.

## 1.3 Stakeholders

The findings from this project will help to broaden the understanding of how wet pavement affects vehicle motion resistance and road load. The stakeholders in Table 1.1 will be impacted the most by the findings, to therefore make better decisions in the future for mobility.

Table 1.1: *Volvo Cars Stakeholders*

Stakeholders at Volvo Cars
Vehicle Energy Efficiency team
Road Load and Verification team
Vehicle Contamination team
Vehicle Motion and Control team
Tire team
Support team

## 1.4 Delimitations

The project will not cover:

- Using existing measurement tools available to quantify the water film thickness, only . Meaning that the measurement method to quantify WFT will be regarded as

correct.

- Exclude physical rain scenario due to possible impact on vehicle aerodynamics and added resistance that might be hard to quantify.
- Dividing the water effect on road load into several components. That is, it's assumed that WFT and velocity are the only two parameters contributing to road load. The water resistance isn't split up into cooling down of tire, splashing water etc.
- Tire temperature was planned to be incorporated in post processing results, before testing. Unfortunately the battery life in the tire sensors was depleted. Only one sensor provided results, leading to insufficient data and the tire temperature was omitted from the report.

## 1.5 Learning outcomes

1. Demonstrate an understanding of tire rolling resistance and energy consumption in BEVs, and relate this knowledge to current research on rolling resistance and the effect of road surface conditions on propulsion efficiency.
2. Justify the selection of Coast Down and Constant Speed testing methods based on their relevance to quantifying real-world energy impacts in wet driving conditions.
3. Contribute research in BEV technologies by evaluating how environmental variables (e.g., road wetness, tire temperature) influence efficiency, and relate the results to scientific and industry efforts in mobility.
4. Critically and creatively address the complex challenge of measuring real-world energy consumption by incorporating multi-variable dependencies (speed, wetness, temperature) into a generalized road load equation and assessing its practical implications.
5. Identify the ecological implications of increased rolling resistance in wet weather—such as range loss, safety, and infrastructure planning.
6. Recognize areas of uncertainty in the project, such as the varying levels of wetness and the accuracy of torque estimation methods, and recommend directions for future applications.

# 2

## Theory

This chapter introduces preliminary in-depth literary information about water film thickness (WFT), rolling resistance, sensors using IR spectroscopy, industry certified coast down procedure. These topics are helpful to understand the direction of the thesis work.

### 2.1 Terminology of Wet Pavement

When rain falls on a pavement surface, a water film thickness (WFT) forms. Some researchers, such as Chesterton et al., have used the terms WFT and total water flow thickness ( $y$ ) interchangeably [6]. Others, like Gallaway et al., define WFT strictly as the thickness of the water layer on top of the pavement texture [7].

To maintain clarity and avoid further confusion, this report adopts the definition used by the developers of PAVDRN [8, 9]. According to this definition, the total water flow thickness ( $y$ ) is measured from the bottom of the pavement texture, while WFT is measured from the top of the pavement asperities, typically defined using Mean Texture Depth (MTD) or Mean Profile Depth (MPD). This distinction is illustrated in Figure 2.1.

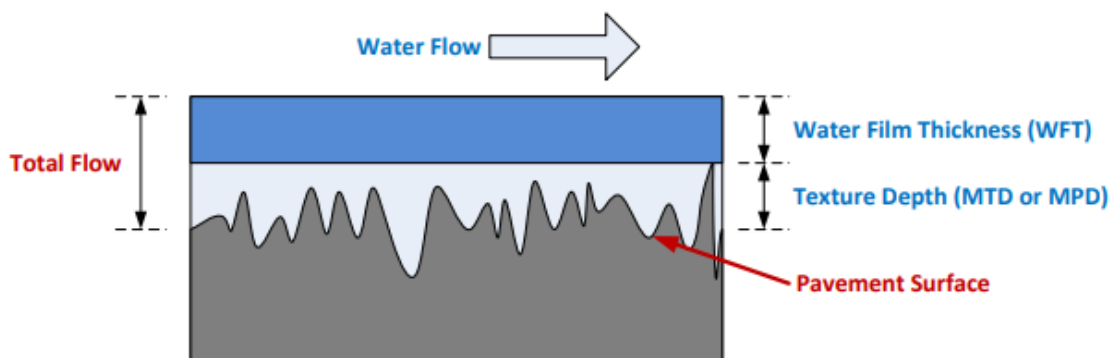


Figure 2.1: Definition of water film thickness, mean texture depth, and total flow

The pavement surface can be classified as either moist or wet, depending on the water layer thickness. A moist pavement has a thin water layer, whereas a wet pavement has a significant water layer that can lead to water splashing and potentially hazardous driving

conditions.

## 2.2 Effect of Water on Rolling Resistance

Previous literature studied on the effects of wetness on rolling resistance by Annelie Carlson and Tiago Vieira has proven that wetness on the road contributes to rolling resistance through various sub-components. [1] This includes decreasing tire temperature, affecting the viscoelastic properties in the rubber compounds, also displacing the water away from the tire path. Understanding the physics of these forces helped to identify a test plan that can accommodate appropriate water layer thickness, while monitoring changes in surface temperature to identify how much the water layer acts as an energy sink.

The following is an excerpt on how water effects rolling resistance “Water on the road surface has noticeable effects on the functional aspects of the road surface, which includes rolling resistance. When a tire rolls over a wet road, it must displace water before making direct contact with the texture of the road surface. Rolling resistance on wet roads is affected by the volume of water, which is determined by the water depth, the width of the tire and the speed of the tire” [10] .

“Figure 2.2 illustrates a tire on a dry road surface. The tire rolls at an angular velocity  $\omega$  and the corresponding linear velocity  $v$ . The normal force,  $F_N$ , presses the tire against the road surface and initiates a contact pressure over that contact length  $L_C$ .  $F_T$  is the total braking force equal to the rolling resistance plus the air resistance,  $F_T = F_R + F_L$ ” “When the tire rolls on a wet road surface at the same speed, the rolling resistance force is affected by the water film, which is shown in Figure 2.2. There, the rolling resistance effect is described as a braking force against the movement of the tire. To make it clearer, the rolling resistance is divided into different sub-components. An alternative, more comprehensive description of rolling resistance could be made by means of a division into energy components. The water depth also affects the tire’s deformation, which leads to a changed contact surface between the tire and the road surface.” The power balance will then be affected by an extra force due to water,  $F_v$ . Total forces will be:  $F_T = F_R + F_L + F_V$  [1] Thus, it is possible to calculate the effects of the water by comparing rolling resistance measurements made on dry road surfaces with those made on wet road surfaces.” [1].

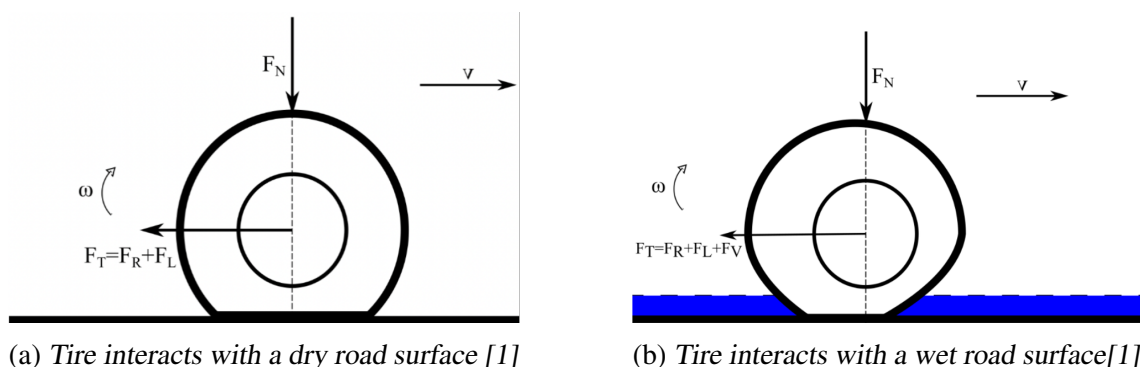


Figure 2.2: Difference in tire deformation from dry surface compared to wet surface

"Since rolling resistance in water is affected by water volume at the contact surface between road and tire, the width of the tire's contact surface and speed play an important role. Gengenbach (1967) has measured rolling resistance in water by comparing results from dry and wet surfaces. The result is shown in part in Figure 2.3 and applies to a tire with a landing width  $b=14$  cm, water depth between 0.2 and 2 mm and speeds between 5.6 and 19.4 m/s (20 and 70 km/h). The measurements were made in a stationary state." [1].

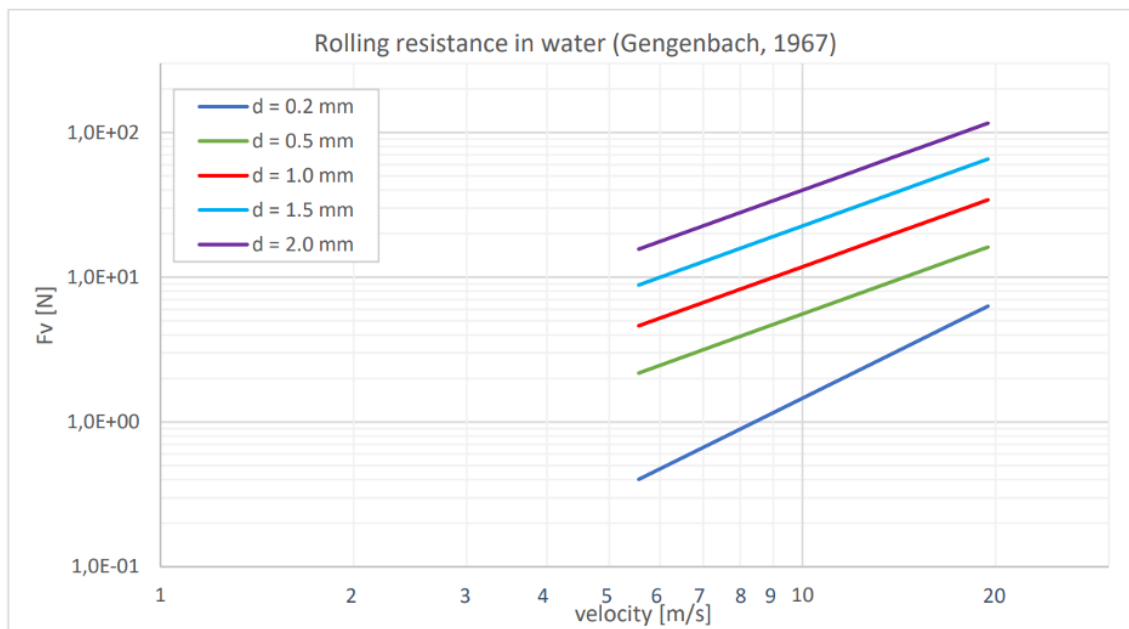


Figure 2.3: *Rolling Resistance increases with depth of water film thickness according to Gengenbach 1967 [1]*

From Geigenbach it was found that rolling resistance had already been tested in water using a "controlled environment" with a controlled water level. However those results explained tire dynamics and rolling resistance only. [11]

## 2.3 Sensor: Road Condition Monitor



Figure 2.4: A picture of the road condition monitor and how it might be mounted on the vehicle

Teconer supplies an IR detection laser that can identify different types of contamination on a road surface such as water, snow, ice. For the purposes of the thesis the RCM511 and RTS411 (temperature) was used to detect water film thickness. Correspondence between the VEE department and Teconer took place in order to establish an understanding of how the sensor interpreted a specific depth along the pavement. As seen in the figure ?? a closeup view of pavement shows that there are peaks and valleys and the surface roughness is not simple and flat. Teconer defines a “base level” of measurement for their contamination detection technology, as the average between “instantaneous” max peaks and min valleys. They described the laser signal “determined as a loss of signal compared to dry surface and the loss is due to passing a water layer. It is the “average distance” what the sensors sees, since the reflection is coming from a spot of a few centimeters.” [12].

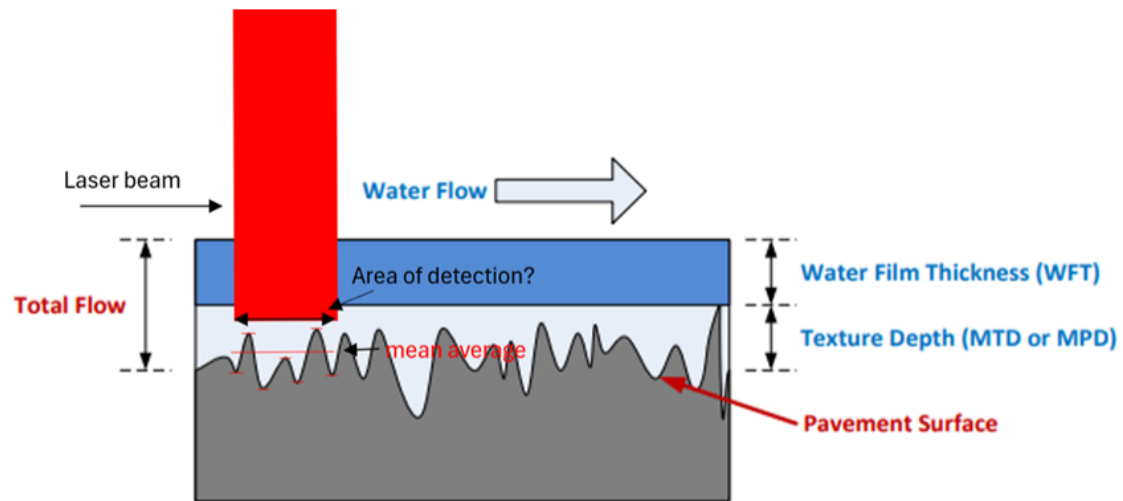


Figure 2.5: Illustration on how the road condition monitor measures the WFT

The sensor we used to detect the water film thickness was essential to our project and identifying a water film layer. The following specifications are presented on Teconer RCM511 brochure available on their website “Road Condition Monitor RCM511 is designed for a quality control and optimization tool for winter maintenance. The RCM511 sensor also measures water layer thickness in fractions of millimeters up to 5 mm.” [13].

- Temperature range: -40 ... 60 °C [13]
- Resolution of thickness: 0.01 mm, detection limit 0.03 mm, 0.03 mm to 5 mm [13]
- Accuracy of thickness: 0.10 up to 1.0 mm, 10 % above 1.0 mm [13]

To substantiate the sensor’s accuracy, we explored research performed by Teconer’s CEO Taisto Haavasoja using this technology. Here he is explaining a laboratory test using an older model of the RCM sensor. “The sensor is called Road Condition Monitor RCM411 and it is based on optical detection of surface condition by near infrared spectroscopy” [2]. The following is a lab test performed to explain the accuracy in detecting water layer thickness.

