Connected Tyres

Real-time Tyre Monitoring System for Fleet and Autonomous Vehicles with Tyre Wear Estimation through Sensor Fusion

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Abstract

Tyres are one crucial part for vehicles, as they are the only contact point between the vehicle and the road. Intelligent tyres are a trending new subject in the tyre industry. They are designed to monitor various tyre states and send this information to both drivers and remote servers. The master thesis focuses on the proposal of a real-time tyre monitoring system for fleet and autonomous vehicles. It includes developing a tyre wear model and analysis of the current tyre pressure monitoring functionality by leveraging the connectivity of fleet vehicles equipped with a Volvo web cloud service. The tyre wear model indirectly monitors the tread depth of the vehicles all four tyres by identifying characteristics between worn and fresh tyres. The two characteristics are identified by monitoring and analyzing vehicle speed and braking signals. The two characteristics is input to a voting scheme which decides when a worn tyre is detected. The test vehicle was a Volvo XC40 with three types of tyres: winter tyres, summer tyres and worn summer tyres. The wear model gives 90% accuracy to 10 set of test data, randomly selected from all dataset at Hällered Proving Ground (Sweden). The connectivity realizes the data transmission from the raw data of onCAN and FlexRay signals stored in a Volvo web cloud service to the tyre monitoring fleet system. The signals are filtered and resampled, leaving the required signals of the tyre pressure monitor system and the tyre wear model. Two signals, Calibration Status and iTPMS Status, are used to perform a statistical analysis on tyre pressure by categorizing the calibration status and the tyre pressure conditions. The project outcome is an interface built on MATLAB GUI for demonstration of vehicle identification and tyre health conditions, with the embedded tyre wear model and connectivity.
**Sammanfattning**

# Contents

1 **Introduction** .................................................. 1  
   1.1 Problem statement .............................................. 5  
   1.2 Research significance and motivation ...................... 5  
   1.3 Research objectives .......................................... 5  
   1.4 Thesis outline ................................................ 6  

2 **Tyre Wear Model** ........................................... 8  
   2.1 Approach ....................................................... 8  
      2.1.1 Test site ................................................. 8  
      2.1.2 Test vehicle ............................................. 9  
      2.1.3 Test tyres ............................................... 10  
      2.1.4 Test plan ................................................ 11  
   2.2 Features of worn tyres ........................................ 12  
      2.2.1 Speed analysis .......................................... 12  
      2.2.2 Braking analysis ........................................ 15  
      2.2.3 Frequency analysis ...................................... 20  
   2.3 Tyre tread depth indicator .................................. 20  

3 **Connectivity** ................................................ 22  
   3.1 Introduction .................................................. 22  
   3.2 WICE .......................................................... 23  
   3.3 Measured signals ............................................. 23  
   3.4 Data processing ............................................... 23  

4 **User interface** ............................................. 25  
   4.1 Introduction .................................................. 25  
   4.2 UI design ...................................................... 25  
      4.2.1 Main interface .......................................... 26  
      4.2.2 Interface of statistics on tyre pressure ............... 26
Chapter 1

Introduction

Tyres are essential for vehicles, as tyres are the only component that contacts the roads. The longitudinal force generated by tyres affects the accelerating and braking performance, while the lateral force, also called cornering force, offers the capacity to resist sliding sideways when in a corner. Besides, tyres support the load of the vehicle and absorb shocks when driving in uneven roads, which improves the ride comfort. Therefore, the quality of tyres has a crucial impact on the driving experience.

In fact, a lot of research have been conducted on modeling of tyres. As a result, the linear model, brush model and magic formula have been proposed for many years and they are very typical and useful tools to study the characteristics of tyres. For example, the magic formula is a classic mathematical model of tyres, which only uses one set of formulas to completely express the mechanical characteristics of tyres under pure working conditions [1]. With sensor fusion, the tyre-road contact forces are possible to be estimated in electric control units (ECUs) [2]. One of the most important systems, the tyre pressure monitoring system (TPMS) is installed in the vehicle to monitor the tyre pressure and temperature. TPMS is able to monitor the tyre condition in real time through electronic sensors installed inside the tyre. An alert is given to the driver when TPMS detects low pressure of any tyre. The National Highway Traffic Safety Administration, U.S. Department of Transportation, stipulates that there must be an alert from TPMS for the driver when the tyre pressure is less than 75% of the standard value [3]. The tyre manufacturer suggests that when the tyre pressure drops by 30% of the standard value, TPMS needs to give an alarm to remind the driver.

TPMS has proved as a very effective method to reduce the tyre-related accidents over the last decade. It is a standard configuration for many countries
and regions now. For instance, U.S. law requires that all passenger cars and light trucks sold in the U.S. must be equipped with a TPMS since August 2007. Shortly after, European and Chinese regulations have also been issued since November 2014 and January 2020 respectively. Nowadays, almost every new car is equipped with a TPMS.

Up till now, two kinds of TPMS are installed in the vehicles. They are direct TPMS (dTPMS) and indirect TPMS (iTPMS) respectively.

The dTPMS uses a pressure sensor, usually located on the inside wall of the valve, to measure the pressure of each tyre. Then the tyre pressure information is transmitted to ECUs by a wireless transmitter. With temperature sensors, the tyre temperature information can be obtained as well. Finally, pressure and temperature of every tyre are displayed in the user interface of the vehicle. When any tyre has the characteristic of excessively abnormal pressure or temperature, there will be a warning signal in the car central control interface.

As the dTPMS uses extra hardwares to measure the tyre pressure, it increases the vehicle production cost. Therefore, the vehicle companies prefer iTPMS, which does not require extra sensors, but only some algorithms. There have been a lot of research and study projects on iTPMS. The iTPMS relies on two parts: vibration analysis and wheel radius analysis [4]. Vibration analysis monitors the vibration frequency from the torsional spring-damper systems and detects abnormal values of the frequency. Wheel radius analysis uses the fact that the effective rolling radius of the wheel becomes smaller if the tyre pressure is low. Applied with a voting scheme, two feature analyses have made iTPMS reliable.

