Slippery Road Detection

Detection of hydro-electrical ABS (Anti-lock Braking System) activation in vehicles using external sensors

Master's Thesis in Automotive Engineering and Biomedical Engineering

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ABSTRACT

SRIS (Slippery Road Information System) was a research project where road conditions were estimated in real-time based on data gathered from internal signals in vehicles together with data from weather stations. The system showed good results, though it has not been realised due to practical limitation caused by difficulties in accessing and decoding the data from the vehicle's internal sensors. To circumvent these obstructions, it was proposed to use external sensors to obtain alternative information to detect the activation of various vehicle stability systems (e.g. ABS).

The hydro-electrical anti-lock braking system in a passenger vehicle was discovered to cause measurable disturbances in the electrical system of the test vehicle used in this thesis. The disturbances showed repetitive and continuous characteristics. A logging equipment was assembled to record the vehicle's voltage level as well as the vehicle's CAN-bus and GPS-position for validation purposes. A series of provocative driving-test were conducted in a winter environment to gather data for analysis and development of signal detection algorithms.

Three algorithms have been developed which detects the activation of the ABS (Anti-lock Braking System) through the use of external sensors only. These three algorithms were developed using different design-strategies utilizing voltage sensor only or voltage sensor in combination with a longitudinal mounted accelerometer and thereby obtaining different properties in order to widen the implementation possibilities. All three algorithms have shown promising results with high detection reliability through cross-validation with recorded data from naturalistic driving during both winter and non-winter conditions.

Keywords: ABS activation, signal detection, SRIS, BiFi, signal processing, IIR digital filter.

Halkdetektering
Detektering av hydro-elektrisk ABS aktivering med hjälp av externa sensorer
Examensarbete inom Automotive Engineering och Biomedical Engineering
Institutionen för Signaler och System
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Chalmers Tekniska Högskola

SAMMANFATTNING

SRIS (Slippery Road Information System) var ett forskningsprojekt där väglaget uppskattades i realtid baserat på data som samlats in från interna sensorer i fordon tillsammans med data från väderstationer. Systemet visade goda resultat, även om det inte har realiserats på grund av praktiska begränsningar i form av svårigheter att få tillgång till och avkoda data från bilens interna sensorer. För att kringgå dessa hinder uppstod tanken att använda externa sensorer för att erhålla alternativ information för att upptäcka aktivering av fordonets stabilitetssystem (t.ex. ABS).

Det upptäcktes att det hydro-elektriska låsningsfria bromssystemet i en personbil orsakar mätbara störningar i fordonets elektriska system. Störningarna visade sig vara repetitiva och ha kontinuerlig karakteristik. En loggutrustning monterades ihop för att logga bilens batterispänning tillsammans med signaler på CAN-bussen och GPS position i valideringssyfte. Ett antal provokativa körningar utfördes på vinterväglag för att samla in data till analys och algoritmutveckling.

Baserat på insamlad data från ett testfordon, har tre algoritmer utvecklats för att upptäcka aktivering av ABS med hjälp av endast externa sensorer. Dessa tre algoritmer har utvecklats med olika design-strategier med spänningsövervakning eller med voltmätning kombinerat med acceleration i longitudinell riktning och på så sätt erhållit olika egenskaper för att bredda implementeringsmöjligheterna. Alla tre algoritmer har visat lovande resultat med hög träffsäkerhet genom korsvalidering med loggad data från bilkörning på både vinterväglag och övrigt väglag.

Nyckelord: ABS aktivering, signalbehandling, SRIS, BiFi, signaldetektion, IIR digitala filter.

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Acknowledgements

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Special appreciations directed to the department of Electrical and Electronics at Semcon Caran AB for offering the opportunity to carry out this thesis.

Göteborg, December 2012

Christopher Skaloud & Marcus Bengtsson

PREFACE

The reader should be informed that some content of this report are censored due to confidentiality.

1 INTRODUCTION

This chapter describes the background, purpose and basic information regarding the project.