"Figure 2.5 shows a laboratory test of water layer thickness. A small area on a test piece of asphalt was separated by a barrier and fixed amounts of water were added over this area. The x axis shows the actual calculated thickness of water layer and the y axis the response of the RCM411 in millimeters from 0 mm to 3 mm. The resolution limit of detection is on the order of about 30  $\mu\text{m}$  which corresponds to thinnest layers of ice able to reduce friction a measurable amount (8). The upper limit at about 3 mm is caused by increasing absorption with thick layers." [2].

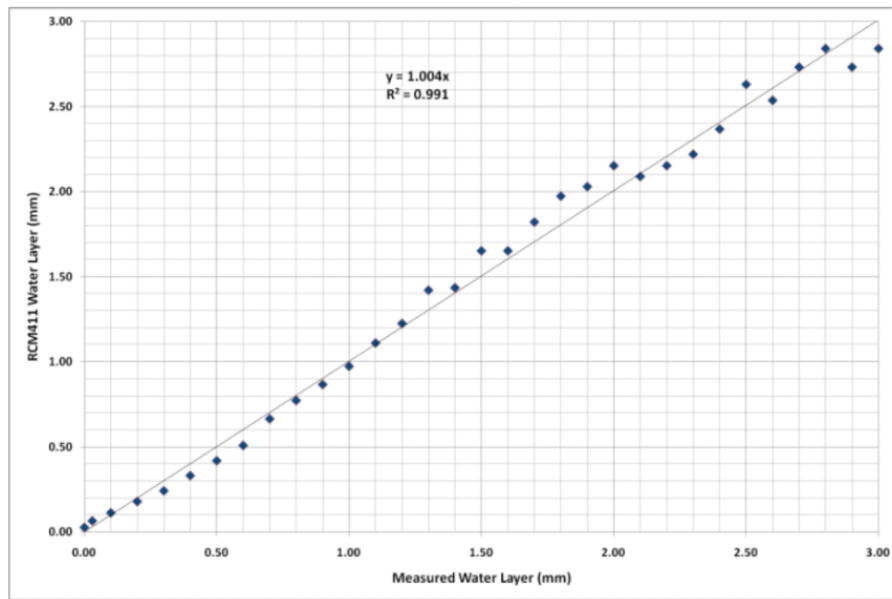


Figure 2.6: RCM411 performance in measuring thickness of water layer[2]

## 2.4 Infrared Spectroscopy

Before proceeding with using the suggested Teconer RCM 511 and RTS411 sensors, a literary research deep dive was necessary to define IR spectroscopy and how common it is used to ensure proven results. From the following, it was substantiated that using IR spectral intensity is a "non-contact" way to measure WFT.[3]

Categories of detection method	Principle of detection method	Advantage	Disadvantage	Scope of application
Spectral intensity detection technology	The high-precision laser sensor is used to perform spectral analysis on the road surface material, which is divided into emission spectrum and absorption spectrum; the measured data is processed by software to obtain the average WFT in the area	Strong environmental adaptability, simple equipment installation, long detection distance, and high measuring range	Overcomplicated instrument structure and technical confidentiality is not easy to promote	It is suitable for road condition identification and WFT measurement of highway and bridge covered by ice, snow and water

Figure 2.7: Table 2 Summary of non-contact pavement WFT detection methods. [3]

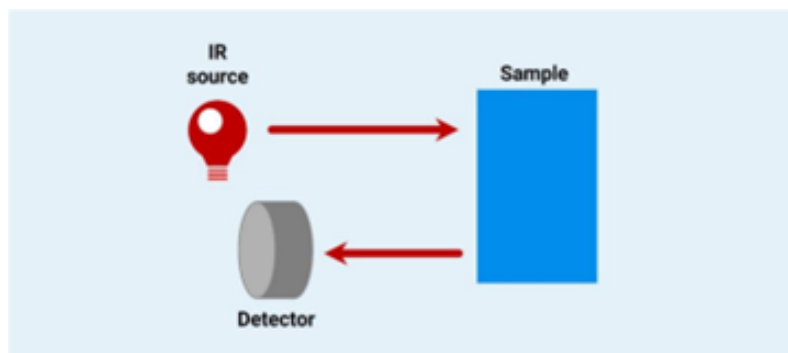


Figure 2.8: Visual of IR Spectroscopy

Sourcing from Bruker's product website "Guide to FT-IR Spectroscopy" they state that "With this technique (reflection), the IR light that is reflected off the surface of the sample is detected rather than the IR light that passes through the sample. This makes Reflection IR Spectroscopy useful for examining solid samples that are difficult or impossible to analyze with transmission or ATR. There are many ways to perform Reflection IR spectroscopy depending on the sample being analyzed." [14].

Figure 2.8 shows how the test vehicle and IR sensor operated during testing. When there was a water film present the sensor would detect a "signal loss" passing through the water.

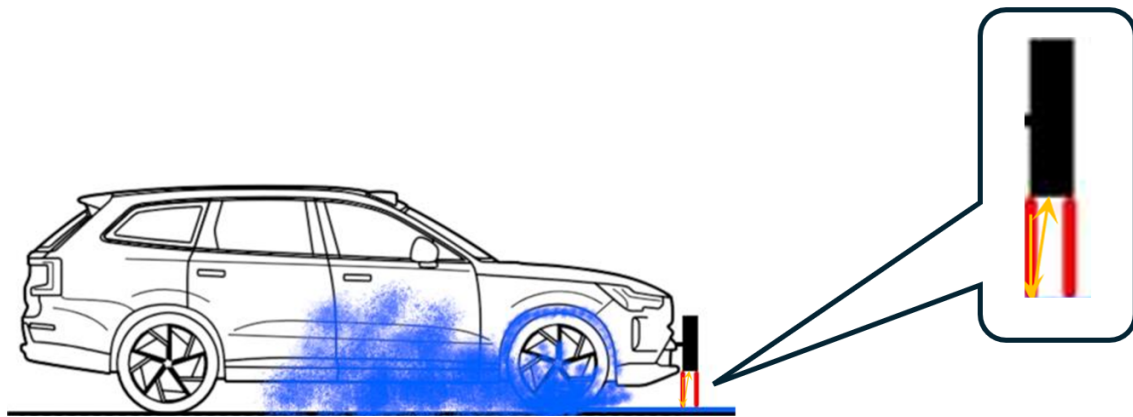


Figure 2.9: Illustration of how the sensor is detecting WFT during testing

## 2.5 SAE Specified J2263/J2264 Road load and Coast Down Test Procedure

"The coastdown test procedure is used to measure the coefficients required to model drag forces and ultimately determine the road load force coefficients for calculating the vehicle's final road load. The procedure begins by accelerating the vehicle to a desired speed. Once stabilized, the transmission is shifted to neutral, allowing drag forces to be the sole cause of deceleration. The rate of deceleration, as a function of vehicle speed and time, is measured periodically." [15] (often 10km/h interval). Refer to Figure 2.11 for a standard road load report. The road load is the thrusting force required to maintain a constant speed at a given speed. The road load is speed-dependent mainly due to aerodynamics.

In that way, the road load can be estimated by knowing some deceleration forces at a specific speed and then using a regression model to generalize the speed dependence. An advantage of a CD is that many forces can be neglected, such as powertrain efficiencies. If the gradient of the test track is known, then that effect can also be canceled out. Figure 2.10 shows how different forces may be acting on a moving vehicle:

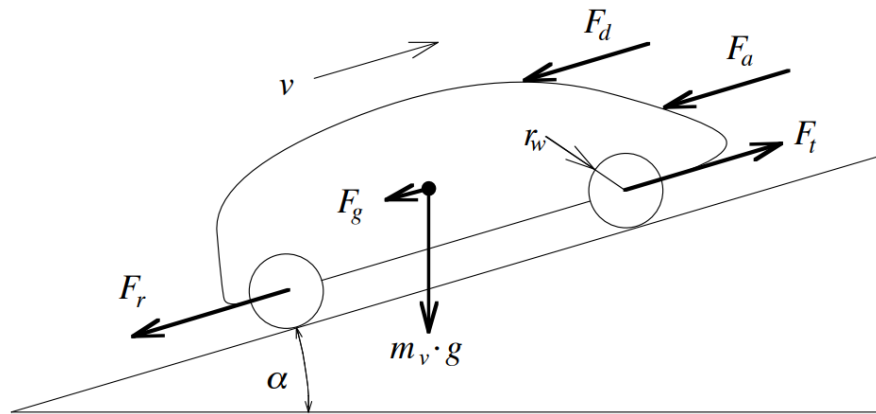


Figure 2.10: Schematic representation of the forces acting on a vehicle in motion

The procedure measures the time for the vehicle to decelerate from a higher velocity to a lower velocity (often 10km/h interval). This is commonly done on a straight path with no interruptions. According to specification documents SAE J2263/J2264, if a long straight path is unavailable, it is appropriate to use a shorter distance and split up the CD into different speed sections. The CD is also driven in both directions to cancel out eventual benefits of going in one direction (such as wind direction). From here, the averaged deceleration can be calculated for the velocity in the middle of the interval.

$$\frac{v_1 - v_0}{t_1 - t_0} = \frac{\Delta v}{\Delta t} = a_{avg}$$

Knowing the vehicle's mass, the averaged force can be calculated through Newton's third law. Finally, a linear regression using the averaged speeds and forces is made. From here  $F_0$ ,  $F_1$  and  $F_2$  can be obtained.

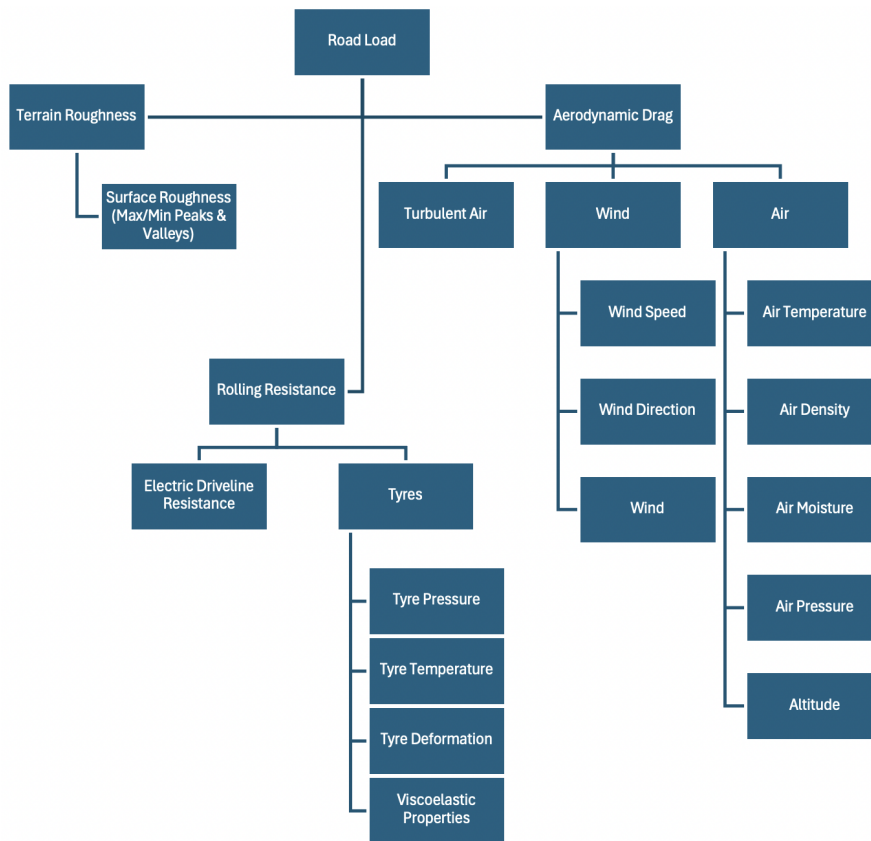
$$(M + m_r) \cdot a = F_{\text{rolling}} + F_{\text{air-drag}} \approx F_0 + F_1 \cdot v + F_2 \cdot v^2$$

Where:

$M$ :	Vehicle mass [kg]
$m_r$ :	Rotational inertia (3% of $M$ ) [kg]
$a$ :	Acceleration [ $\text{m/s}^2$ ]
$v$ :	Velocity [km/h]
$F_0, F_1, F_2$ :	Road-load coefficients

CD tests are normally performed using a long constant distant. CD tests are not usually performed "under special circumstances" meaning the track's "straight portion" is shorter compared to a "normal" coast down procedure. When using a "shorter" distance, the CD divides up into a number of speed sections and is also driven in both directions of the track, balancing the effect of wind.



Figure 2.12: *Different contributions to road load*

## 2.7 Calculating Power to Road Load

For obtaining road load from CD tests only speed and time is necessary. However, the road load could also be calculated by calculating the thrusting force from the inverter. This gives more opportunity for measuring the road load. The difference is that more parameters are needed to obtain the road load. First, power has to be calculated and gradient, acceleration and efficiency must be known. If a test procedure could be done under certain circumstances such as constant speed, no gradient and 100% efficiency, then there are two main ways to calculate the battery power from an EV to road load:

$$F = \frac{P}{v} = \frac{U \cdot I}{v} \text{ or } F = \frac{P}{v} = \frac{T \cdot \omega}{v}$$

where:

- $P$ : Power [W],
- $v$ : Vehicle speed [m/s],
- $U$ : Voltage [V],
- $I$ : Current [A],

- $T$ : Torque [Nm],
- $\omega$ : Angular velocity [rad/s].

# 3

## Methodology

The methodology chapter explains how the physical testing was developed, resources used, and the action taken to perform the tests. It also includes how the theoretical research was incorporated to develop the live action practical testing.

The proposed testing was to perform Coast down and Constant Speed using a realistic setting, in order to simulate a wet surface that experienced rainfall. The testing was performed at Volvo Cars Hällered Proving Grounds providing a proper realistic setting; including a "normal" surface (pavement), varying temperature of the pavement (solar radiation), outdoor environment (accounting for air moisture, wind conditions). The planned testing used a certain duration on a dry surface for reference, then use the provided water truck to deploy water at varying speeds to accumulate varying amounts of water on the surface. The water would only be applied on the straights of the track, to simulate a usual (CD) which uses a long straight path, we excluded the corners due to track design, the corners were elevated therefore there would be increased resistance and interrupt the values on the straights. The "dry cornering" logged data could then be removed in post-processing. Then perform the same CD and CS tests with different WFT on the pavement. The expectation was that there would be added resistance on the vehicle to displace the water, hence increasing the propulsive forces used by the vehicle to pass through the water and increasing the energy.