Despite the wide application of TPMS, among other safety centric features, there are still 1.35 million death in traffic accidents every year. Between 20 and 50 million people are injured in different serious situations according to the statistic on road traffic injuries of World Health Organization [5]. Road safety is still a concern and needs to be improved. It is necessary and urgent to look for more effective and creative methods to monitor more factors of tyres, such as tyre wear conditions. Besides, the automotive industry is undergoing a revolution. The most frequently-mentioned changes are: autonomous, connected, electric and shared (ACES) [6]. In order to keep up with the industry trends in this transformation, many car companies and even Internet companies have already moved towards the four new directions.

During the Corporate Side Presentations at the 2019 Fleet Europe Summit, the experts working on connectivity and mobility from all over the world presented their latest ideas and future visions [7]. Yaël Bennathan, the Head of Arval Mobility Observatory, says that all new cars produced by 2025 will be
connected [7]. As more and more cars are becoming connected, it promotes the development of connectivity of tyres. In fact, many well-known tyre companies have already conducted several studies and experiments on this topic and some cases of connected tyres have already been put into practice.

The ContiConnect, shown in Figure 1.1, designed by Continental monitors tyre information with built-in sensors. The data are transmitted to a web portal through a yard reader station. The yard reader station is a communication bridge between data from the tyre sensors and back-end. The data transmission can only happen when there is a yard reader station. Usually the yard reader stations are distributed in gas stations and some other public places where cars often go. Otherwise, the driver can use the hand-held tool to import tyre data to the web portal when no yard reader stations are nearby. The drivers can enter the web portal to see the tyre conditions of their vehicles using their smartphones and computers. The drivers will be informed by email and text message with some recommended measures when there is great risk of tyre-related breakdowns [8].

![Tyre sensor](image1.png) ![Yard reader station](image2.png)

![Hand-held tool](image3.png) ![Web portal](image4.png)

Figure 1.1: ContiConnect components [8].

The intelligent tyre system developed by Hyundai Motor Co, Mando Corp and Corechips uses the sensors mounted in the inner liner of tyres to measure the tyre deformation, which is transmitted to the surface acoustic wave sensor
by passive radio communication. After that, the data are imported to the ECU of the intelligent tyres and converted into tyre force information finally by a force conversion algorithm [9].

Michelin developed Pilot Sport Cup 2 tyres with Track Connect technology in 2018. The tyre pressure and temperature are measured by the sensors placed in each tyre. The measured data are transferred to the vehicle by a radio signal and then transmitted to a phone by Bluetooth [10]. The data are visualized in the interface of the APP in the end so that the drivers can read the information easily. This technology tells the driver the information about the tyre pressure and temperature all the time during driving. Besides, it is also possible to tell the driver’s driving behavior in the case of turning by analyzing the pressure balance between front and rear tyres [10].

Similarly Pirelli once tried to introduce a mobile APP Connesso to display the data gathered from sensors. Now the company is working on Cyber Tyres system, shown in Figure 1.2, combined with 5G technology as 5G improves the data transmission speed greatly. The special sensor is mounted inside the wheel and a radio transmitter inside is used to transmit the data to other electronic devices in the car [11]. With the Pirelli Cyber Tyre system, it is not only possible to monitor the basic signals from tyres, but also has the potential to identify the tyre grip, tread wear and the road information.

Figure 1.2: Pirelli’s Cyber Tyres describe the road surface [12].
1.1 Problem statement

Nowadays, connected tyres are applied into practice on some vehicles, most being buses and heavy duty trucks. One reason is that because losses and injuries caused by accidents related to buses and trucks are more serious than passenger cars. The other reason is the cost of connected tyres. As equipped with data transmit devices and sensors in tyres, the cost of connected tyres is much higher than normal tyres.

Meanwhile, the autonomous driving is one popular subject. In order to guarantee safety, tyre health information of autonomous cars must be monitored. Intelligent tyres on the market are one solution to establish connectivity between cars and servers, but are often too expensive for car companies.

1.2 Research significance and motivation

Tyres with good tread depth can reduce risks of aquaplaning and decrease the braking distance when driving in wet road surface [13]. Intelligent tyres use built-in sensors to calculate all the information about the tyres so as to decrease the tyre-related driving risk, such as each tyre pressure, temperature, wear condition, traction force, friction potential and slip condition [14]. Furthermore, connectivity of intelligent tyres can be used to collect road information and driving behavior. Through the fleet system, the user can monitor all tyre information of various cars remotely. The data obtained from sensors can be used for different organizations. For example, relevant government departments can use the road information to monitor the urban road surface condition. Experts can optimize autonomous driving by analyzing the information related to drivers’ driving behavior. These users do not need to go to testing grounds and do tests by themselves; instead, they can sit in their offices or their laboratory and extract the data they need from the fleet system. The data can be from every vehicle with connected tyres.

To keep up with the development of autonomous driving and Internet of Things (IoT), it is necessary to develop more advanced tyre monitoring systems.

1.3 Research objectives

This thesis aims to develop a real-time tyre monitoring fleet system. The information is not limited to tyre pressure, but also including tyre wear condition.
Additionally, no extra sensors is needed for saving cost. In details, it consists of three parts, the tyre wear model (TWM), the connectivity and the real-time tyre monitoring system (RTMS).

- **TWM**: It indirectly estimates the tread depth of four tyres through identifying certain features of worn tyres. A warning indicator will be given if worn tyres are detected. The two features are speed difference between tyres and braking slip difference between worn and new tyres.

- **Connectivity**: Within Wireless Information Collection Environment (WICE), data are collected and sent from vehicles to company portals through a WICE Communication Unit (WCU). With data pre-processing, signals are filtered and re-sampled for TWM and other applications.

- **RTMS**: The two parts, TWM and connectivity, are embedded in this system. A user interface (UI) is designed by MATLAB GUI to display tyre health information of vehicles on roads, including tyre pressure and wear condition.