1.1 BACKGROUND

Statistics show that the number of fatal traffic accidents in Sweden is directly proportional to the total travelling distance independent of the season, which is surprising since one might think that more accidents would occur during the winter when the road conditions are worse. The fact that accidents are evenly distributed over the year is believed to be closely connected to the average speed which is 10-25% lower during the winter season since drivers adapt to changes in road conditions, [**1**].

According to Johan Strandroth et al, [**2**], 68% of all fatal accidents during the 2009-2010 winter season in Sweden occurred either on snow or ice. The study shows that a fatal accident is at least three times more likely to be caused by the driver losing control of the vehicle on snow or ice covered roads compared with the same scenario on dry or wet road conditions during the winter season.

The conclusion is that snow and ice covered parts of the road have big impact on traffic safety since drivers apparently do not take proper precautions when driving during these road conditions. This shows the need for safety systems that inform drivers and road maintenance about current road surface conditions in order to prevent this type of accidents.

1.1.1 SLIPPERY ROAD INFORMATION SYSTEM (SRIS)

SRIS - Slippery Road Information System was a research project involving several private actors and the Swedish Road Administration. SRIS aimed to map and distribute information about local critical road surface conditions, which vary over time. Weather stations are used to determine the road condition; however, the issue is to get an accurate estimation between the stations. This is why SRIS uses the vehicle's built-in sensors to complete the information from the weather stations in order to make a better estimation of the road conditions further away from the stations. The vehicle data is gathered by accessing the vehicle's Controller Area Network (CAN) and logging signals and messages to see if certain automotive subsystems are active or not at a certain position. Two types of information is gathered, "event data" and "background data". Information about windshield wipers, temperature and position is a part of the background data and is collected every 30 seconds. Other information, such as ABS, Traction Control is sent only upon its activation and belongs to event data, [**3**] and [**4**].

Background and event data is gathered from a large number of cars on the roads. The data from the vehicles is compared with information from nearby weather stations that has been processed through a “weather model”, which estimates the climate situation of the specific location. The data sets are then evaluated by processing both data through an analyse model and a road condition is estimated and categorized into any of the three following grades:

- Grade 1 – very slippery
- Grade 2 – slippery
- Grade 3 – not slippery

This way SRIS can map which certain parts of the roads are in a “risk zone” of causing accidents due to slippery road surface conditions, [**3**] and [**4**].

Further on, the information is used to both notify drivers out on the road and the road administration about critical road sections. Proper measures can be taken to avoid accidents e.g. speed reduction, redirect road maintenance resources respectively. This project has been proved to be a very successful method in preventing traffic accidents [**4**].

Field tests of SRIS were carried out twice. The first test in 2006/2007 involved 80 weather stations and 20 vehicles. The second field test in 2007/2008 involved 80 weather stations and 100 vehicles. According to Pär Ekström, research engineer deeply involved in the SRIS project, ABS activation showed to be the best indication of a slippery road surface.

SRIS is currently not an active system. The issues are mainly political, in the industrial politics where the OEM:s are reluctant to share signal databases which is one of the reasons why the system has not been commercialized yet.

The disadvantage with SRIS is that each vehicle (manufacturer or even car model) uses different designations to code messages on the CAN-bus and requires a library to be interpreted. The consequence is that a custom solution is needed for most car models, which limits the flexibility of the system, [**3**] and [**4**].

1.1.2 BiFi – Bärighetsinformation genom Fordonsintelligens

BiFi is an on-going project run by Semcon along with other actors. The purpose of BiFi is to develop a new tool through which one can estimate load-bearing capacity of roads in real-time. The system estimates the load bearing capacity of the road (decreased by phenomena such as spring thawing, heavy rain etc.) based on analysis of the chassis-vibrations. The BiFi hardware is equipped with a GPS, vibration sensor, external temperature sensor, analogue inputs, GPRS modem and SD-memory card for local storage, [**5**].

1.2 Purpose

The purpose of this project is to address one of the main obstructions regarding the SRIS project, which is that a unique database for each vehicle manufacturer or model is needed to interpret the CAN messages.