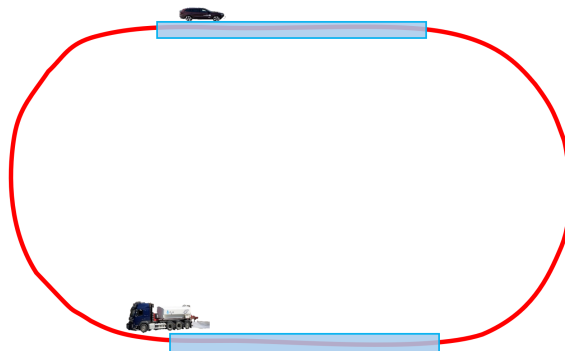


Figure 3.1: *Illustration of water deployed from water truck (blue) during coast down at high speed track*

### 3.1 Determine a Testing Method

The test method was chosen in advance to make data collection more efficient and to ensure the results could support the aim of the thesis. The experimental test setup for the proposed options was planned in collaboration with data acquisition team at Volvo Cars and Hällered proving grounds facility. The test methodology was determined based on a cost benefit analysis which was weighing the positives against the negatives. This included, for example, feasibility and accuracy. 5 different testing methods were purposed in table 3.1 with corresponding positives and negatives:

Table 3.1: Comparison Between Possible Testing Methods

	Coast down	Constant Speed	Public Roads (Constant Speed)	Big Fleet Data	Wind Tunnel
<b>Positive</b>					
+	Neutral gear	More points at certain speeds (robust)	More data	Big data	WFT controlled
+	Covers all speeds	Flexible	Real-world conditions		Possible to exclude wind (only measure RRC)
+	Hällered	Hällered			
<b>Negative</b>					
-	Long test duration	$F_x$ accuracy issues	$F_x$ accuracy issues	$F_x$ accuracy issues	$F_x$ accuracy issues
-	Constrained setup	Difficult to maintain constant speed	Difficult to maintain constant speed	Difficult to maintain constant speed	Possible (?)
-		Engine warm-up required	Uncontrollable factors	No WFT!!!	Not real-world conditions
-			Limited range (below 130 km/h)	Lack of knowledge	No pavement
-			Other traffic interference	Other traffic interference	
-				Uncontrollable variables	

- **Coast down (CD):** Conducting coast down tests on wet surfaces to measure the deceleration at different velocities and then calculate road load. It will start with a reference CD on dry pavement. Then perform more CDs at varying wetness levels (The WFT will be measured with Teconer). This test would be performed at Hällered due to size of test track and feasibility.
- **Constant speed (CS):** The test vehicle will drive at varying constant speeds with different levels of wet surfaces to measure the increased resistance. The resistance is measured through the power to the inverter and then converted to force. This test would be performed at Hällered due to size of test track and feasibility.
- **Data Acquisition Vehicle (EX90):** An inner fleet vehicle that has a Teconer RCM511 sensor rigged on the front bumper. The data is then used to approximate how the WFT affects energy consumption. A positive is that the vehicle is constantly driving in various locations meaning there is a lot of fresh and realistic updated data provided. A negative aspect would be the external factors that is hard to filter out and differentiate towards the wetness resistance (such as vehicles driving in front of the test vehicle which interferes with the aerodynamics data or the uncertainty of external wind speed and direction).
- **Fleet Big Data Analysis:** Same procedure as the Data Acquisition vehicle except more vehicles to obtain data from. The difference is that there has to be a way to approximate the WFT or assume the wetness on the road and how that may impact the power consumption.
- **Wind Tunnel:** Mount the car in the climate wind tunnel and spray water directly in front of the tracks. The positive is that the wind could be turned off which would isolate the increase of rolling resistance. The WFT could also be widely adjusted. The problem is to quantify the WFT since it was difficult to change the position of the Teconer sensor.

Using Table 3.1 it could be concluded that with the available time and resources, such as the high speed track and the data acquisition vehicle, the most sensible options were to perform tests on a outdoor track instead of in a lab setting. Too many factors existed to use the alternative options (Wind Tunnel, Big Fleet Data, Public Roads). The final testing procedures were CD and CS.

Figure 3.2 is a process diagram of requirements to acquire data and then log data from the high speed track.



Figure 3.2: *Requirements to acquire data*

## 3.2 CD and CS Test Expectations

Before onsite testing began, expected outcomes were developed and proper functionality of the sensors/vehicle was confirmed. After reading existing reports on CDs and CS, estimations were made of how the test results should look. [18].

The CD expectation can be seen in figure 3.3. One important difference to note between a industry certified CD and a high speed test track CD was that a track had much shorter straight portions. A typical CD was performed on a single long track. Those CD tracks were rare and not available resources so a high speed track that is "testing for functions, reliability, performance, and durability at speeds up to 200 km/h" was used.[19]. Thus the CD was sectioned to speeds in km/hr (130-105, 105-85, 85-65, 65-35). The 4 decelerating sections were driven 2 times in opposing directions (to balance directional wind effect). That was, one speed section per lap.

Regarding the CS expectation, it was clear that the power requirement to maintain the given speed would increase as the speed increased. Similar to the CD expectation, it was assumed that the road load would increase if the pavement was wet. Therefore, it would require more power for driving on a wet road compared to a dry one for a given speed. The expectation is illustrated in figure 3.4. If the CS road load values would look stable, a combined dataset with both CD and CS could be made for an even more comprehensive and robust model.

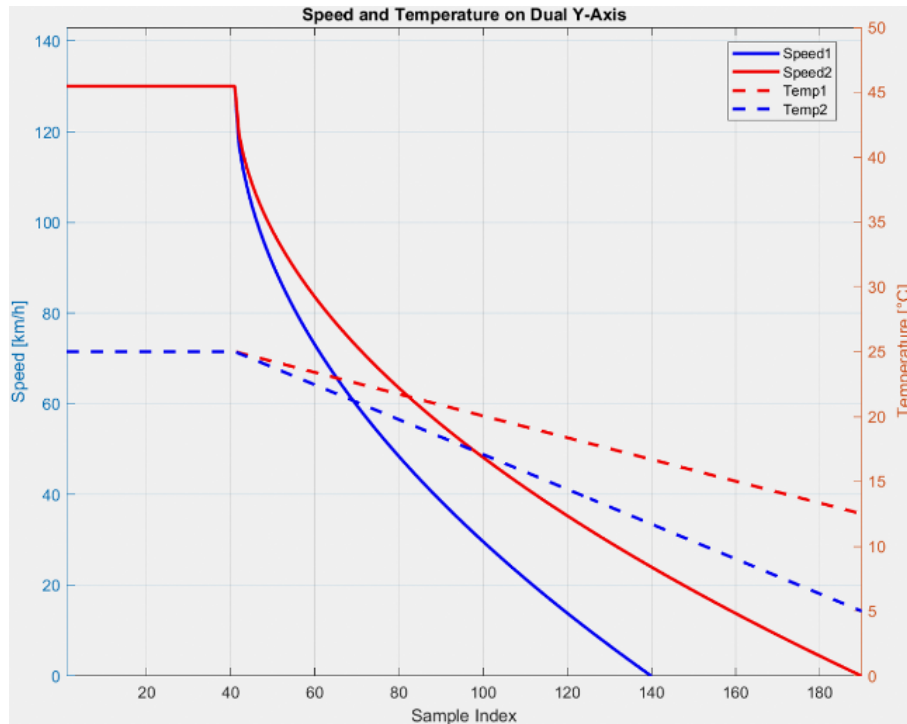


Figure 3.3: Visual representation of expected CD and tire temperature. Red = Dry conditions and Blue = Wet conditions

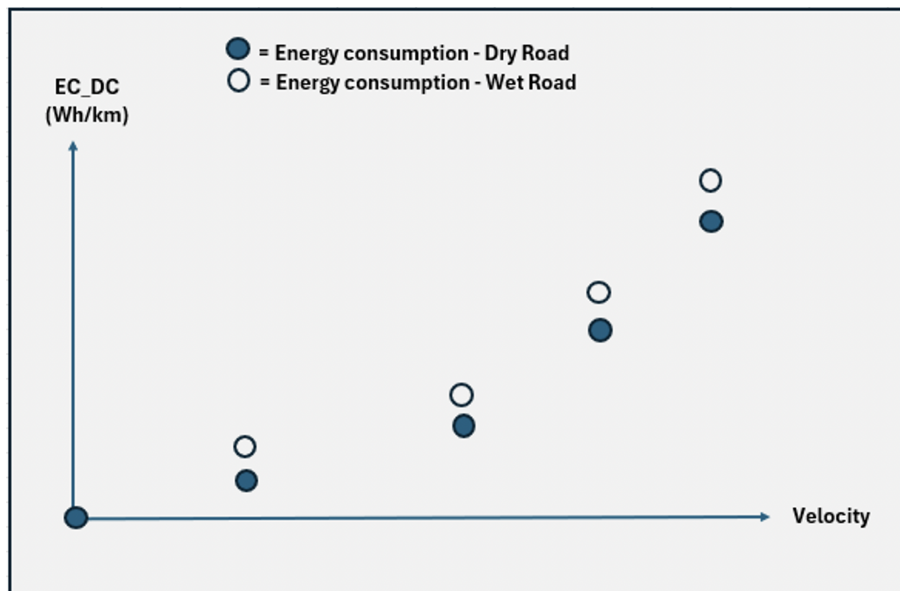


Figure 3.4: Visual representation of the constant speed expectations

### 3.2.1 Water Resistance Hypothesis

To get an understanding of the size of increased road load, a sanity check was estimated. Assume that all water that the tires are rolling over will be splashed up on the chassis.

This means that this water must be accelerated up to the car's speed. The vehicle is driven at 70 km/h, the WFT is 1 mm and all WFT is splashed up onto the chassis. Then we get:

$$P = \dot{E} = \frac{\dot{m}v^2}{2} = \frac{\rho \cdot h \cdot w \cdot \dot{s} \cdot v^2}{2} = \frac{\rho \cdot h \cdot w \cdot v^3}{2} = \frac{998 \cdot 0.001 \cdot (0.2 \cdot 2) \cdot (\frac{70}{3.6})^3}{2} = 1468W \quad (3.1)$$

or

$$P = F \cdot v \implies F = \frac{P}{v} = \frac{998 \cdot 0.001 \cdot (0.2 \cdot 2) \cdot (\frac{70}{3.6})^2}{2} \approx 75N \quad (3.2)$$

Then, calculate what a typical road load is at this speed: **Given:**  $m = 3000\text{kg}$ ,  $v = 70\text{ km/h} = 19.44\text{m/s}$ ,  $C_d = 0.35$

$$F = F_r + F_d = C_{rr} \cdot m \cdot g + \frac{1}{2} \rho C_d A v^2 = 0.012 \cdot 3000 \cdot 9.81 + \frac{1.225 \cdot 0.35 \cdot 2.6 \cdot (19.44)^2}{2} \approx 564\text{ N}$$

This means that if all water on the pavement would be splashed up to the chassis and accelerated up to 70km/h, then the WFT would increase the road load with roughly  $\frac{75}{564} \approx 13\%$ .

### 3.3 Testing Procedure

The physical testing began on April 1st, 2025 at Hällered proving grounds. The purpose for the testing is to investigate using a "real life" environment, how varying levels of wetness affect the energy consumption of a BEV. The aforementioned CD and CS tests will be conducted on a designated high speed track, specifically utilizing the straights. The study aims to quantify the impact of water on rolling resistance and overall vehicle energy consumption. The testing begins by establishing accurate dry reference runs and consistent (warmup) tire temperatures. Then using a water truck to wet the surface to try to isolate the effect of wetness using different speeds.

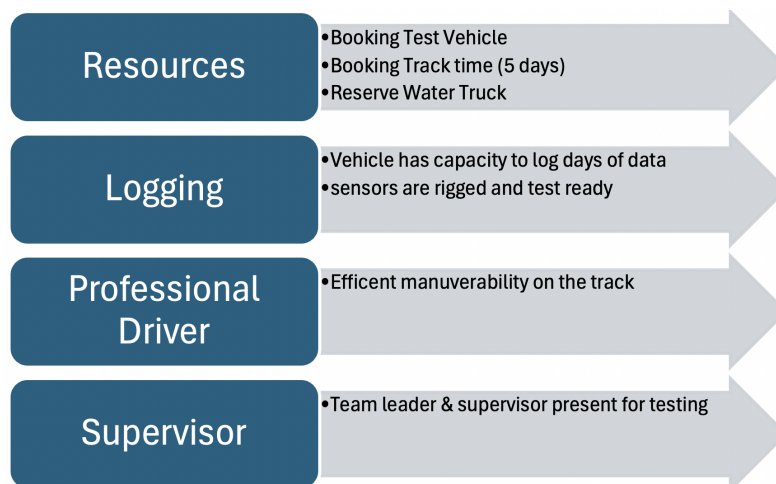
The test procedure directions are listed in bullet format and Figure 3.8 displays the process flow of testing.

Table 3.2: *Test Day Conditions*

Information	Details
Vehicle	EX90 AWD BEV
Wheels	Summer Tires
Opening hours	8-16
Test Days/Duration	Tues April 1st-Thurs April 3rd
Outside Temperature	15°C
Wind Speed	0.4-4.0 (m/s)

	Day	Front		Rear	
		Left	Right	Left	Right
	1,2,3				
	April 1st 10:51	687	711	808.5	820
Axles		1398.00		1628.50	
Total		3026.5			
	1				
	April 1st 16:26	690	710	808.5	820
Axles		1400.00		1628.50	
Total		3028.5			
	2,3				
	April 2nd 14:19	694.5	709	819	825
Axles		1403.50		1644	
Total		3047.5			

Figure 3.5: Vehicle Mass



Start with the **Coast down** testing since it doesn't have to be relied on torque.

- Start with **DRY** road (reference test).
  - Warm up the tires!
  - Drive up to 130km/h
  - Put the car in neutral (zero torque in electric vehicle)
  - Drive as straight as possible (no drive input)
  - Split into several takes (130-105, 105-85, 85-65, 65-35) due to not being able to perform the test in one straight path.

- Drive in both directions to negate the effect of wind.