### 1.4 Thesis outline

The thesis is organised into the following chapters:

- **Chapter 1** introduces the background and research significance of this topic. Besides, it explains the framework of the report to give readers a rough understanding of the whole report.

- **Chapter 2** explores the possibility of indirectly detecting worn tyres on a vehicle. It includes data analysing of two tests and how TWM is constructed.

- **Chapter 3** presents the data transmission of the on-board signals through WCU.

- **Chapter 4** demonstrates the UI design of RTMS as well as a data analysis interface of tyre pressure.

- **Chapter 5** illustrates RTMS with embedded TWM and connectivity. An example of RTMS is shown with the designed UI.

- **Chapter 6** discusses the performance of RTMS appropriately. Furthermore, the results of the system verification test are discussed.
• Chapter 7 summarises the background and results. This chapter also highlights what can be done about RTMS in the future.
Chapter 2

Tyre Wear Model

In this chapter, the focus will be on the Tyre Wear Model. Beginning with the tests that have been done, this chapter will show how each feature is identified and calibrated.

2.1 Approach

According to the literature research in Chapter 1, tyre manufacturers are putting lots of resources into intelligent tyres. However, the cost of those tyres are high due to extra sensors and ECU installed within them. The possibility that the tyre state can be indirectly estimated has not been fully explored. This section will focus mostly on the wear degree of tyres. It only requires the sensors that already exist in the vehicle. Tests have been done to identify such possibility.

2.1.1 Test site

There were two tests in total, one on February 26th and the other on May 19th and 20th in 2020. The tests were done at Hällered Proving Ground. The first test on February 26th was a sunny day during winter around 5 °C and the tracks were dry. The first day of the second test was sunny around 8°C but just after raining. The tracks were wet during the morning and became dry in the afternoon. The second day was sunny around 14°C and the tracks were dry. A top view of Hällered Proving Ground is shown in Figure 2.1.
In order to identify the feature of worn tyres, the following tracks were chosen:

- **Track I: Country Road Track**
  This track contains a long straight road, where most of tests were done. This represents one usual driving scenario, starting from standstill, driving straight with a constant speed and then braking until stop.

- **Track II: High Speed Track**
  The track is an oval track with four lanes, where a car can run up to 250 km/h at the outside lane for licensed drivers. It imitates running on a highway with high speed.

- **Track III: Handling Track II**
  The handling track is a complicated track. It has uphills and downhills, turning and uneven surfaces. This track shows the driving experience within mountain areas, which is common in Sweden.

### 2.1.2 Test vehicle

A Volvo XC40 (Figure 2.2) was used as the test vehicle for both tests. The test vehicle was an on-going Volvo project for testing. No modifications were made to the test vehicle except the tyres.
The data collection were done through CANoe and FlexRay. CANoe is a comprehensive software tool for development, test and analysis of individual ECUs and entire ECU networks. It supports network designers, development and test engineers throughout the entire development process from planning to system-level test [17]. FlexRay is a scalable, flexible high-speed communication system that meets the challenges of growing safety-relevant requirements in the automobile [18].

For the test vehicle XC40, the CANoe module for transmitting bus signals was positioned underneath the driver’s seat. After connecting the two cables named as FlexRay from the module and Vector VN7640, the access to bus signals was established on the laptop. In the interface of CANoe, the database of FlexRay was imported and chosen to be recorded from the real-time signals.

### 2.1.3 Test tyres

The two worn tyres used for tests were Pirelli summer tyres, 245/40R21, with the tread depth of 4.9 and 5.1 mm respectively. The threshold of worn tyres, not worn-out, is hence set as 5 mm. According Swedish law, the legal requirement for worn-out tyres is 3 mm for winter tyres and 1.6 mm for summer ones [19]. During the first test, it was winter, so winter tyres with the same radius and tread depth of 7.1 mm were mounted on the test vehicle for testing. For the second test, four fresh tyres, which had the same tyre size and brand, were ordered and tested with the worn tyres.

The cold tyre pressure for all tyres were controlled as 2.3 kPa, which was
the recommended pressure for these tyres. Since tyre pressure can greatly affect the performance of tyres, it is essential to control the tyre pressure as the same for all test tyres. There is also no difference in tyre temperature between the four tyres on the test vehicle.

### 2.1.4 Test plan

The test goal was to find the features of worn tyres compared to fresh tyres. Hence, different tyre combinations were planned for testing. For the first test on Feb 26th, the tests were carried out according to Table 2.1.

<table>
<thead>
<tr>
<th>Tyre Group</th>
<th>Mounted Tyres</th>
</tr>
</thead>
<tbody>
<tr>
<td>I (worn)</td>
<td>4.9 mm summer tyre on the front left with three 7.1 mm winter tyres</td>
</tr>
<tr>
<td>II (reference)</td>
<td>four 7.1 mm winter tyres</td>
</tr>
</tbody>
</table>

For each tyre group, same tests were done based on

1. **Straight Case** Driving on Track I at 40, 60, 80 and 100 km/h respectively with two trials.

2. **Braking Case** Hard braking until stop on Track I from 50 and 60 km/h respectively with two trials.

3. **Handling Case** Driving on Track III at 40, 60, 80 km/h and free-run respectively with two trials.

The second test happened on May 19th and 20th in order to verify what have been found in the previous test. The procedure were similar as Table 2.2.

<table>
<thead>
<tr>
<th>Tyre Group</th>
<th>Mounted Tyres</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>5.1 mm tyre at front left with three fresh tyres</td>
</tr>
<tr>
<td>II</td>
<td>5.1 mm tyre at front left and 4.9 mm at front right with two fresh tyres</td>
</tr>
<tr>
<td>III</td>
<td>4.9 mm tyre at rear left with three fresh tyres</td>
</tr>
<tr>
<td>IV</td>
<td>four fresh tyres</td>
</tr>
</tbody>
</table>

1. **Straight Case** Driving on Track I at 40, 60 and 80 km/h respectively with two trials.
2. **High-speed Case** Driving on Track II at 100 km/h with two trials.