The aim is to have a "universal" stand-alone system that can be plugged into any vehicle and detect if the car loses traction by activation of the ABS brakes of the vehicle. This system should detect ABS activation without any communication with the vehicle's CAN-bus whatsoever.

1.3 Problem description

The idea is that, by measuring the 12V power supply in the lighter plug in the vehicle, determine whether ABS is activated or not. This is based on the idea that the relatively large current and power consumption of the anti-lock brake pump when it is engaged causes a noticeable voltage drop in the electrical system of the vehicle. By first recognizing the character of this voltage fluctuation, an algorithm that detects these fluctuations and determines whether any of the systems have been activated can be developed.

1.4 Goal

The aim is to develop an algorithm in MATLAB-environment that detects when the ABS in the vehicle is activated, and thereby revealing that the vehicle has lost traction.

1.5 Limitations

Following limitations are set to fit the limited timeframe for this Master's Thesis and the provided hardware:

- Algorithm is limited to only use signals available from the already existing hardware used in the on-going BiFi (Bärighetsinformation genom Fordonsintelligens) project, that is:
    - GPS position, yaw-rate, acceleration (longitudinal and lateral), vehicle speed, outside temperature.
- System development for one specific vehicle model (Volvo V70 DriveE, model year 2010) although it should be adjustable to suite several vehicle models.
- No embedded coding, verification only by simulation with data sets collected from test drives.

1.6 Pre-study: proof of concept

The phenomena which spawned the idea to detect the activation of vehicle safety systems by monitoring the vehicles electrical system was a noticeable flickering of the vehicles headlight when the ABS system was activated. During the initial stages of this project a pre-test was performed to prove that the flickering was actually measurable and consistent enough before proceeding with further investigations. This test was performed on a last generation SAAB 9[5] with an oscilloscope measuring the voltage via the lighter plug. The test was performed on loose gravel to be able to force activation of the ABS system during braking. The voltage drop was clearly measurable and quite continuous with a fundamental frequency of [redacted] Hz and baseline to peak voltage difference between [redacted] V.

2 THEORY

This chapter covers theory about relevant subjects that create a basis for the thesis work and its background. The essential subjects in the thesis are the following ones: fundamental knowledge about the ABS hardware functionality and theory regarding digital filters used for signal processing. A comprehensive description of the CAN-protocol is available in Appendix C.

2.1 ANTI-LOCK BRAKE SYSTEM (ABS)

This chapter describes the functionality of anti-lock braking system. The chapter will only describe the hydro-electrical ABS, since it is the one that is the most relevant to this thesis. It should be noted that there are other systems, such as hydro-mechanical ABS (for passenger cars) and air/electric ABS (mostly for commercial vehicle) that are commonly used in the automotive industry, [**6**].

2.1.1 GENERAL FUNCTIONALITY

Due to the difference in adhesion between road and tire between the wheels of a vehicle, one wheel will always have a tendency to lock-up easier than the other on a conventional braking system during braking.

The anti-lock braking system is a closed-loop control system that prevents the wheels from locking up during braking, and there for maintaining the steerability and control of the vehicle. In order to maintain stability and avoid lockup, the brake slip must not exceed the stable region. However, to obtain maximum brake retardation, there should be a small amount of brake slip. In order to achieve optimal longitudinal brake force, a brake slip of approximately 15 % is required. This value is directly in conflict with the maximum lateral force (for optimal steerability), which occurs during minimal slip (see Figure 2.1). Most antilock braking systems operate in the range of 8-30 % brake slip as a compromise, [**7**] and [**6**].