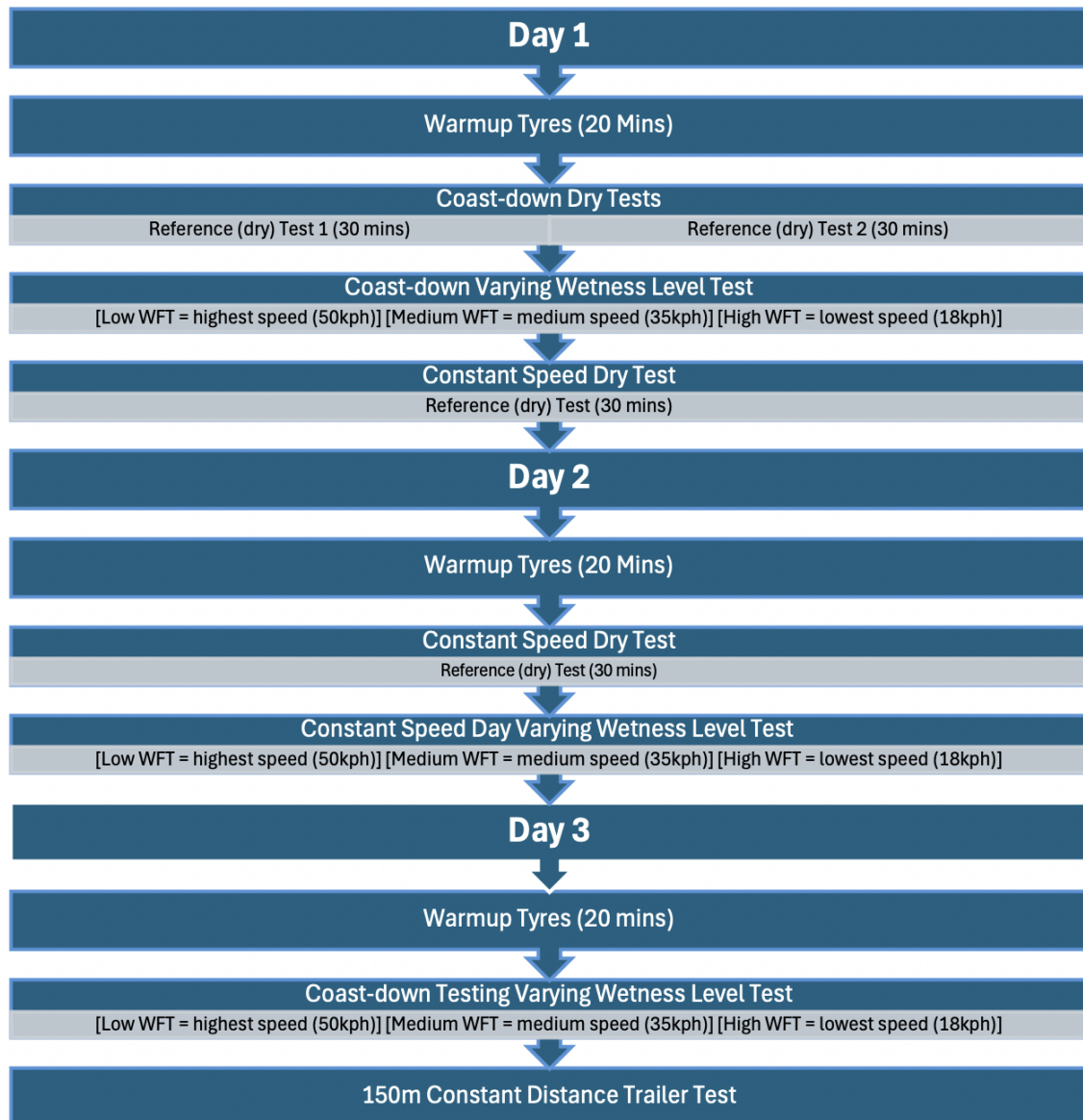
Next, perform the same procedure for **varying water wetness**. To test varying levels of water film thickness, a water truck was used to deploy water. Due to no flow control, varying speeds were used.

- The WFT process:
  - \* Low WFT = highest speed (50kph).
  - \* Medium WFT = medium speed (35kph)
  - \* High WFT = lowest speed (18kph)

Next is the **constant speed**. This can only be done if the output torque can be estimated properly. There are two ways of doing this. The first is calculating the power into the engine and then estimating the output power by knowing the inefficiencies in the engine and gears etc. The second method is having a measuring device at the end of the (inverter/gear) to get the torque. This was an option considered to be accurate but it was not used to due availability of the torque sensor.

- Warm up the tires
- Drive on the dry road to get reference data. Using varying speeds (30, 50, 80, 110) km/h for 1 lap at each speed.
- Drive at varying speeds (30, 50, 80, 110) km/h for 1 lap on wet surface.
- Change the wetness level.
- Perhaps "constant" speed isn't necessary but this needs to be validated.

From this on, the internal fleet that have Teconer mounted can also be used to gather data (depending on how good the torque estimation is). This is mainly for the robustness of our results.

Figure 3.6: *Test Procedure*

### 3.4 Vehicle Signals

Ensuring the correct signals were logged, it was important to understand the data collection process since it could impact the final results. A (Scalable Platform Architecture) Topology schematic was referenced to identify which signals were associated to which vehicle CAN (Controller Area Network) busses. For example the "Bearing, Longitude, Latitude, Vehicle Speed" signals were obtained from the vehicle internal GPS. The "Yaw Rate" signal was obtained from the internal inverter, and used to identify when the vehicle direction was far away from centerline, insinuating the corners of the track, which was cut in post processing. The temperature signals were separate sensors that used a 16 channel radial design inside the tire to capture the interior temperature in the tires. Unfortunately only 1 out of 4 temperature sensors had enough battery during testing. For testing purposes,

Figure 3.7 displays all the signals used.

Vehicle ECU Configuration for Testing Purposes	
Name	
<b>Voltage</b> (measured on HVDC side at Electric Machine Inverter)	
<b>HV Direct Current (DC)</b> (in Inverter High Voltage for Electric Machine)	
<b>Longitudinal Acceleration</b>	
<b>Lateral Acceleration</b>	
<b>Water Film Thickness</b>	
<b>Vehicle Speed Longitudinal</b> (based on wheel speed sensors & longitudinal acceleration)	
<b>Estimated EM Torque</b>	
<b>Bearing, Longitude, Latitude, "Real Time," Vehicle Speed</b>	
<b>Requested Torque to EM</b>	
<b>Yaw Rate - Angular Rate Data</b>	
<b>Actual Steering Wheel Angle</b> (from actual centre position of the steering wheel)	
<b>Thermal Tire Sensor Channels (radially) 1-16</b>	

Figure 3.7: Vehicle ECU Signals

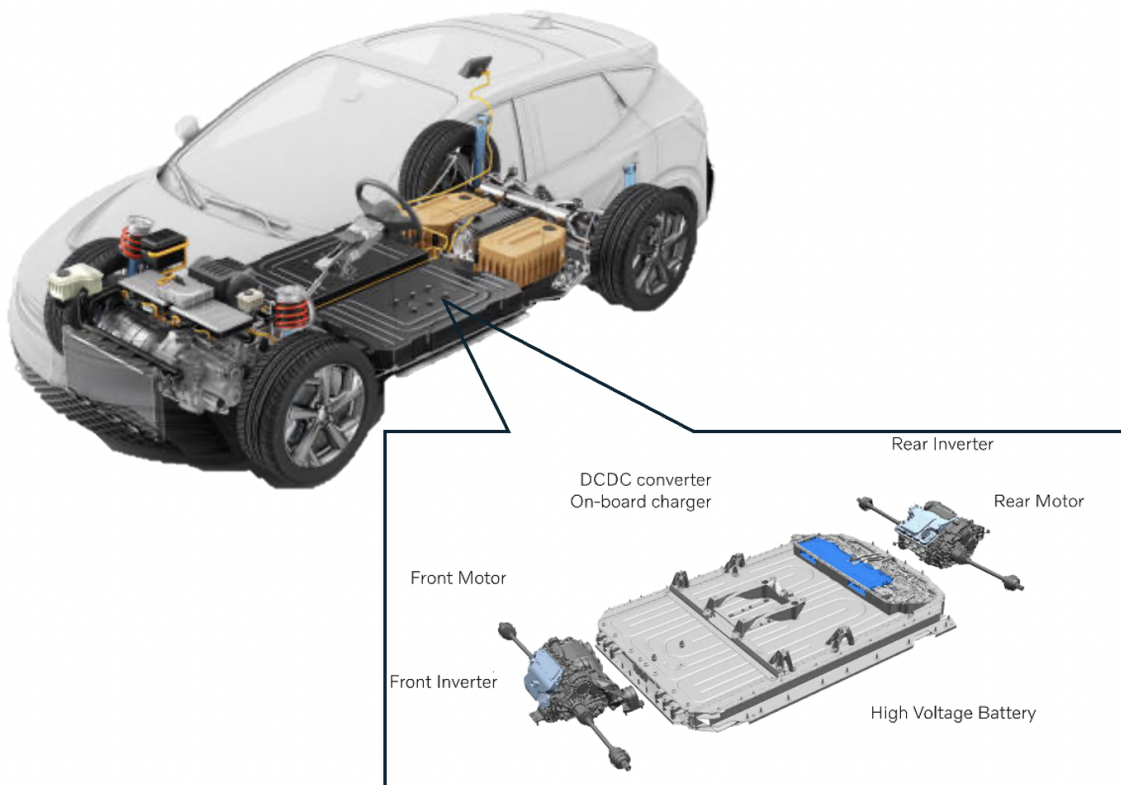


Figure 3.8: Understanding of Vehicle Inverter [4]

### 3.5 Data Analysis and Quantification of Energy Consumption

The collected test data was analyzed to quantify the impact of rain and wet road conditions on BEV energy consumption. This involved evaluating road load variations and potential efficiency losses. The parameters used were the speed  $v$  and the WFT  $h$ . Speed was already known to change the road load and WFT was the indication that the pavement was wet. The tire temperature  $\Delta T$  was also one of the parameters that originally was going to be in the equation. However the tire temperature sensors all got their battery depleted during testing.

A preliminary proposal for the road load function with tire temperature and WFT as parameters is presented below:

$$F_{RL}(v, h, \Delta T) = F_0 + F_1 \cdot v + F_2 \cdot v^2 + F_3 \cdot h + F_4 \cdot h \cdot v + F_5 \cdot h \cdot v^2 + F_6 \cdot \Delta T + F_7 \cdot h \Delta T + \dots$$

Where  $F_0$ ,  $F_1$  and  $F_2$  are the original model for road load at dry pavement while  $F_3$ ,  $F_4$ ,  $F_5$ ,  $F_6$ ,  $F_7$  etc. are the parameters that affect the resistance when the pavement is wet or the tire temperature is different from the ambient temperature.

Note that the visualization could be problematic since it would be an object in 4D space. This was however not a problem since tire temperature wasn't included.

### 3.6 Testing Summary

The primary goal was to quantify the effects rolling resistance and energy consumed using test methods; coast down (CD) and constant speed (CS) on post-rainfall driving conditions. All tests were conducted using a Volvo EX90 AWD BEV equipped with summer tires. The test procedure followed a systematic structure beginning with dry pavement reference tests, followed by wet pavement tests using varying degrees of wetness achieved by using water truck at 3 different speeds. The tests were executed over four days during track availability from 8:00 to 16:00. Some key findings from onsite testing will be explored in the results section.

# 4

## Results and discussion

The results are split up into three sections followed up by a discussion of each result. The first results are from **CD**. The second results are regarding the **CS**. Lastly, the third section is **combined results**, implementing WFT as its own variable. Both the CD and CS tests were conducted in such a way that Test 1 would have the least amount of wetness and Test 3 would have the most amount of wetness. The results showed that each test had more or less the same wetness level for the given day, meaning that the pavement was already saturated with water during the first wetness test. However, the WFT would vary depending on which day the wetness tests were done, with generally higher WFT on the third day compared to day 1 and day 2.

### 4.1 Coast down Test - SAE Calculation

The CD test results present a road load for each test. A summary of the SAE approach road load is depicted in Figure 4.1. These results utilize the SAE (Society of American Engineer) Doc J2264 [17] standard for Road Load Measurement. A standard road load curve shows the resistive forces acting on the vehicle using  $F = MA$  and  $A$  is determined using  $T$  and  $\Delta 10$  km/hr deceleration intervals. These are our results portrayed using industry standard J2264 and  $\Delta 10$  km/h deceleration intervals. There was also another way to analyze the data and determine the road load curve. This is called the thesis approach and will be described in section 4.2.

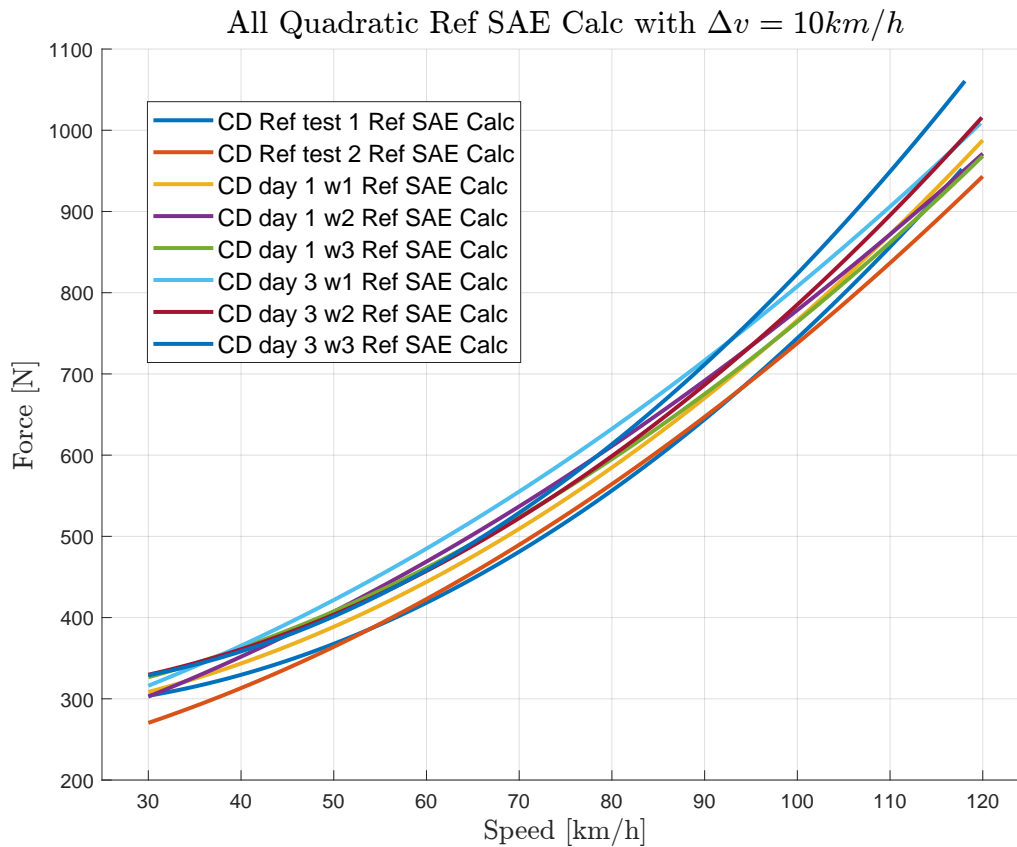


Figure 4.1: Comparison using the SAE approach to calculate the road load curve

From the comparison figures 4.1 it's hard to see a clear pattern to how the WFT affects the road load. However, it's determined that the road load is higher at almost all speeds when the pavement is wet. A problem with the reference is that they don't align, which they should. This the case is at high and low speeds. To easier show how water may impact the road load, figure 4.2 shows the comparison by subtracting the road load from the averaged reference test. That is  $F_{roadload} = F_{0,test} + F_{1,test} \cdot v + F_{2,test} \cdot v^2 - (F_{0,avgref} + F_{1,avgref} \cdot v + F_{2,avgref} \cdot v^2)$ . Figure 4.2 shows the averaged road load from the reference tests compared to the other tests.