3. **Braking Case** Hard braking until stop on Track I from 40, 60 and 80 km/h respectively with two trials.

4. **Handling Case** Driving on Track III at 60, 80 km/h and free-run respectively with two trials.

For simplicity, the tyre location is abbreviated as FL (front left tyre), FR (front right tyre), RL (rear left tyre) and RR (rear right tyre).

### 2.2 Features of worn tyres

In this section, two features will be shown. The two features were first found during the first test and then verified in the second one. In the first test, winter and summer tyres were compared, but the difference between tyres were not only tyre tread depth, but also tread patterns. The second test was a test with control on variables. The difference is only the tyre tread depth. The findings of both tests will be shown, but it should be noted that the first test comes with a bias on tyres, as what was found in the first test was intentionally found.

#### 2.2.1 Speed analysis

The first and most obvious difference between worn and fresh tyres is the speed difference of four wheels during the first test. Figure 2.3 shows the speed signals of the vehicle, worn and fresh tyres in the straight driving cases.
Figure 2.3: Speed signals during straight driving cases of first test (blue line as 5.1 mm tyre, orange line as 7.1 mm tyre and yellow line as vehicle speed).

The blue line in Figure 2.3 is the speed signal of FL tyre, which is the worn tyre. During the straight driving cases, the worn tyre has a much lower speed than the other three tyres, as well as the vehicle speed. Since the worn tyre was also a summer tyre while the other three winter tyres, it is unclear which factor is more significant. During the second test, the same worn tyre is compared with new tyres of the same model.

Figure 2.4 shows the speed signals of four wheels compared to the vehicle speed.

Figure 2.4: Speed signals during straight case of second test.

However, a clear difference cannot be found in those cases, and thus the
slip of the four wheels are calculated as

\[ \text{slip} = \frac{r \omega - v}{r \omega} \times 100\%, \] 

(2.1)

where \( r \) is the radius of tyres, \( \omega \) is the wheel rotation speed and \( v \) is the vehicle speed. Taking the median value of the slip, each test case has four values of the median slip of the four wheels respectively. While driving at a constant speed, the median slip of a wheel has a certain relationship with the vehicle speed. Different speed requires different driving force on tyres, which results in different slip value. Figure 2.5 shows the relationship between slip and vehicle speed. The consistent difference between tyre groups is the slope of the linear fit. For Group IV, which all four tyres are fresh, the slope is the minimal as shown in Table 2.3. The slip of four tyres at one case are determined by the median value of the data.

Figure 2.5: Median Slip vs vehicle speed during straight cases (dot as data points and lines as linear fit).
Table 2.3: Result of linear fit for straight cases.

<table>
<thead>
<tr>
<th>Group</th>
<th>Slope of linear fit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FL</td>
</tr>
<tr>
<td>I</td>
<td>0.1592</td>
</tr>
<tr>
<td>II</td>
<td>0.0135</td>
</tr>
<tr>
<td>III</td>
<td>0.0169</td>
</tr>
<tr>
<td>IV</td>
<td>0.0003</td>
</tr>
</tbody>
</table>

The test vehicle of groups I, II and III are installed with worn tyres (5.1mm or 4.9mm), demonstrating a higher slope compared to group IV, around 10 times larger. The maximal slope as group I implies that road condition would affect the relationship between vehicle speed and slip, as tracks were wet just after rain, which is mentioned in section 3.1.1. Overall, the straight cases of the second test supports the speed feature found in the first test. The vehicle with worn tyres tend to have a larger slip compared to that with fresh tyres. Moreover, worn tyres, no matter the number and location of worn tyres, will influence the slip of all four wheels. The mean value of slopes of four wheels is thus used to determine whether a vehicle has worn tyres or not.

### 2.2.2 Braking analysis

So far, estimating tyre pressure has proven to be practical in vehicles, which is called iTPMS. The tyre state however includes more than just tyre pressure. According to a United States patent, tyre wear state can be estimated through a similar method, wheel speed signal feature extraction [20]. In details, it uses the existing speed signals of four wheels during braking and extracts a first and second features from them, median slip ratio and median slip rate. Then, a support vector data classification algorithm is applied to find the wear state of tyres. Inspired by this patent tests are hence carried out in field.

\[
\text{SlipRatio} = \frac{v - r\omega}{v} \times 100% \tag{2.2}
\]

\[
\text{SlipRate} = \frac{d\text{SlipRatio}}{dT}\text{ime} = \frac{\text{SlipRatio}(n) - \text{SlipRatio}(n-1)}{\text{time}(n) - \text{time}(n-1)} \tag{2.3}
\]

Using Eq 2.2 and 2.3, speed signals are converted into slip ratio and rate. Next, the values of slip ratio and rate is plotted with the density function in Figure 2.6. The density function is a function providing a relative likelihood that the value of the random variable would equal that sample [21].
The worn winter tyre in test 1 tends to have a peak shift to left and a higher peak compared to the other tyres. In order to apply a classification algorithm, the median value (location of peaks in Figure 2.6) of these two features are extracted and plotted in Figure 2.7.
The data implies a linear discrimination between two different tyres. Compared to fresh tyres, the worn tyre has a smaller median slip ratio and median slip rate. However, due to the limited number of data points, the classification algorithm cannot be determined. More tests are done in the second test, and results are shown in Figure 2.8 with the same method.

The data are categorised into worn and fresh tyres, corresponding to 4.9/5.1mm and newly-ordered ones. The same pattern is found in the second test as the
first one. There exists a discrimination between worn and fresh tyres, and a proper classification algorithm is then to be fixed.

Statistical learning, also known as machine learning, is a highly powerful and common tool in modern world. For this braking feature classification, supervised learning is a proper method. In other words, there is a set of variables that might be denoted as inputs, which are measured or preset. These have some influence on one or more outputs. For each example the goal is to use the inputs to predict the values of the outputs [22]. In this case, inputs are the median slip ratio and median slip rate, while only one output is the wear state of tyres.