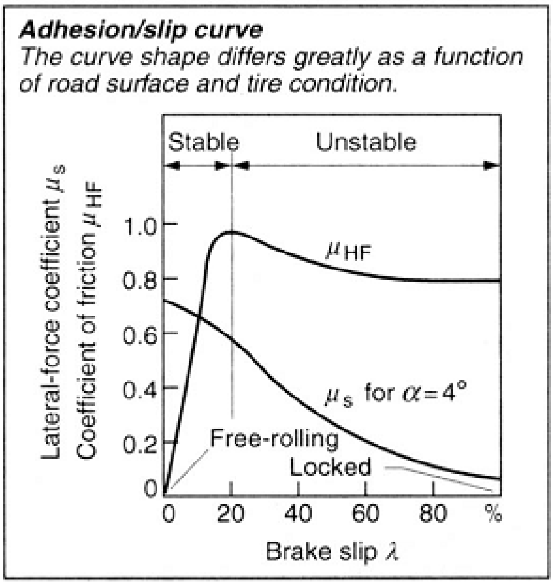

*Figure 2.1 Adhesion/slip curve. Source: [**8**].*

2.1.2 SYSTEM OVERVIEW

The ABS is generally built up from following components (as can be seen in Figure 2.2): Wheel speed sensors, Electronic Control Unit (ECU) for signal processing and control, and Hydro-electrical modulator, [**7**].

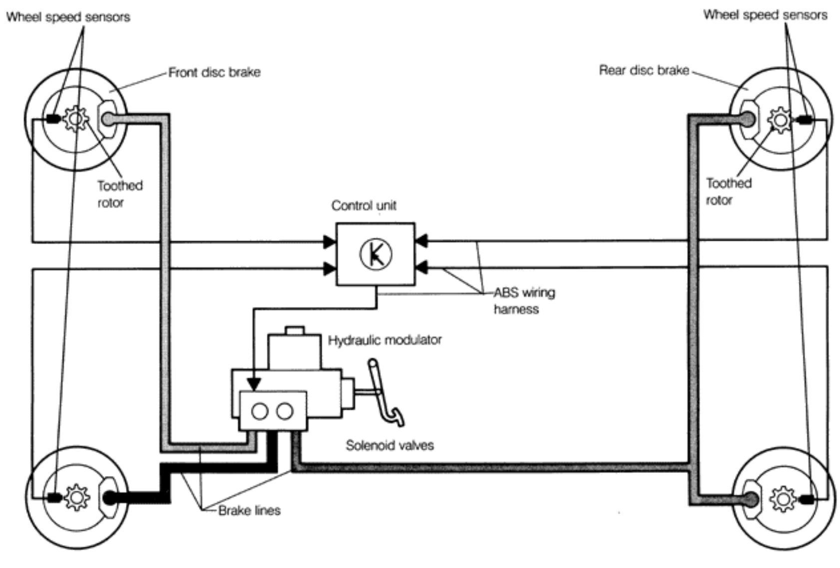

*Figure 2.2 Brake system overview. Source: [**9**].*

- **Wheel sensors:** Each wheel is equipped with a inductive sensor connected to an exciter, most often a toothed or ribbed/slotted ring placed on the drive shaft or the rotating part of the wheel hub. As the ring rotates it induces electromagnetic impulses in the sensor, which sends the signal to the control unit. The frequency of the impulses reveals the rotational speed, as well as the acceleration and deceleration of the wheel.
- **Electronic Control Unit (ECU):** The ECU amplifies, processes and computes the signal that is received from the wheel sensors and based on that evaluates maximum wheel acceleration and minimum deceleration in order to achieve optimal braking performance. After computation and evaluation, it empowers the current to the individual solenoid valves and thereby controls and regulates the brake cylinder pressure.
- **Hydro-electrical modulator:** The hydro-electrical modulator consists of solenoid control valves for each of the wheels, the accumulator for each of the two brake circuits as well as the 2-cylinder flow pump driven by an electrical motor. By switching the solenoid between fully open, half- or fully closed the brake fluid pressure between the master cylinder and brakes is interrupted several times per second. When the solenoid valve opens the return passage, the accumulator releases the pressure in the brake fluid pipeline with the aid of its diaphragm space, absorbing the outflow fluid. The flow pump transports the fluid from the accumulator to the output of the master cylinder to the brake callipers and cylinders.