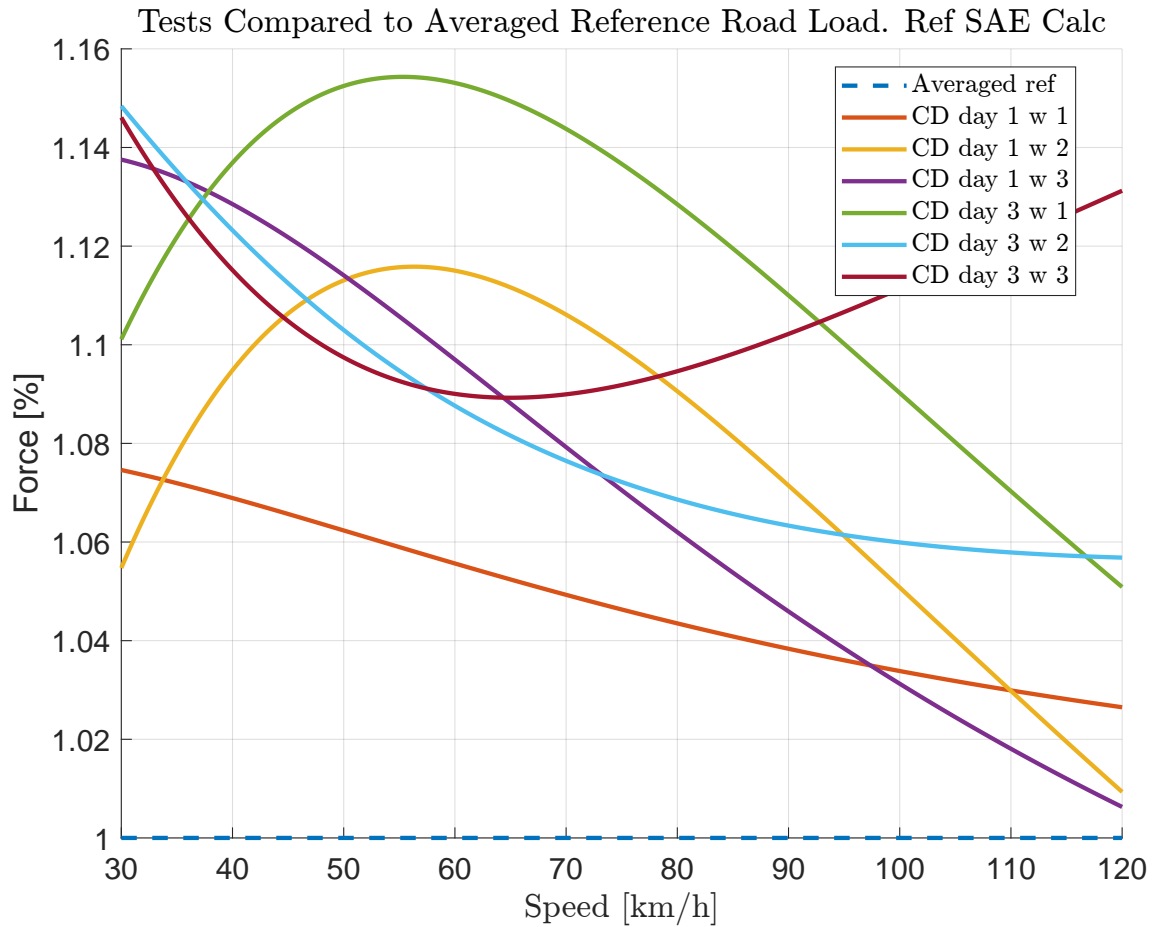


Figure 4.2: Averaged road load reference compared to the other road loads in %. SAE Approach

This suggests a pattern where the road load is higher for wet pavement at all speeds. The results suggest that the resistance decreases as speed increases. The resistance differs between 2 to 15 % higher compared to the reference tests averaged.

Lastly, the F parameters, the  $p_{overall}$  value and the  $R^2$  value is summarized in table 4.1. The  $R^2$  value measures how good of a fit the data points are to the regression model. A perfect fit is  $R^2 = 1$ . The p value shows if the regression model is statistically significant. A value of  $p < 0.05$  is considered statistically significant. A high p value fails to reject the null hypothesis (that the model (or parameter) might be 0).

Table 4.1: Regression coefficients,  $p$ -value (overall  $F$ -test), and  $R^2$  for each coast down test run.

Test Name	$F_0$	$F_1$	$F_2$	$p$ -value (overall)	$R^2$
CD Ref test 1	300.53	-1.75	0.0618	0.000664923	0.9835
CD Ref test 2	189.76	1.49	0.0399	0.000977044	0.9871
CD day 1 w1	263.95	-0.03	0.0505	0.00161826	0.9914
CD day 1 w2	193.29	2.70	0.0315	0.000702109	0.9833
CD day 1 w3	270.86	0.54	0.0440	0.001490353	0.9897
CD day 3 w1	234.13	1.50	0.0434	0.000323904	0.9692
CD day 3 w2	303.27	-0.81	0.0563	0.002238986	0.9934
CD day 3 w3	323.33	-1.87	0.0688	0.001105696	0.9909

Note that the  $R^2$  values are very high. This is because the points are averaged out over  $\Delta 10km/h$  intervals meaning a few averaged values. This is not a representative way of measuring the  $p$ -values and  $R^2$  values since the points aren't necessarily a part of the data set. Moreover, negative  $F_1$  values are uncommon in road load curves and may indicate measurement or analyzing uncertainty. Therefore, the conclusions drawn from these tests should be interpreted with caution.

## 4.2 Coast down test - Regression Model

The difference between the certified way and the regression model is that the regression model is using all points available in the CD to calculate the corresponding road load via the built-in acceleration signal. In other words, each value comes from  $F = m \cdot a$  where  $m$  was measured after the test (assumed constant if the driver wasn't changed) and  $a$  was taken from the car's internal longitudinal acceleration CAN signal. An example of the result showing all measurements is shown in figure 4.3. The certified road load curve is also shown in the figure as a comparison.

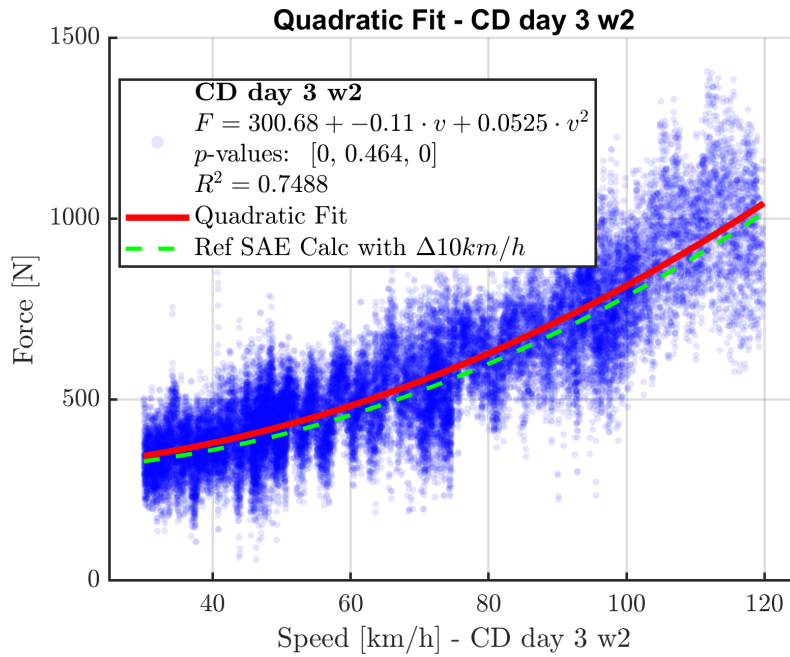


Figure 4.3: Example of an CD with both the Thesis approach and SAE calculation is presented

As seen, the scatter cloud introduces a lot of noise but removes potential human error and therefore gives a more robust model (as long as bad signals are filtered out). All road load curves using the thesis approach are summarized in figure 4.4.

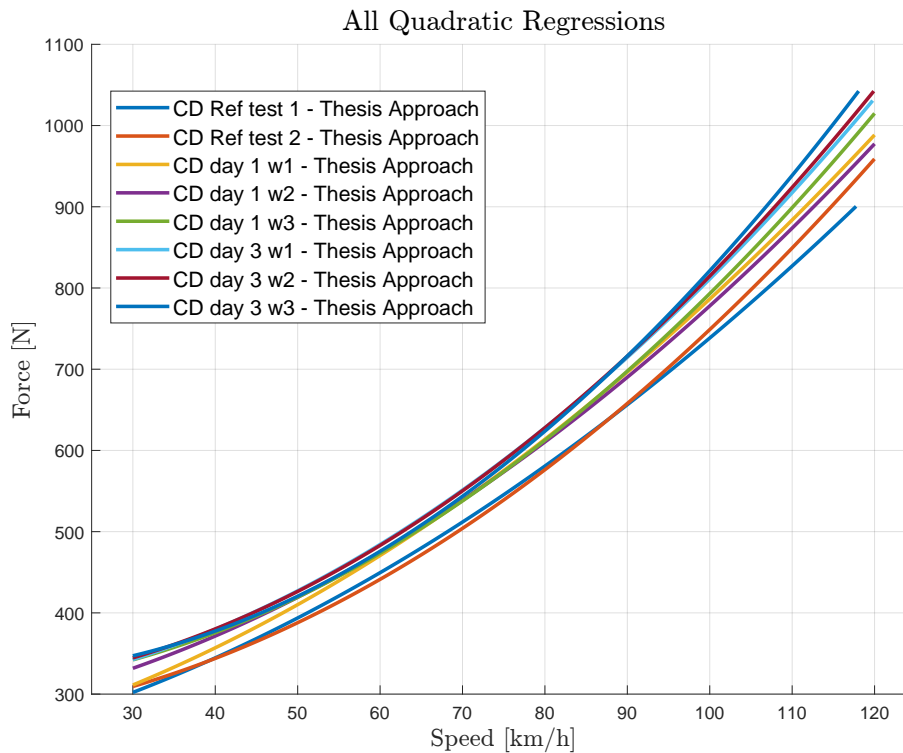


Figure 4.4: Road load curve. Regression model method. Comparison figure

Same as before is the comparison figure depicted in figure 4.5 but this time using the regression model.

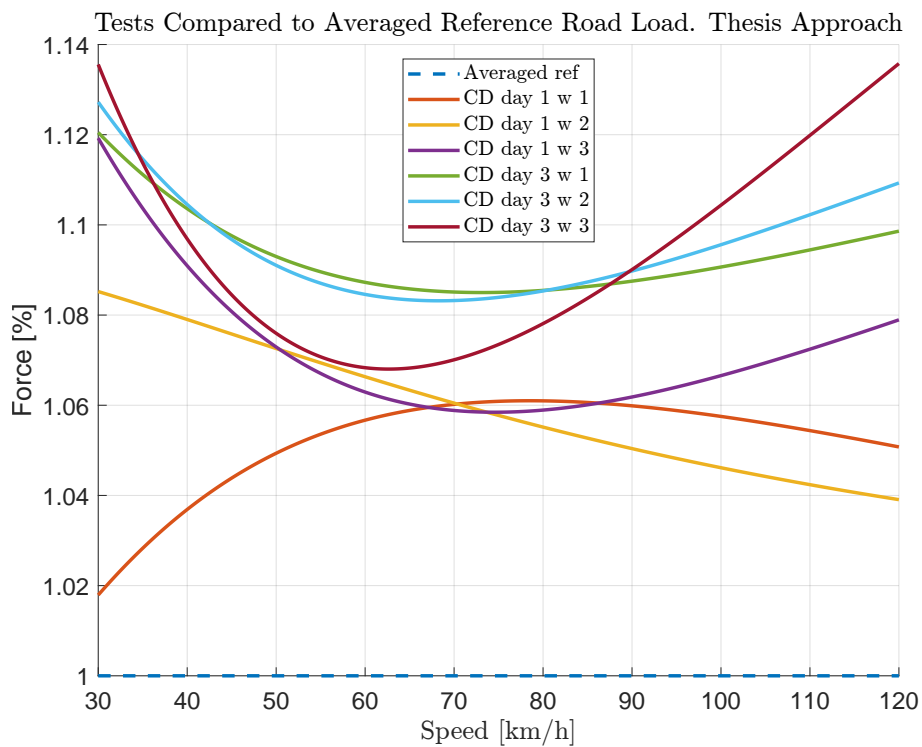
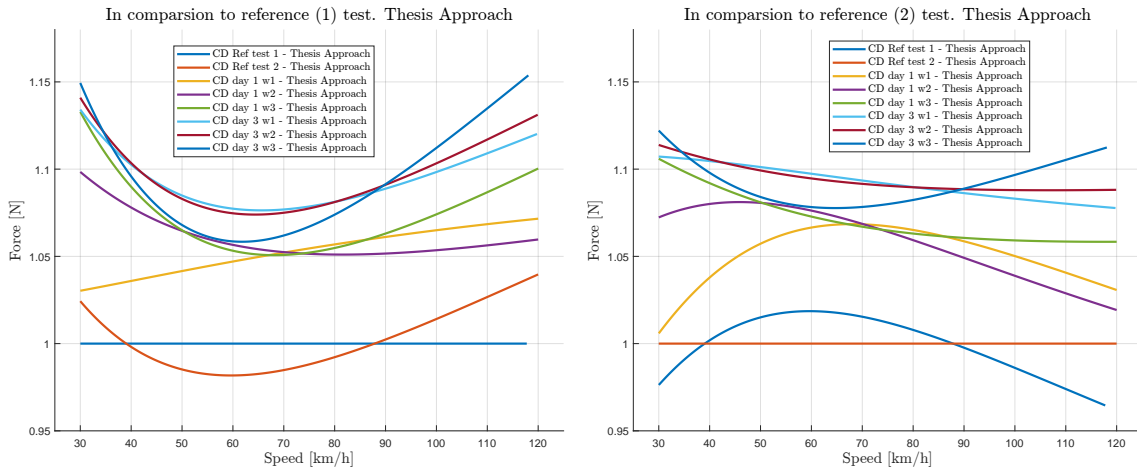


Figure 4.5: Comparison between road load curves compared to the reference (dry) test. Obtained through the Thesis approach

This explains a pattern where the resistance goes up for the majority of the road loads compared to the averaged reference test. The resistance is still lower for middle speeds (50-80 km/h). To further understand if there is something weird with the averaging of the reference test, figure 4.6 shows the comparison for each reference test.



(a) Comparison between each road load and 1st reference test. (b) Comparison between each road load and 2nd reference test.

Figure 4.6: Comparison between the road load and the reference test separately. Thesis approach

This shows that there is a difference of up to 4% between the two reference tests. This strengthens the assumption that one of the tests is bad. A third test would have been preferable to rule out the bad test. However, the figures still show that road load increases if water is present on the pavement. This is the case for all speeds. A reason for the odd pattern at both high and low speeds could be due to slip conditions on the wheels, but this hasn't been studied.