The Classification Learner toolbox in MATLAB, as shown in Figure 2.9, allows an easy way to perform supervised learning. With the input of features extracted from braking cases, the toolbox gives results of different classification algorithms.

![Classification Learner toolbox in MATLAB.](image)

Figure 2.9: Classification learner toolbox in MATLAB.

After performing training to all algorithms, the linear support vector machine (SVM) yields the highest accuracy as 89.6%. SVM uses a technique called the kernel trick to transform the data and then based on these transformations it finds an optimal boundary between the possible outputs [23]. In this model, the linear SVM means that the boundary is a straight line that cuts features into two groups, where the line is determined by SVM. The confusion matrix of linear SVM is shown in Figure 2.10. Each class has 24 data. The
linear SVM accurately predicts 20 for fresh tyres and 23 for worn ones, which in total is 43 out of 48. The accuracy is then found as 89.6%.

The linear SVM model is then exported and saved in a mat file. It can be used for analysis of more test data. The linear SVM gives the classification equation Eq 2.4, which is shown in Figure 2.11. The crosses are the misclassified points, while dots represent the correctly-classified ones.

\[ y = -1.498 \times x + 53.99. \] (2.4)
2.2.3 Frequency analysis

One method used in iTPMS is the vibration analysis, which considers the rubber of tyres that behave like springs [4]. The tyre pressure affects the resonance frequency of tyres significantly, and thus is used to predict tyre pressure. The tread depth implies the thickness of rubber in tyres, which is an influencing factor to the resonance frequency.

During the analysis of test data, the speed signals of four wheels were converted into frequency domain through fast Fourier transform (FFT). The resonance frequency of tyres could be identified as the frequency where there appears to be peaks. However, after two tests, this feature is found to be irrelevant to tyre tread depth, but to the tyre itself.

![Figure 2.12: Plot of frequency response during the straight cases of test 1.](image)

The blue line in Figure 2.12 represents the worn winter tyre during test 1. Compared to the other three tyres, it has a lower peak frequency and amplitude, which is also found in other cases in test 1. However, the worn tyres in test 2 shows no such feature. Hence, it sums that the difference of frequency peaks is only related to the tyre, not tyre tread depth.

2.3 Tyre tread depth indicator

In this section, the tyre tread depth indicator is constructed based on two features in Section 2.2. Figure 2.13 shows the flow chart of the tyre tread depth indicator. The function of the indicator is written in MATLAB, taking in data
collected through CANoe. The output is an indicator showing whether any tyre is worn or not.

For each feature analysis, the signals of four tyres are compared to the reference data (tyre group IV) separately. The speed analysis compares the slope of the linear fit between median slip and vehicle speed, while the braking analysis uses the linear SVM for classification. The output of both features is a flag, $t_i (i = 1, 2)$, representing the result as

- $t_i = -1$: Not enough data
- $t_i = 0$: No worn tyres detected
- $t_i = 1$: Worn tyre(s) detected

The voting scheme sums the two flags and the indicator shows different colors for different situations. If either flag is negative (not enough data), the indicator is gray, meaning the function unavailable. The sum of the two flags then corresponds to green and yellow indicators based on

- **Gray** $t_1 < 0$ or $t_2 < 0$
- **Green** $t_1 + t_2 = 0$
- **Yellow** $t_1 + t_2 > 0$
Chapter 3

Connectivity

WICE collects vehicle signals through the dedicated component mounted on company cars and saves the data in the cloud. In this chapter, the raw data stored in WICE cloud are processed for further application in the UI. Connectivity between raw data and the back-end is realised by python scripts.

3.1 Introduction

To collect vehicle signals and transmit the data to the fleet and other applications in real time, it is achieved by telematics technologies in most cases. Nowadays this function is realized primarily by wireless communication, such as trunked radio and cellular communication [24].

Tyre companies have started to use Radio Frequency Identification (RFID) tyre tags to trace the tyre in its whole life. When a tyre with the RFID tag pass through the reader areas, the tyre information and its data will be transmitted to the fleet so that the operator can understand the tyre’s lifecycle better. Compared with wireless local area network (WLAN), the RFID is more suitable for large areas where the wireless network cannot completely cover. Therefore, it is more widely applied [25]. Besides, bluetooth is also applied in data transmission. Although it costs very little, it is limited by the transmission distance to a high degree. So its application is not very wide.

Thanks to the rapid development of mobile communications, it provides the opportunity to reach faster and more large-scale data transmission as long as the place is covered by antennas coat cell towers [26]. Especially because 5G greatly increases the speed of data transmission, the application in aspect of cellular communication is becoming more and more popular.
3.2 WICE

WICE is a system which collects vehicle signals in real time. The data of measured signals are collected by the external Wireless Communication and Data Acquisition Units installed in vehicles. The system supports the testing and validation stages of automotive development by telematic technology, the wireless local area network in the company in most cases. Each car is configured with a Wireless Communication Unit (WCU), the special device to handle the communication between the car and the portal. With the GSM/GPS/WiFi antenna inside the car, the big data are stored in a network address.

To monitor one signal, the signal name should be added to the signal reader through the WICE portal at first. The signal reader is a measurement module that allows monitoring and logging of vehicle signals. Once the signals exist in the signal reader, they will be recorded and saved automatically. The data for every vehicle in every driving cycle will be downloaded and stored as a .sy data file in the network address. Every day a new folder which is named by the date is created to store the data files.

3.3 Measured signals

In this thesis, all the test cars are equipped with iTPMS. The signals used to indicate the status of tyre pressure and calibration are required to be measured. The signals are shown in detail in Table 3.1. All the signals are measured from the company cars mostly in Gothenburg area.