2.1.3 Operational functionality of ABS

During ***normal braking***, i.e. braking within the lower part of the stable region (see Figure 2.1), the solenoid valve is in a position that lets the brake fluid flow unrestricted between the master cylinder and brake cylinder and deceleration of the vehicle can take place.

In order to regulate the wheel acceleration and deceleration and thereby controlling the lockup prevention, the ABS works in three stages:

- Pressure hold
- Pressure decrease
- Pressure increase

This procedure is repeated as long as there is a risk of the wheel locking up.

- **Pressure hold:** When the wheel is decelerating and reaches a certain critical value where there is a risk that the wheel could in fact lockup, the ECU orders the solenoid valve engage and thereby block any further pressure increase from the master cylinder to the brake cylinder. At this stage, the brake fluid pressure is held at a constant level.
- **Pressure decrease:** In case the ECU should still receive information that the wheel is decelerating at an abnormal rate that is most likely to cause wheel lockup, it orders the solenoid valve to enter a position that opens the return flow passage. This causes the pressure to drop, since the pressurized fluid escapes into the earlier mentioned accumulator, where it is redirected back into the output of the master cylinder. With reduced pressure, the wheel will start accelerating again and traction can be resumed.
- **Pressure increase:** Due to the previous stage (pressure decrease) the wheel has changed from deceleration to acceleration again. At this point the ECU disengages the solenoid valve, creating a free passage for the brake fluid between the master cylinder and brake cylinder, allowing the pressure to be built up again and start braking the wheel and thereby the vehicle. From this point the next stage is the pressure hold, and the cycle 'hold-decrease-increase' is repeated again as long it is needed.

2.1.4 DYNAMIC STABILITY SYSTEMS

Many of the vehicles produced today, use several dynamic stability safety systems that take advantage of the ABS in order to counter-act skidding of the vehicle. Examples of such systems are Active Yaw Control (AYC) and Traction Control (TC).

- **AYC:** This system monitors the yaw rate of the vehicle and detects whether the vehicles starts to understeer or oversteer. By taking advantage of the ABS unit it can brake the wheels individually and thereby prevent the vehicle from deviating from the path desired by the driver.
- **TC:** Traction Control is a system that actively assists the driver to maintain control of the vehicle by brake intervention when the driven wheels start to loose traction.

Stability Control (SC) is another stability system that prevents wheel spin during acceleration by reducing the engine torque output instead of the ABS-unit as in the case with TC.

2.2 DIGITAL FILTERS

Digital filters have many practical advantages over analogue filters and are commonly used in signal processing. The precision of an analogue filter is affected by the manufacturing quality of its components, which may differ greatly between individual components. The more complex the filter is, i.e. more components, the more will the filter properties change due to variances in component values. The Analogue components are also affected by temperature and age, which will affect the filter properties. Digital filters are numerically defined and will not change randomly and the filter will always perform the same. What makes digital filters so interesting in signal processing is that they are very flexible and can also be adaptive. Complex high order filters are easy to realize and implement since they do not suffer the shortcomings of analogue components. Development time are shortened with active filters since complex passive filter are very time consuming to build and if any changes to the filter design are necessary the whole filter will often have to be rebuilt, [**10**].

2.2.1 INFINITE IMPULSE RESPONSE DIGITAL FILTER (IIR FILTER)

IIR-filter has as its name implies a nonzero impulse response over an infinite time period, due to the feedback design of the filter, i.e. the output of the filter is dependent on previous outputs. An IIR may be either an analogue filter or a digital filter and they share the same design principles. The filter is designed as an analogue filter, ex. Butterworth or Chebyshev, and then discretised through the use of a discretization algorithm. The advantage of IIR filters compared to other digital filter types is that they have a very steep roll of at low filter orders which makes them computational more effective. The disadvantage is that the IIR isn't automatically stable and this has to be taken into consideration when designed, unlike Finite Impulse Response (FIR) filters which are always stable since its poles are always placed in the origin, [**10**].