Another interesting part is that the WFT pattern was the same for each test but different depending on which day it was. If the tests for day one and day three were averaged and the reference likewise, then figure 4.7 depicts the outcome.

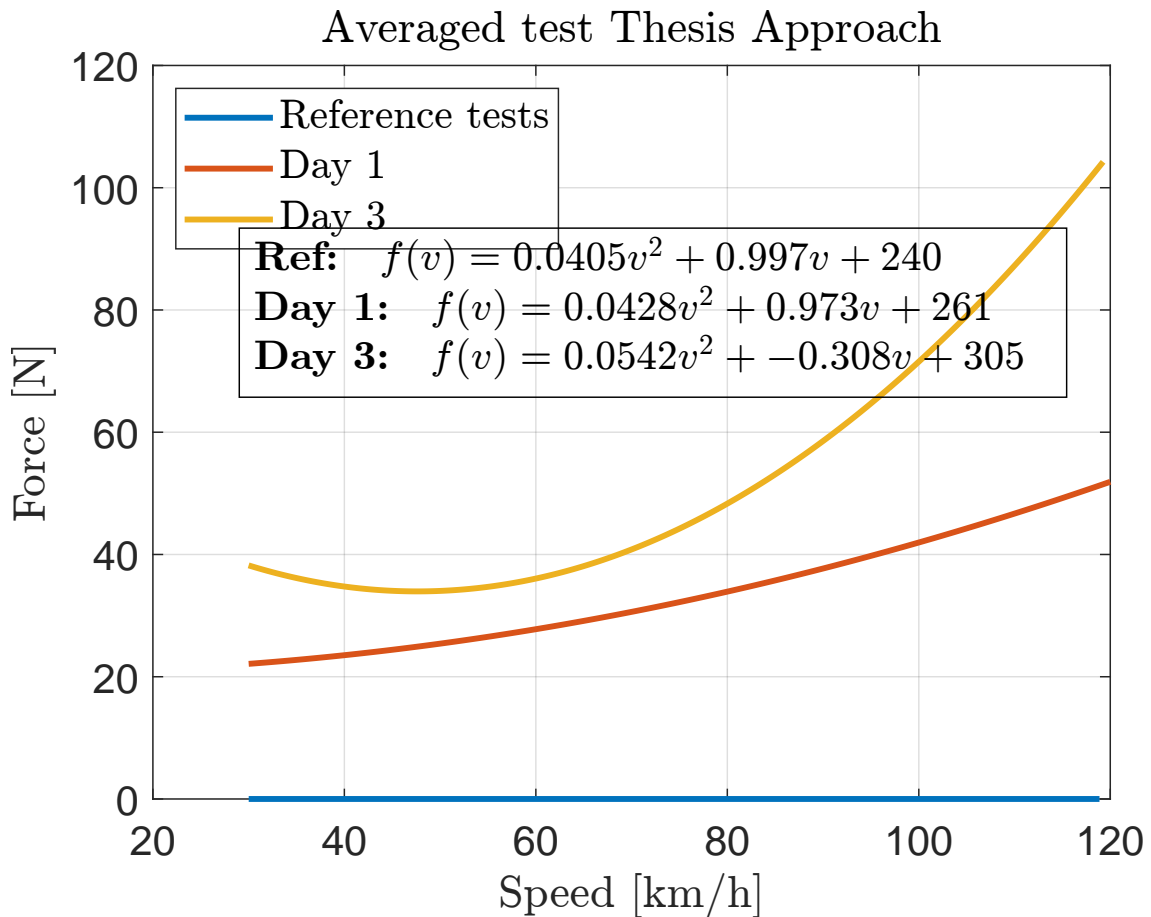


Figure 4.7: Thesis approach: Averaged road load curves with blue being averaged reference test, red is all road load from day 1 and yellow all road load from day 3.

Since the WFT was on average higher on the third day, this might indicate that WFT has a speed dependence on the resistance.

The coefficients for the thesis approach road loads is in table 4.2. The p value for reference two is high, indicating that that test might not be significant enough as a proper test. However, both reference tests have low  $R^2$  values in comparison to the other tests. This might be because the shifting to neutral wasn't as smooth in the beginning of the tests. This lower the belief that the reference test values are appropriate to compare to.

Test Name	$F_0$	$F_1$	$F_2$	$p$ -values	$R^2$
CD Ref test 1	213.93	1.95	0.0330	[0, 6.37e-31, 1.92e-166]	0.6556
CD Ref test 2	262.12	0.17	0.0470	[0, 0.288(!), 0]	0.6856
CD day 1 w1	218.04	2.00	0.0368	[0, 1.17e-41, 1.36e-299]	0.7405
CD day 1 w2	260.67	1.17	0.0400	[0, 5.34e-15, 0]	0.7347
CD day 1 w3	303.94	-0.28	0.0517	[0, 0.075, 0]	0.7236
CD day 3 w1	289.45	0.29	0.0492	[0, 0.0427, 0]	0.7559
CD day 3 w2	300.68	-0.11	0.0525	[0, 0.464(!), 0]	0.7488
CD day 3 w3	330.26	-1.30	0.0621	[0, 2.96e-16, 0]	0.7486

Table 4.2: Regression coefficients,  $p$ -values, and  $R^2$  for each coast down test run.

Each individual quadratic approximation can be closer inspected in Appendix 5. The road load difference between the dry reference tests and the wetness tests are (according to the regression model) usually around 9-11% higher at all speeds. At the extreme cases the differences increases to around 15% for high speeds or decreases to as low as 6% higher for low speed than the reference values. The certified road load curves pattern implies that the wetness tests achieve higher road load compared to the dry reference tests.

### 4.3 Constant speed test

The CS test was about determining the median power consumption to maintain a specific speed. The reason for using median power instead of mean power is that it was harder to filter out inaccurate signals from CS meaning that often very high or very low numbers would be included. One way to get around those data points was to take the median values. The different speeds were [30,50,80,110] km/h. These were held by observing the speedometer inside the car. Therefore, the actual constant speeds were lowered to approximately [28.5, 47.5, 77, 106.5] km/h. The values were found by observing the speed signal and taking the average speed of what was a part of a constant speed interval. Figure 4.8 shows an example of one of the CS tests.

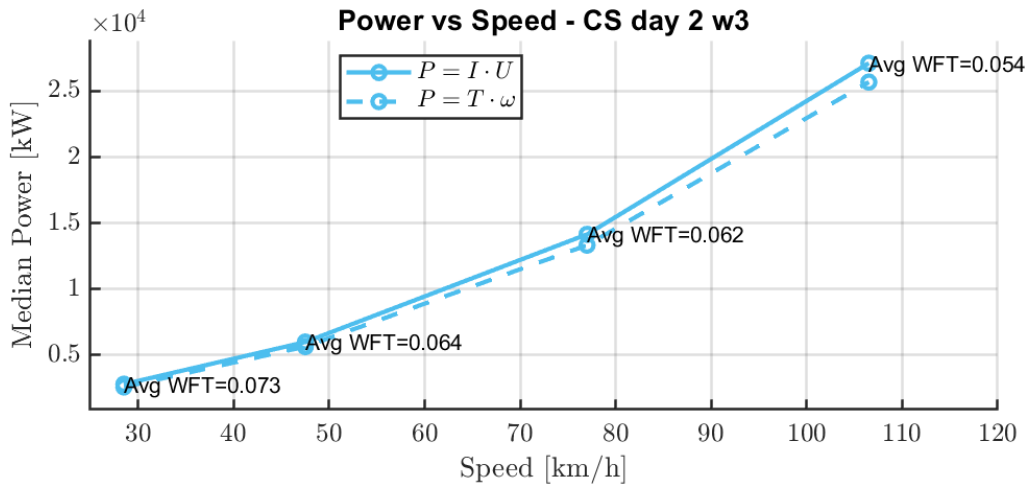


Figure 4.8: CS test the second day with the third wetness level. The average WFT is in mm

The **solid lines** in the plot represent power calculated from the DC voltage and DC current ( $P = U \cdot I$ ) and the **dotted lines** show power estimated using torque and angular velocity ( $P = T \cdot \omega$ ) with  $T$  being the "Estimated EM Torque" and  $\omega$  the angular velocity derived from motor speed (in RPM, converted to rad/s). As seen, these are close to each other. Only the power calculated from current and voltage will be used for later comparison.

Comparisons between each test is shown in Figure 4.9. The comparison shows that the reference tests have the lowest power consumption except for Day 1 reference test but a possible explanation was that the speed was held manually in the beginning while testing and the active cruise control hadn't been activated yet. Like previously, a more detailed comparison can be seen in figure 4.11.

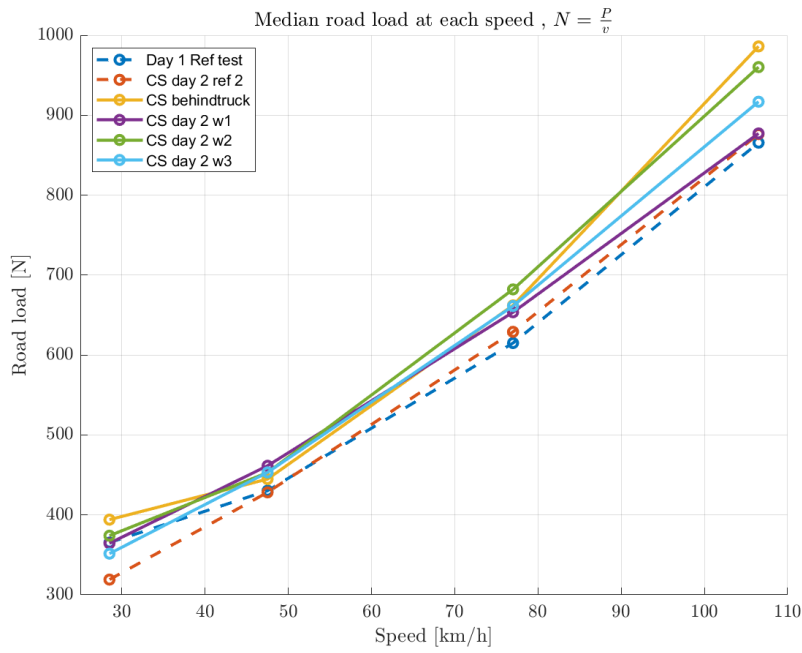


Figure 4.10: Comparison of each test. Approximated road load calculated from the power on the inverter

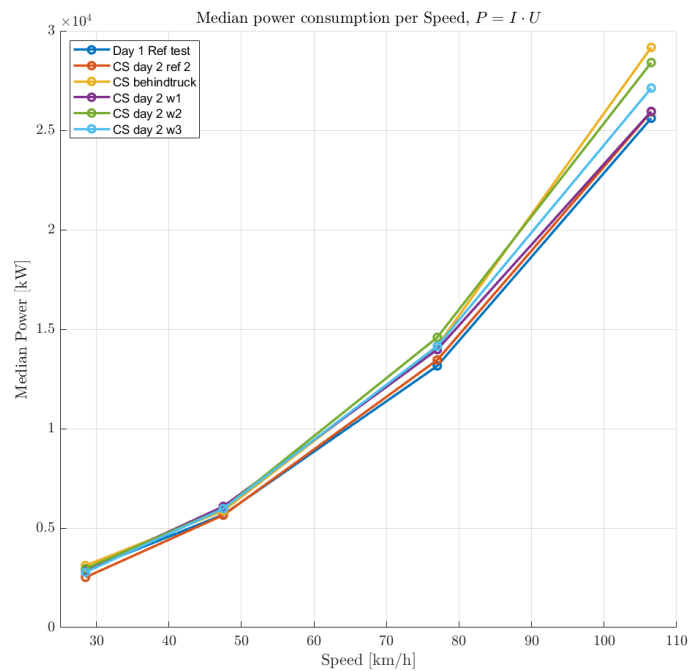
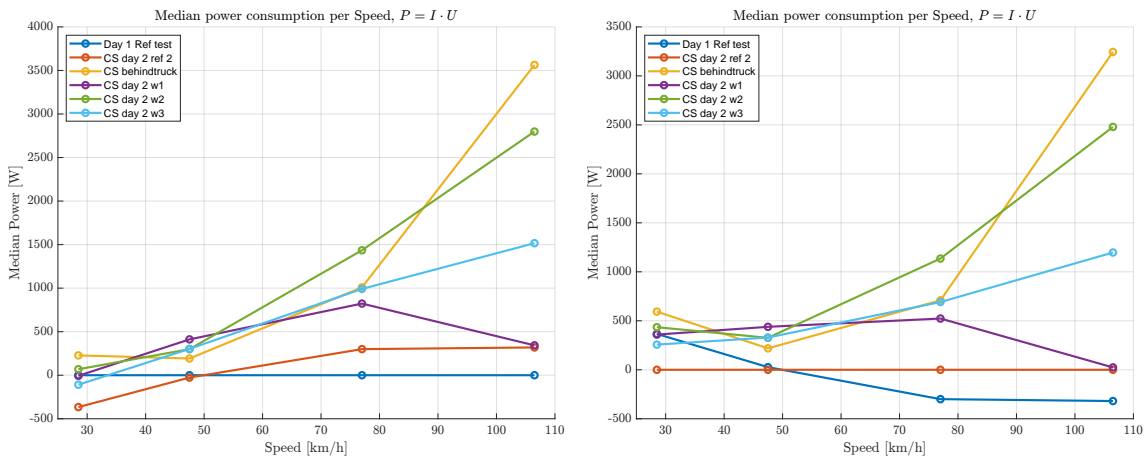


Figure 4.9: Comparison of each test. Median power to maintain each speed

An easier comparison might be the road load at each speed. This is presented in figure ?? Note that this includes the possible inefficiencies on the inverter and gearbox.

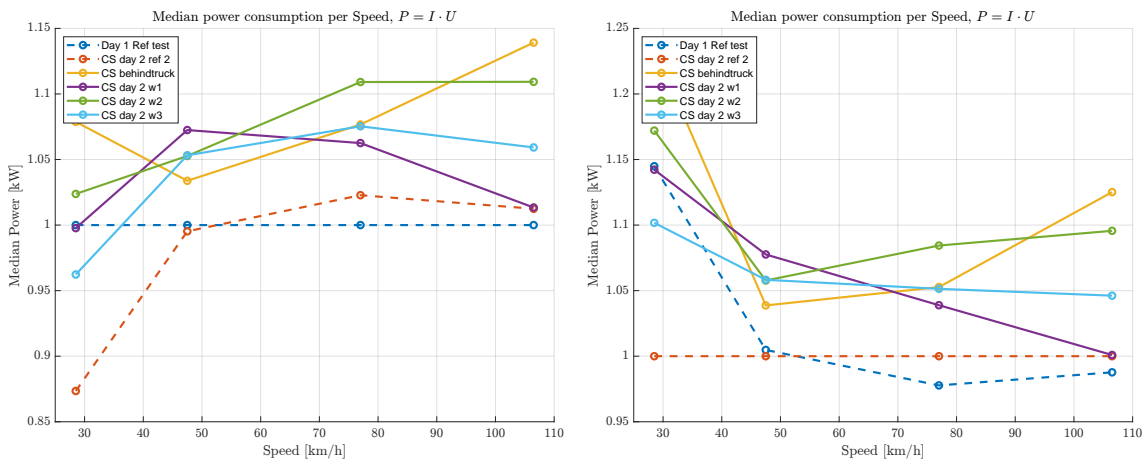
To further analyze the data and remove the possible inefficiencies, the power difference between each reference test is shown in 4.11.