<table>
<thead>
<tr>
<th>Signal names</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CalSts</td>
<td>Indicating calibration status</td>
</tr>
<tr>
<td>iTPMSSts</td>
<td>Indicating tyre pressure warning or iTPMS malfunction</td>
</tr>
</tbody>
</table>

3.4 Data processing

The raw data consist of all signals in the signal reader. The data of redundant signals should be removed at first. Another problem is that the sampling time is not constant. Consequently, data processing is needed before utilising the data. Then the processed data can be used for further application for different
purposes. The data processing is done by python scripts. The data transmission process is shown in Figure 3.1.

![Flow chart of data transmission.](image)

Figure 3.1: Flow chart of data transmission.

The data processing is consisted of three parts, as listed:

- **Signal filtering**
  The signals are filtered by specifying signal names so that only the data of specific signals will be handled later.

- **Time vector re-sampling**
  The sampling time is adjusted to be 1 second so that the data are recorded at fixed time interval and the redundant data will be removed.

- **Data extraction**
  Processed data are saved in an excel or a mat file in the local computer for further application in MATLAB.

Through the three steps of data processing, only data of needed signals will be saved in the new data file, which can be read by MATLAB directly. Accordingly, the connectivity between vehicle signals and back ends is achieved.
Chapter 4
User interface

The UI is a platform to demonstrate RTMS. It allows an easy interaction between users and RTMS, which is realised by categorising all date files by date and visualising data of the chosen file. In addition, tyre pressure conditions and calibration status are analysed in this chapter, such as the frequency statistics of different scenarios in a month.

4.1 Introduction

The UI helps the user to extract desired information and visualises the information. The information is displayed in a certain pattern to allow people to get the information which is relevant to their goals quickly [27]. While designing a UI, there are many aspects that need to focus on, which are essential to make the UI concise, such as the font size, the graphics and placement of text and images, the colors and the page layout [28]. To create a good UI, its function must match its design and it must have a clear interface and quickly guide users.

4.2 UI design

In this thesis, as RTMS is based on MATLAB, the UI is also created by the MATLAB GUI tool. The UI is designed to visualise the information including tyre health conditions and vehicle identification, such as tyre pressure conditions, calibration status, tyre wear estimation results, car alias and car ID. Different colours are used to present different conditions, which is noted in main interface. The UI has two interfaces: main interface and the interface of statistics on tyre pressure. In the main interface, the operator can check any
document at any time to see its result. In the interface of statistics on tyre pressure, tyre pressure conditions and calibration status of all cars in a month are classified. The frequency of each scenarios is calculated and recorded. The results are shown in line graphs, pie charts and tables in detail.

4.2.1 Main interface

Main interface is shown in Figure 4.1. There are mainly four colours which are used to indicate different conditions for tyre pressure conditions, calibration status and tyre wear estimation results. When the UI is opened, the operator clicks the Log button and then choose the specific date. The filtered data files with CalSts and iTPMSSts signals appear in the Datafiles list. When one data file is clicked, the vehicle identification and tyre health conditions information will be displayed automatically in the corresponding places. The switch of data file under the same date can be achieved effortlessly by clicking another data file. Similarly, it is straightforward to choose another date.

![Main interface of UI for RTMS.](image)

4.2.2 Interface of statistics on tyre pressure

Analogously in Figure 4.2, the list in the bottom left of the interface corresponds with the month list in main interface. Once the Start button is clicked, the month will be chosen accordingly. Furthermore, there are two line graphs
and two pie charts. As for the line graphs, the top one is used to record the number of vehicles with *iTPMSS* signals as well as the total number of vehicles. The other one represents *CalSts* signals. Similarly, the pie charts demonstrate the proportion of different signal values of the cars with those two signals in the selected month individually. As some parts of pie charts are pretty small, resulting that the values of the percentages coincide in the same place, all values are noted in the left of the pie charts so that users can see the values clearly. If the user wants to see the results of another month, it can be done by changing the month in main interface and then click *Start* button in the new data analysis interface, while the previous interface will not be closed. By comparing the results of two or more months, the user can obtain the total number of vehicles with measured *iTPMS* signals and analyse the frequency of calibration.

![Figure 4.2: The interface of statistics on tyre pressure.](image)
Chapter 5

Results

Tests to validate the TWM and RTMS are conducted in this chapter.

5.1 Test on TWM

The accuracy of TWM is tested with the test data of the second test. In order for two features to work at the same time, three test cases of the same trial number are combined; in other words, there are totally eight groups of test data (I.1, I.2, II.1, II.2, III.1, III.2, and IV.1, IV.2), as explained in Table 2.2. The tyre wear model uses these groups to predict accurately results. Table 5.1 shows the results of TWM for data of second data.

<table>
<thead>
<tr>
<th>Group</th>
<th>Mounted Tyre</th>
<th>Tyre Wear Indicator</th>
</tr>
</thead>
<tbody>
<tr>
<td>I.1</td>
<td>FL worn</td>
<td>Worn tyre detected</td>
</tr>
<tr>
<td>I.2</td>
<td>FL worn</td>
<td>Worn tyre detected</td>
</tr>
<tr>
<td>II.1</td>
<td>FL &amp; FR worn</td>
<td>Worn tyre detected</td>
</tr>
<tr>
<td>II.2</td>
<td>FL &amp; FR worn</td>
<td>Worn tyre detected</td>
</tr>
<tr>
<td>III.1</td>
<td>RL worn</td>
<td>Worn tyre detected</td>
</tr>
<tr>
<td>III.2</td>
<td>RL worn</td>
<td>Worn tyre detected</td>
</tr>
<tr>
<td>IV.1</td>
<td>All fresh</td>
<td>No worn tyre detected</td>
</tr>
<tr>
<td>IV.2</td>
<td>All fresh</td>
<td>No worn tyre detected</td>
</tr>
</tbody>
</table>

In order to verify the model, a random sampling was made based on the data of the second test to test the accuracy of TWM. The difference between this method and the test in Table 5.1 is that a random sample can eliminate the bias of sampling from the training data, as the test data is the training data.
In Figure 5.1 the number of sampling files is first chosen with the default number being 10. After pressing the START button, random samples are chosen and shown in the first column of the table. The second column demonstrates the tyre conditions of each sample, while the third column shows the prediction of TWM. The accuracy is then calculated and shown below the table. One random validation is shown in Figure 5.2.