DISCRETIZATION

There are three principal discretization methods for IIR filters:

1. Impulse invariant: The impulse response of the continuous time filter is sampled to form the discretized filter. This results in a discrete frequency response, which is approximately equal to the continuous frequency response as long as the frequency of the continuous system is limited to the Nyquist frequency of the sampled filter. This method will cause aliasing effects when the sampled signal approaches the Nyquist frequency.
2. Matched z-transform: The zeros and poles of the continuous time filter is transformed directly to the discrete-time domain by transform function $z = e^{sT}$.
3. Bilinear transform: The bilinear transform maps all poles and zeros from the s-plane on to the unit circle in the z-plane for all frequencies and thus eliminates aliasing. The transform preserves the shape of the transfer function, though on to a restricted frequency interval which results in the gain and phase being frequency shifted. Frequency warping is applied to correct this frequency shift. The Bilinear transform is the most commonly used transform since it preserves causality and does not introducing any aliasing effects, [**10**].

2.2.2 FILTER REALIZATION

The digital filter is realized with delays and arithmetic operators. This may be done with different design technics. Cascading of lower order filters is usually used to form higher order filters, this is done because higher order recursive filters are sensitive to round of errors and can become unstable. The most common form of cascaded higher order filter is the biquadratic filter, which is built up by second order recursive filters connected in series with transfer function as following:, [**10**].

$$H(z) = \frac{b_0 + b_1 z^{-1} + b_2 z^{-2}}{1 + a_1 z^{-1} + a_2 z^{-2}} \quad (2.1)$$

DIRECT FORM I

The Direct Form I is the direct realization of the filter difference equation and uses 2 times the filter order operations when applied. The strength of the design is its simplicity and thus easily applied on small filter designs. The drawback with the Direct Form I approach is that it may become unstable for high order filter and the use of 2 delays for each filter order makes it computational inefficient compared to other design methods. Figure 2.3 show the flow diagram of a second order Direct Form I filter, [**11**].

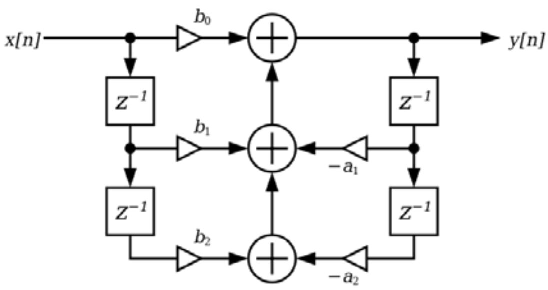

*Figure 2.3 Flow diagram of 2nd order Direct Form I filter. Source: [**12**].*

With difference equation:

$$y(n) = b_0 x(n) + b_1 x(n-1) + b_2(n-2) - a_1 y(n-1) - a_2 y(n-2) \quad (2.2)$$

DIRECT FORM II

The Direct Form II method uses the minimum number of delay blocks for the given filter difference equation. The number of delays is equal to the order of the transfer functions denominator, i.e. the number of operations is equal to the filter order. In practice this design becomes an all-pole filter in series with an all-zero filter, which may cause arithmetic overflow since the signal is first amplified by the nominator and then decreased by the denominator. Figure 2.4 shows the flow diagram of a second order Direct Form II filter, [**13**] and [**14**].

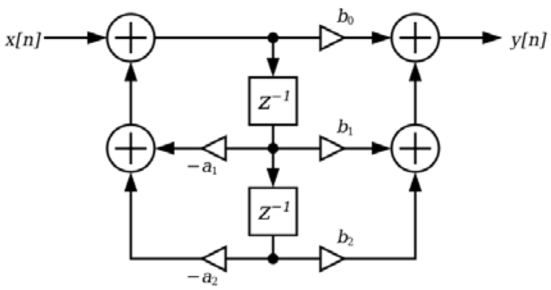

*Figure 2.4 Flow diagram of 2nd order Direct Form II filter. Source: [**12**].*

With difference equation:

$$\begin{cases} v(n) = x(n) - a_1 v(n-1) - a_2 v(n-2) \\ y(n) = b_0 v(n) + b_1 v(n-1) + b_2 v(n-2) \end{cases} \tag{2.3}$$

2.3 SOFTWARE

This chapter contains a brief description of the different software used in the project.