(a) Comparison of each test subtracting reference test 1 (b) Comparison of each test subtracting reference test 2

Figure 4.11: Each median CS power subtracted by the reference median power

Now it's clear that WFT together with speed affects the resistance. The difference is up to 2.5kW for the highest speed. Figure 4.12a shows the relative difference in comparison with reference test 1 (median power difference in percent) while Figure 4.12b show the relative difference to reference test 2.



(a) Comparison of each test subtracting reference test 1 (b) Relative difference to reference test 1 for CS

Figure 4.12: Relative difference to the reference tests for CS. Dotted lines are the reference tests

The relative increase in power consumption is shown in table 4.3.

For reference test 1, the median power consumption is around the same for speeds at 30

Speed [km/h]	vs Day 1 Ref test (%)				vs CS day 2 ref 2 (%)			
	27.5	47.5	77	106.5	27.5	47.5	77	106.5
Day 1 Ref test	0.0	0.0	0.0	0.0	+14.5	+0.5	-2.2	-1.2
CS day 2 ref 2	-12.7	-0.5	+2.3	+1.2	0.0	0.0	0.0	0.0
CS behindtruck	+7.9	+3.4	+7.7	+13.9	+23.5	+3.9	+5.3	+12.5
CS day 2 w1	-0.2	+7.2	+6.3	+1.3	+14.2	+7.8	+3.9	+0.1
CS day 2 w2	+2.4	+5.3	+10.9	+10.9	+17.2	+5.8	+8.4	+9.6
CS day 2 w3	-3.8	+5.3	+7.5	+5.9	+10.2	+5.8	+5.1	+4.6
<b>Avg (excl. ref)</b>	<b>+1.6</b>	<b>+5.3</b>	<b>+8.1</b>	<b>+7.9</b>	<b>+16.3</b>	<b>+5.8</b>	<b>+5.7</b>	<b>+6.7</b>

Table 4.3: Relative Power IU per Speed (% Deviation from Two Reference Scenarios)

km/h, 5% higher for 47.5 km/h, 8% higher for 77 km/h and lastly around 8% higher for 106.5 km/h though the power variance at the last speed is high and hard to make certain claims. For example, regarding the CS behind truck test, the relative power consumption increased 14%.

Regarding the relative comparison to reference test 2, the increased median power consumption is around 15% higher for 30 km/h, 6% higher for 47.5 km/h, 6% higher for 77 km/h and lastly around 7% higher for 106.5 km/h.

It seems that reference test 1 resistance at 27.5 km/h was a bit too high. Regarding reference test 2, the resistance was way too low at 27 km/h and maybe a bit too high at 77 km/h and 106.5 km/h. Though it's hard to determine which reference value is correct. A third test would've been necessary to determine that. All in all, it looks that the resistance is about 5% higher at all speeds if the WFT is unknown. However, it indicates that the WFT might have an impact on the road load. The CS behind truck is the test where the WFT was as big as possible. The CS test with wetness 2 had the second most water according to the WFT signal. If the WFT is big, then a speed dependence might be present, otherwise the test indicates resistance that isn't speed dependent in regards to WFT.

## 4.4 Speed and WFT as variables

The last part of the results implements WFT as its own variable to the road load curve. In this way, one can draw conclusions on how much WFT solely affects the road load. In this part, only the thesis approach was used (taking speed, force and WFT at every single filtered point) due to time saving. The results with only the CD data are presented in figure 4.13. The model that was fitted against was:

$$F = F_0 + F_1 \cdot v + F_2 \cdot v^2 + F_3 \cdot WFT + F_4 \cdot WFT^2$$

with a  $R^2 = 0.7573$ . A few more parameters were tested but the  $R^2$  value didn't increase more than 0.02.

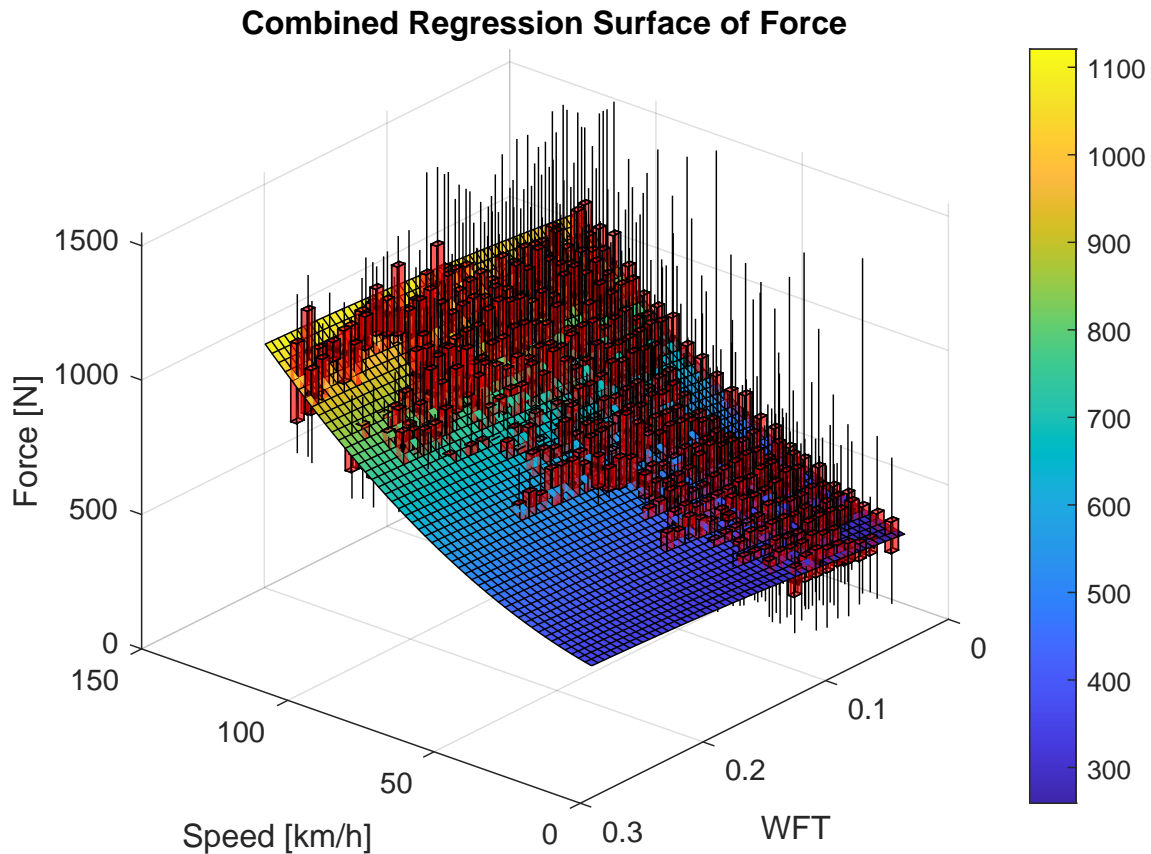


Figure 4.13: Proposed surfplot with higher and lower quartile showing the variance. Data from CD only

Resulting proposed model from the CD data is:

$$F = 233.75 + 10.8 \cdot v + 0.04 \cdot v^2 + 572.45 \cdot h - 832.54 \cdot h^2$$

where  $v$  is in [km/h] and  $h$  is the WFT in [mm]. The figure indicates that the WFT has an impact on road load. When WFT is 0.25 mm, which was the maximum during all CD tests, the road load is up at least 17% compared to dry conditions. However, there are few data points containing low speed and high WFT. Also, the spread at 0 WFT is high, meaning that the dry data points might be skewed. Lastly, since there are a lot more data points at  $h = 0$ , the model might also be skewed to correct more for those points than for the WFT variable. One way to correct this would be to weigh the data points but there wasn't any time.

It was also tested removing the  $h^2$  part which barely changed the  $R^2$  value. Then the proposed Road Load function would be:

$$F = 236.1566 + 1.0830 \cdot v + 0.0409 \cdot v^2 + 469.2127 \cdot h$$

$v$  is in [km/h] and  $WFT$  is in [mm].

### 4.4.1 CS and CD scatter together

When adding the CS points to the whole dataset, more data for low speed and high WFT can be obtained, which might give a more robust model. The results are presented in figure 4.14 below:

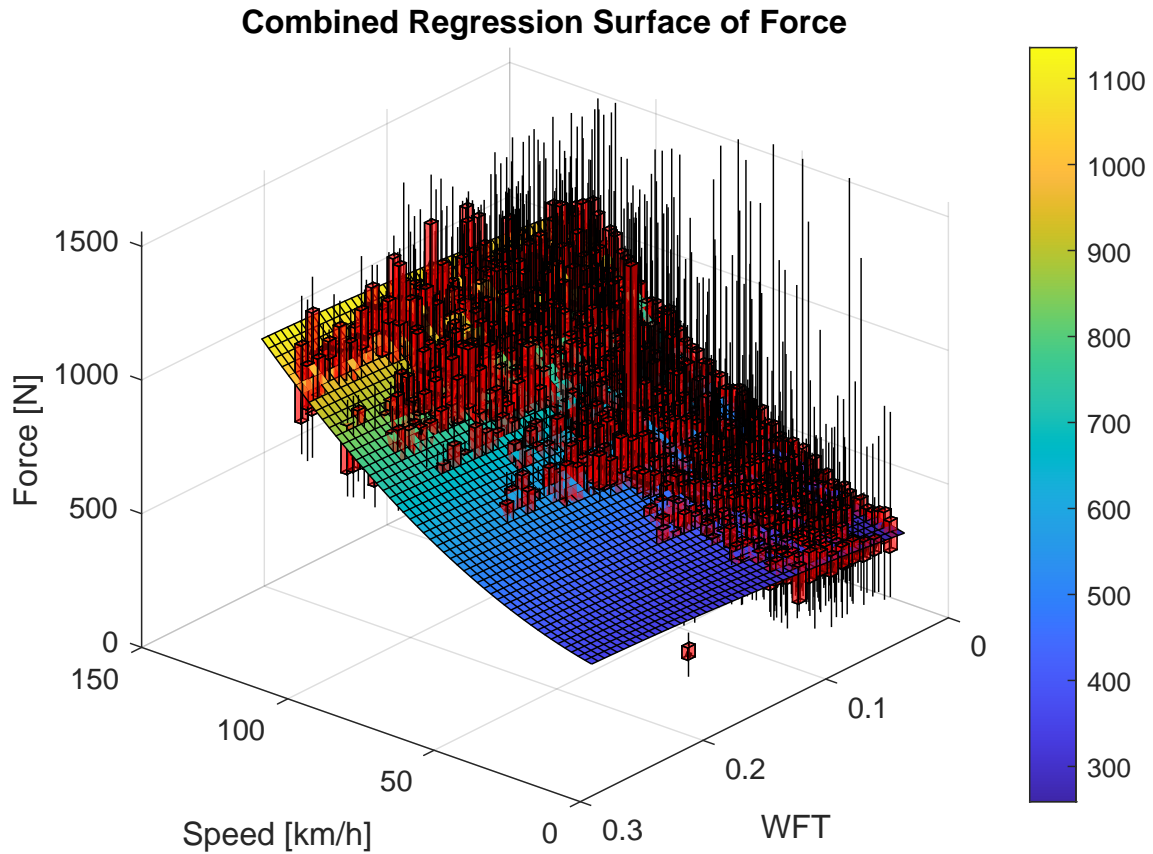


Figure 4.14: Surf plot with spread. Data from both CS and CD

The following parameters were:

$$F = 232.80 + 1.14 \cdot v + 0.04 \cdot v^2 + 607.50 \cdot h + -927.67 \cdot h^2 \text{ with an } R^2 \approx 0.7413$$

More data points are available, but in the meantime, a bigger spread at most speeds is present. This means that CS data might be hard to implement when determining the road load. More data points need to be added for low speed and high WFT to get a more robust model.

# 5

## Conclusion and future work

The question of this master thesis was "How does wet pavement contribute toward overall energy consumption on passenger vehicles?"

In broad strokes, the testing concluded that rolling resistance increases with surface wetness. Power consumption at constant speeds was at least 5% higher at all speeds for most of the tests. If the WFT was large, the resistance seemed to be speed dependent. According to the coast down test, the increased resistance was usually around 10% higher for all speeds compared to the reference test. At low and high speeds, the difference may vary. The impact of tire temperature ( $\Delta T$ ) may warrant deeper investigation under varying conditions such as longer cool-down periods to see noticeable changes in tire deformation and affect rolling resistance.

A proposed model, where the WFT is its own variable in comparison to the road load, has also been presented. The model isn't robust yet and shouldn't be used for measuring the road load. However, if the model increases in robustness and the WFT can be easily approximated, then the impact on road load regarding wet pavement could be further investigated. More parameters should be analyzed in future work in order to get a more comprehensive model.

It seems that coast down tests are the best way to measure accurate road load. However, future attempts should be made on gathering big datasets from data acquisition vehicles rigged with relevant sensors. If the road load could be accurately calculated through measuring the power from the inverter, then a lot more data points could be added and in that way a more robust model could be developed. For this to work, a way to measure or at least approximate the WFT would be needed. Since the sensor used in this thesis isn't common.