Figure 5.1: GUI of test on TWM with random sampling.

Figure 5.2: Result of random sampling to test TWM.

5.2 Trial run of RTMS

The TWM and UI are connected together to check the feasibility of RTMS. The data of the car with all signals needed are analysed in the UI and the results are displayed in the main interface.
5.2.1 RTMS

The required signals for TWM are also added to the signal reader in WICE, shown in Table 5.2. After the same data processing as iTPMS signals, the required signals for TWM are saved in the same excel file and mat file. The excel file is used to save the data of one specific data file while the mat file is used to store the data in a month. In other words, the excel file is for the main interface while the mat file is mainly for the interface of statistics on tyre pressure. Through embedding TWM in the UI and calling the python scripts by MATLAB, RTMS is realised.

Table 5.2: Input signals for TWM.

<table>
<thead>
<tr>
<th>Signal Names</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLWhlSpd</td>
<td>Indicating the circumferential speed of front left wheel</td>
</tr>
<tr>
<td>FRWhlSpd</td>
<td>Indicating the circumferential speed of front right wheel</td>
</tr>
<tr>
<td>RLWhlSpd</td>
<td>Indicating the circumferential speed of rear left wheel</td>
</tr>
<tr>
<td>RRWhlSpd</td>
<td>Indicating the circumferential speed of rear right wheel</td>
</tr>
<tr>
<td>BrkPedv</td>
<td>Indicating the state of braking</td>
</tr>
<tr>
<td>VehSpdLgt</td>
<td>Indicating vehicle longitudinal speed</td>
</tr>
<tr>
<td>VehSpdLat</td>
<td>Indicating vehicle lateral speed</td>
</tr>
</tbody>
</table>

5.2.2 Result of trial run

When the UI is opened and the raw data file stored in WICE portal is selected, the vehicle identification and tyre health information will be displayed in the main interface after the data processing. According to the information displayed in the UI of RTMS which is shown in Figure 5.3, it can be seen that for the selected car, all four tyres have good air pressure and wear conditions and there is no calibration request. The interface of statistics on tyre pressure shows the corresponding statistical results of the selected month in main interface as shown in Figure 5.4.

From the interface of statistics on tyre pressure, it can be seen that around one third vehicles equipped with WICE devices were logging iTPMS signals. 95% of the cars had no warning of low tyre pressure. As for the cars with low tyre pressure warning, 3 quarters of these cars experienced common warning, which means more than one tyre had low air pressure. Only 1 car had the system failure. No cars had system unavailable and system unavailable SWDL. Regarding the calibration, 84.05% of the cars didn’t need
to do calibration and 10.58% of the cars successfully completed calibration. 5.37% of the cars were still experiencing calibration. No calibration failed in May. Moreover, the number of cars with CalSts signal agreed with the number of cars with iTPMSSSts signal according to the scatter plot shown in Figure 5.5. As the number of cars with calibration signal was increasing, the number of cars with tyre pressure warning signal increased as well, which implies the iTPMS inside company cars works well.

Figure 5.3: Result of RTMS.
CHAPTER 5. RESULTS

Figure 5.4: Result of statistics on tyre pressure.

Figure 5.5: Correlation coefficient of cars with CalSts and iTPMSSsts signals.
Chapter 6

Discussion

6.1 Tyre Wear Model

Tyre tread depth is an important factor regarding safety of vehicles and currently is mostly measured with the help of physical tools. TWM is hence developed to identify whether any tyres of a vehicle is worn or not. TWM is developed with its own feature analyses and a voting scheme, which is similar to iTPMS in principle. Moreover, TWM uses the signals that already exist in the bus signal, requiring no additional sensor. The one difference between TWM and iTPMS is that TWM is written in MATLAB with input being the converted data file through CANoe as written in Section 2.1.2. In other words, TWM is not an exactly real-time application like iTPMS, which is installed on vehicle ECUs, but can also be developed on cloud for processing and decision making.

As for feature analyses, assumptions are made before building the model, and each of them needs further testing for validation. Assumptions are listed as

- Tyre pressure of four tyres on vehicles is in good condition, not an influence factor for tyre wear estimation.
- Different tyres and vehicles share the same features as the tested ones.
- Weather and road condition (temperature, road types, etc.) have little, or no, influence on TWM.
- The threshold of being worn tyres is set as 5 mm, while the legal threshed is 1.6 mm for summer tyres and 3 mm for winter tyres [19].
The speed feature is inspired by the radius analysis of iTPMS [4], which uses the difference between wheel speeds and vehicle speed to monitor the effective rolling radius of tyres. A low tyre pressure leads to a smaller effective rolling radius. Tyre tread depth also contributes to the rolling radius, and thus can be indirectly monitored through speed signals. However, it is unclear whether TWM can tell a worn tyre from a tyre of low pressure.

The braking feature is found during the literature research. A worn tyre behaves differently from a new tyre during braking [20]. The braking feature is built on this. In this patent, it also mentions the braking force on a worn tyre has a higher peak than that on a new tyre. The peak is caused by the anti-locking braking system (ABS), as ABS will release the braking pad for a short period, once the braking force is high enough to cause tyres to slip. The braking force can be measured through the pressure sensors of the braking system, and can be added for determining worn tyres. However, the pressure sensors in the test vehicle have a minimal sampling time of 1 s, while ABS responses in milliseconds. The braking force thus are not included in the braking feature analysis, but is worth looking into.

Overall, TWM shows a good accuracy for test data of two tests and is a promising system. With further testing and development in the future, TWM may become one useful function in vehicles like iTPMS, monitoring tyre tread depth in real time.