2.3.1 CANOE

CANoe is a comprehensive analysis, development, diagnostics and test software tool from Vector. It enhances the possibility to analyse a single node or entire ECU networks. The software allows the possibility to set up virtual nodes in the system for different simulations. However, in this project, CANoe was used for analytic purpose.

The software was used to log the CAN-signals from the vehicle's ECU's, an external GPS and the voltage from the CANExtender and merging them. The result is signals from three different channels with one time stamp in one log file.

2.3.2 MATLAB

Matlab is a computer program and high-level programming language created by MathWorks. The Matlab software has many pre-defined functions for mathematical calculation, signal processing, image processing, control design etc.

Typical areas of application are:

- Technical computing
- Algorithm development
- Modelling and simulation
- Data analysis

Calculated results can easily be presented in graphs, displayed as values or saved as files.

3 METHODOLOGY

Chapter 3 describes the methods used to investigate and answer the question at issue.

3.1 DATA COLLECTING

Three different sets of data were logged for the purpose of this project during three logging sessions, one for algorithm development and two for algorithm validation.

During the sessions, all available signals on the CAN-bus were logged, and later on the ones that were of greatest importance were selected and converted to .mat files (Matlab file format).

All tests were carried out with a Volvo V70 DrivE model year 2010 equipped with ABS system from the OEM (Original Equipment Manufacturer) ATE.

3.1.1 LOGGING SESSION 1 – GOTHENBURG AND IDRE, SWEDEN AND ELVERUM, NORWAY

In order for the algorithm to be developed, it required an extensive amount of logging data that contained ABS and TC engagement caused by various types of driving situations and maneuvers. All driving in expedition 1 was carried out on snow-covered road surface.

This data log contained quite aggressive driving, where the vehicle was pushed to its limits and thereby forcing the safety systems to be activated repeatedly. The purpose of this session was to obtain data for ‘worst case scenario driving’.

The following behaviour of the vehicle was provoked:

- Under steer
- Over steer
- Brake lockup
- Wheel spin

Logging session 1 contained 5 hours of driving in total.

3.1.2 LOGGING SESSION 2 – GOTHENBURG – ÖSTERSUND – GOTHENBURG

Another set of logging data was required for the algorithm to be cross-validated against. This logging session was intended to simulate ordinary driving, as it was important to identify how the algorithm behaves during normal driving conditions without ‘unnecessarily’ provoked activation of the safety system.

Expedition 2 covered different types of road surfaces:

- Mud
- Gravel
- Snow
- Ice
- Dry asphalt
- Wet asphalt

Covering all these types of surfaces was of great importance because the purpose was to represents as much real-life situations and driving conditions as possible.

Another important aspect was to cover different road types, such as

- Motorways
- Highways
- Country roads
- City roads

The logging session from expedition 2 had duration of 30 hours.

3.1.3 Logging session 3 – Gothenburg city

The third logging session was carried out in order to simulate low-speed city driving. It involved driving in the city centre of Gothenburg during rush hour for 2 hours.

An additional test was carried out to log disturbances from different power consuming units in the vehicle, to see if any of them have similar behaviour as the ABS-pump and to test the robustness of the algorithm. A selection of power consumers that were tested in the vehicle:

- Power steering
- Electrical windows
- Defroster
- High-beam
- Windshield wipers
- Turning signals
- Seat heating
- An external light bar mounted on the roof

Part of the test was done during standstill of the vehicle (with engine idling) and part of it was done during normal driving.

3.2 HARDWARE DESCRIPTION

This chapter describes the equipment used for logging data.