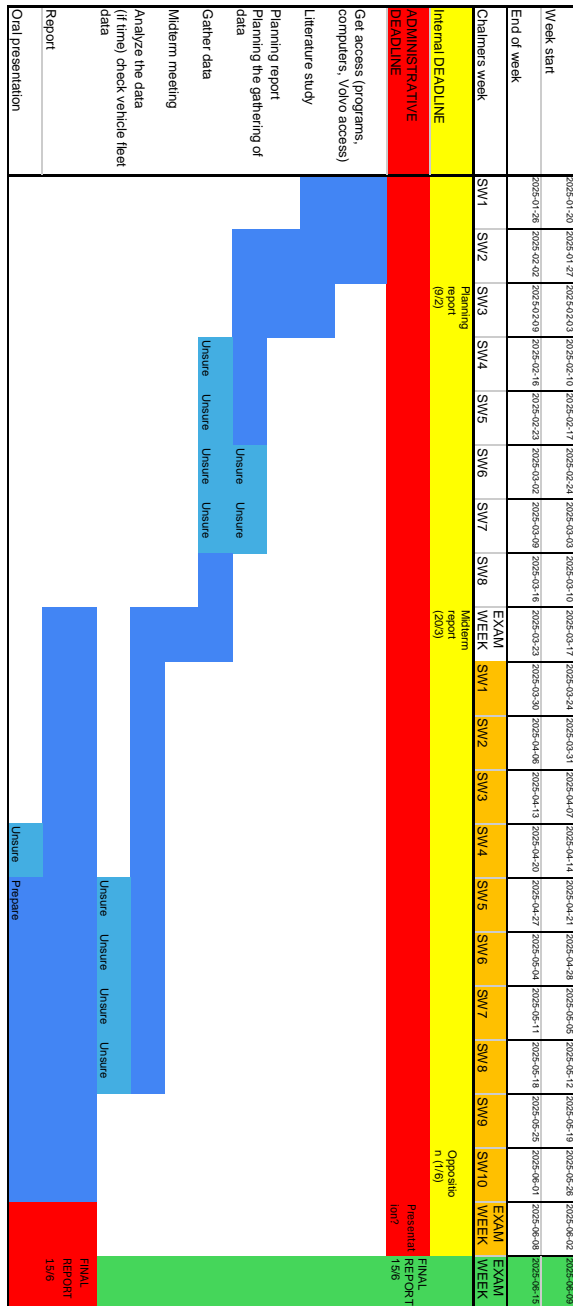
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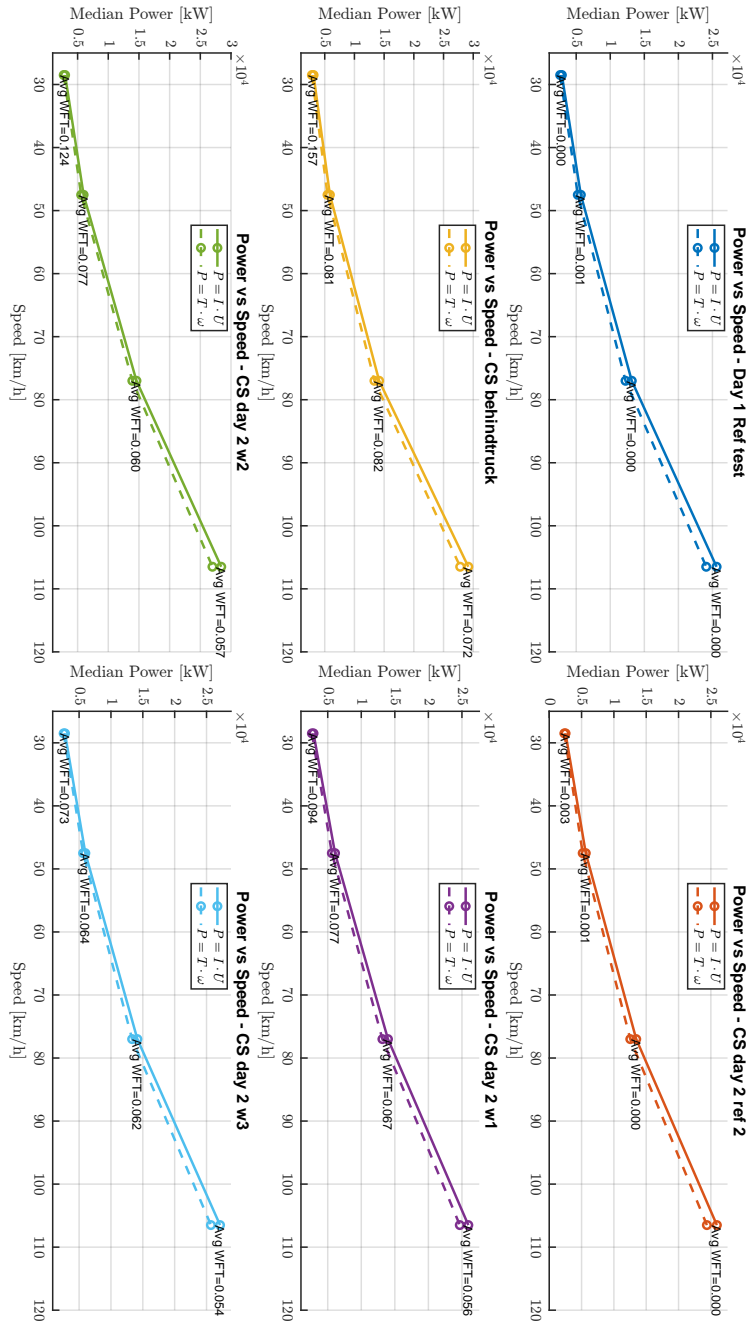
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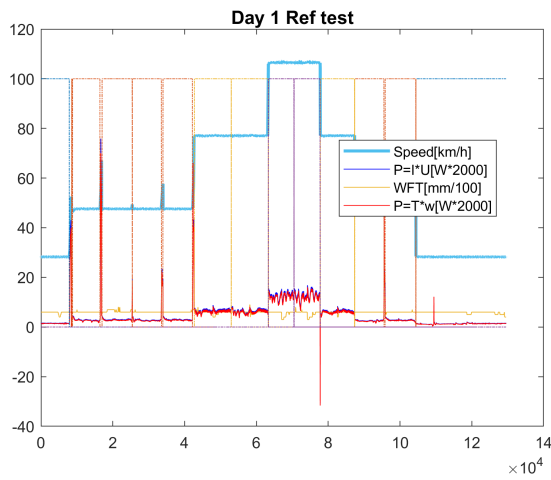
# Appendix I: GANTT scheme



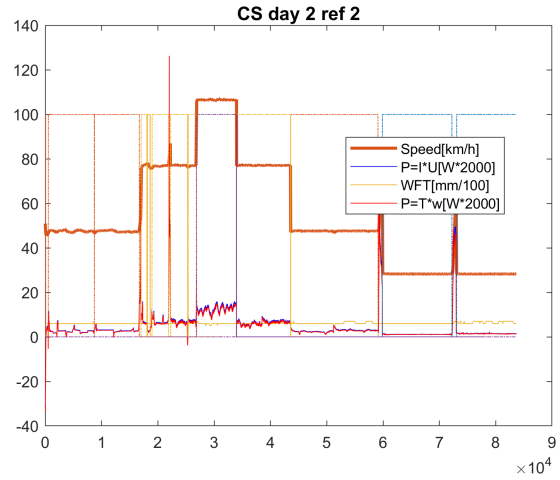
# Appendix II: CS results



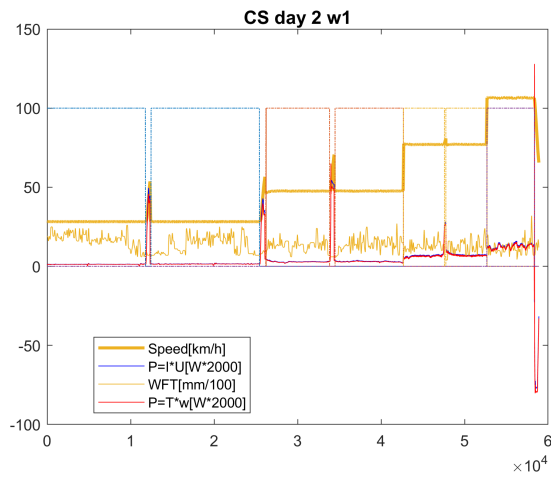
## Appendix III: Individual Test CS



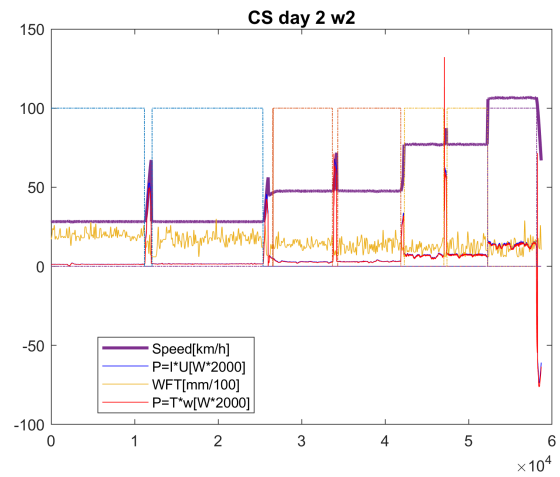
(a) Day 1 Ref Test



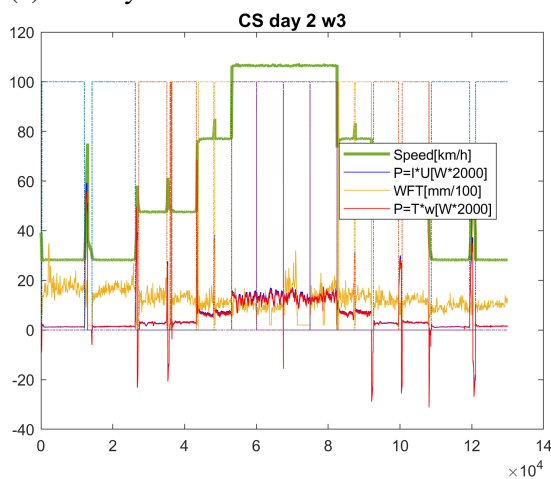
(b) CS Day 2 Ref 2



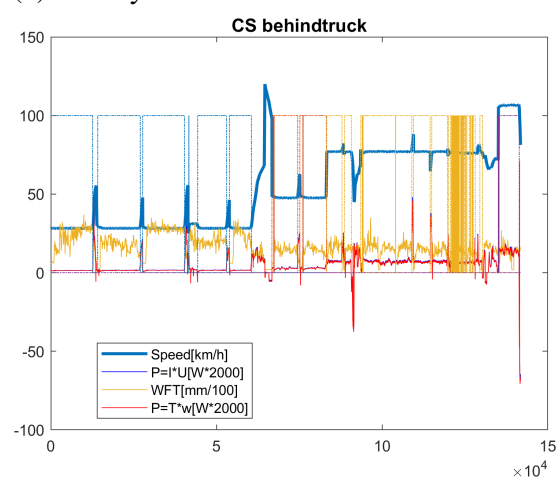
(c) CS Day 2 W1



(d) CS Day 2 W2



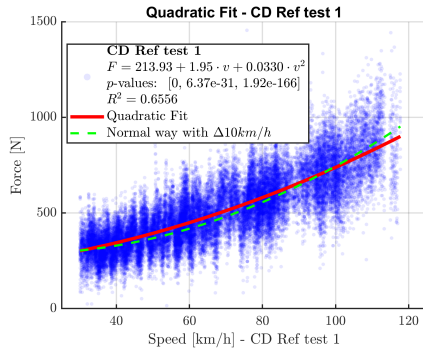
(e) CS Day 2 W3



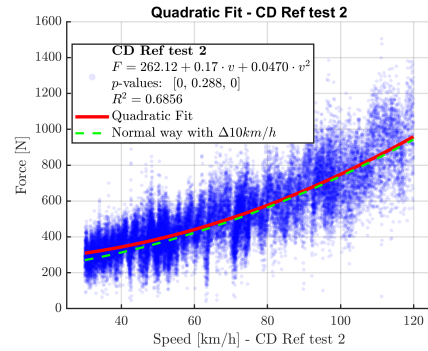
(f) CS Behind Truck

Comparison of individual constant speed (CS) test summaries.

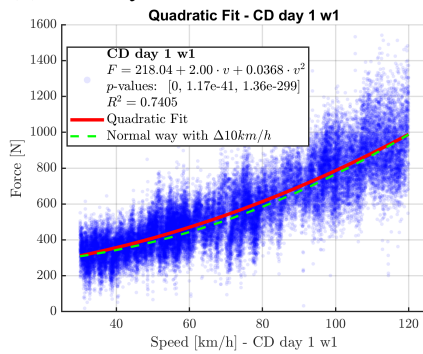
# Appendix IV: Individual Regression Result CD



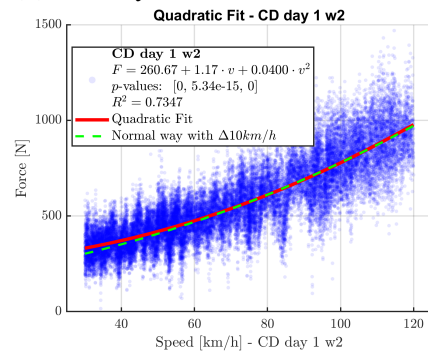
(a) CD Day 1 Ref Test



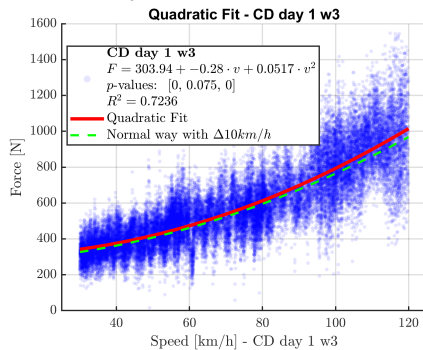
(b) CD Day 2 Ref Test



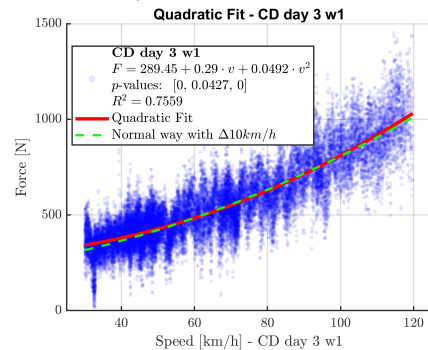
(c) CD Day 1 W1



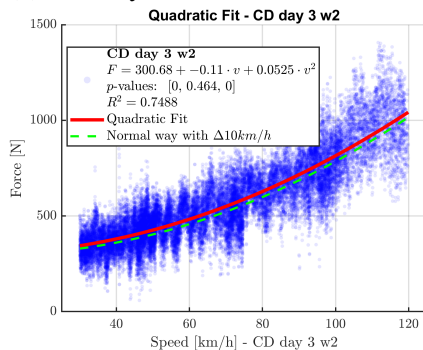
(d) CD Day 1 W2



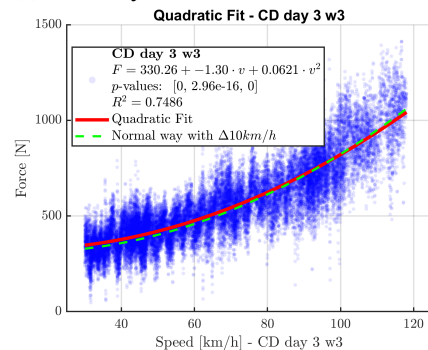
(e) CD Day 1 W3



(f) CD Day 3 W1



(g) CD Day 3 W2



(h) CD Day 3 W3

Regression model on individual coast down (CD) test including normal way of calculating roadload curve.



**CHALMERS**