6.2 Connectivity and UI

In this thesis, the connectivity between raw data in the cloud and the UI is achieved by calling the python scripts in MATLAB. There are two kinds of python scripts for the main interface and interface of statistics on tyre pressure separately. One is used for handling the data of one specific data file while the other is for processing monthly data and daily data.

Some abnormal problems occur when processing the latest data. In some cases, the latest data file is available in the folder. However, it can not be read. This kind of file will influence the performance of RTMS and leads to error when filtering the signals and running the interface of statistics on tyre pressure. Another problem is that the raw data may be unreasonable in some data files. For example, the values should not be decimals but integer values. This may be caused by too few samples.

In addition to the problems of raw data, there exist some methods to improve the performance of RTMS in aspect of connectivity. For example, the raw data can be saved in a database that MATLAB can be directly connected
Another problem is that the UI can only display the result of one selected data file. As there are some occasions that maybe the tyre health conditions of more than one vehicle need to be shown in the UI, the system will be not satisfying under that occasion.

In general, WICE collects the data of vehicle signals and saves the data in the cloud, and then the connectivity realises the data transmission from WICE cloud to the UI of RTMS. With embedded TWM in the UI, the vehicle identification and tyre health information can be visualised in the main interface of the UI.
Chapter 7

Conclusions and Future Work

7.1 Conclusions

The background of this project is that many tyre manufacturers are spending increasing resources into intelligent tyres. Compared to normal tyres, those intelligent tyres are equipped with more sensors to monitor tyre condition, such as tyre pressure, temperature and gripping force. In order to reduce the cost, indirect monitoring of tyre conditions are studied. It means no additional sensors and uses the already-existed ones to predict tyre condition. The previous studies on the indirect monitoring are mainly about iTPMS, which has proven to be a robust system and replaced dTPMS. Another paper is US patent 9610810, using feature extraction to estimate tyre state. Furthermore, as the communication technology develops very fast in recent years, the performance of telematic is significantly improved. One representative technology is 5G which can greatly increase the speed and amount of data transmission. Based on the telematics and new generation communication technology, the potential to monitor big data of vehicle tyres in real-time is possible.

Based on the background information, two functions, TWM and connectivity, have been developed in this project and combined together.

Firstly, the project has developed a Tyre Wear Model to detect worn tyres on vehicles. It contains a speed analysis, braking analysis and a voting scheme. The speed analysis extracts the median value of slip during driving and makes a linear fit of median slip against vehicle speed. The slope of the linear fit is compared to the reference data for classification. The braking analysis, based on US patent 9610810, extracts the median value of slip ratio and slip rate during braking, and applies linear SVM to classify the category of the data. The voting scheme takes the idea of iTPMS and gives warning if either of the
analysis shows warning signals.

Secondly the connectivity is achieved by coordinating with the company’s internal data extraction team to obtain data access permission. After testing the connectivity of the system, valid data are successfully obtained since the mid of May 2020. Three steps are processed for the raw data: data filter according to signal names, data re-sample at fixed time intervals, data format conversion and storage. While doing the data processing, the daily processing volume of raw data is about 70GB. After that, MATLAB GUI is used to design the UI where 6 key indicators are presented, including the information of car itself and tyre health condition. The UI successfully demonstrates Cloud to MATLAB application interaction.

Last, the two systems are combined together to be the RTMS. Through the embedded TWM, tyre wear condition of cars is shown in the main interface of the UI. Moreover, all driving cycle files in a month can be analysed and counted to study the frequency of occurrence of different scenarios according to the proportion of different signal values. This kind of information is presented by pie charts and line graphs in the interface of statistics on tyre pressure.

7.2 Future work

The purpose of RTMS proposed by this project is not only restricted to monitoring tyres, but also having a potential of a new business model. For both fleet and autonomous vehicles, companies can remotely monitor tyre health information in real time. When tyres are in bad condition, such as completely worn out, RTMS is alerted and sends warning to the corresponding company. The company is then able to book a car service based on this information and order fresh tyres ahead that the vehicle arrives. This reduces the risk of accidents due to bad tyre conditions, and more importantly saves money and other resources for companies, such as cost of car inspection and time to wait for fresh tyres being delivered. In order to make this reality, more studies are needed and several parts are listed in this section.

Firstly, regarding the data processing, the raw data are suggested to be stored in a database, which can be directly connected to MATLAB, such as MySQL. Then the data processing can be done without conversing data to excel files by Python. It can save the running time, reducing lagging time.

Secondly, further development of TWM should be investigated. It can be done by validating the assumptions listed in section 6.1 through minimising and controlling assumptions at first. The tests should use worn tyres with 3 mm tread depth, instead of 5 mm. A grinding machine is helpful for making
tyres with desired tread depth. Other tyre parameters should be also tested with TWM, especially tyre pressure. Moreover, it is possible to build a real-time application of TWM in CANoe. This application can be used during the test and save the time to convert data to MATLAB data files.

As mentioned in section 6.2, the main interface of UI should consider the presentation of more than one vehicle, which is possible to be done by adding more rows to display the information and counting the number of times of file list clicks. Similarly with the interface of statistics on tyre pressure, an analytical dashboard of tyre wear can be designed to provide information on tyre orders for vehicle companies and the data can be sold to tyre suppliers. Besides, the interface is made by MATLAB GUI in this project, but it can be written as a web page, allowing to embed more functions.

As now the RTMS handles with static data (data files saved in a server), it is only batch processing, which has a delay and is not a real-time data processing system. Thus, future work needs to include how to deal with the streaming data and collaborate with the data extract team in the company to get access to streaming data.
References


Chapter 8

Appendix

8.1 Abbreviation list

ABS  anti-locking braking system

dTPMS  direct tyre pressure monitoring system

ECU  electronic control unit

FFT  fast Fourier transform

iTPMS  indirect tyre pressure monitoring system

IoT  Internet of things

RFID  radio frequency identification

SVM  support vector machine

RTMS  real-time tyre monitoring system

TWM  tyre wear model

UI  user interface

WCU  wireless communication unit

WICE  wireless information collection environment

WLAN  wireless local area network