3.2.1 HARDWARE OVERVIEW

The logging equipment consists of a CANExtender, a transceiver CANcab cable, an anti-aliasing filter and a PC. The logging computer is powered by a DC/AC 12V-to-230V inverter and the active anti-aliasing filter is driven by an AC/DC 230V-to-19V transformer. Figure 3.1 shows a schematic overview of how the equipment is connected. The output is further connected to the CANCardXL and inserted to the computer and operated by the software CANoe.

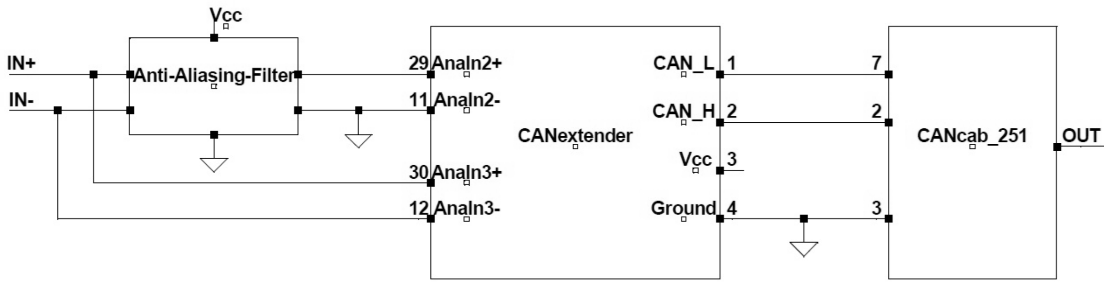

Figure 3.1 Schematic overview of logging equipment.

3.2.2 CANEXTENDER

The CANExtender is a programmable input/output device that is used for logging analogue/digital signals and converting them to CAN-messages. A configuration program written in Log Task Language (LTL) is loaded into the CANExtender via the PC serial interface. This configuration program gives e.g. the user a possibility to specify which CAN messages and how frequently it should be sent out on the bus, specify different variables, timeouts, counters, flags or timers among others. LTL is at equivalent level as C programming language.

Some specifications of the unit:

- I/O interface via DB-37 male connectors
- 1 high-speed CAN interface.
- 8 analogue inputs: -16 V to +16 V, resolution 12 bits, increment 8 mV, accuracy ± 0.1 %.
- 8 digital inputs: 0 to 36 V.
- Supply voltage range 8.5 V to 18 V.
- PC serial interface, RS-232

3.2.3 CANCARD XL

The CANCard is a bus interface of PCMCIA Type II – 16 bit standard. It has two independent channel inputs. This device is inserted in the computer in order to connect the CANExtender to it.

3.2.4 CANCAB 251

The CANcab 251 is a bus transceiver cable used to interlink the CANExtender and the CANCardXL.

3.2.5 ANTI-ALIASING FILTER

An anti-aliasing filter is used when sampling an analogue signal before discretizing it. The analogue filter is used to remove any undesired out-of-band components.

The anti-aliasing filter is an active 4th order Butterworth-filter. The cut-off frequency was set to [redacted] Hz, due to the availability of components. A differentiator is added to remove the common voltage, in order to use the true potential differentiation. Figure 3.2 shows the schematic circuit design of the filter, where the left side is the differentiator and the right part is the 4th order filter.

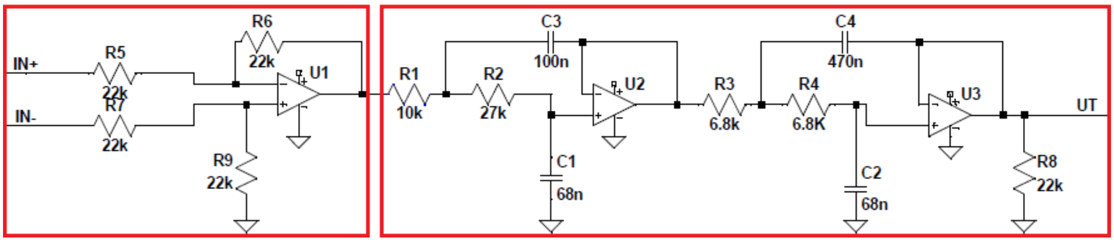

Figure 3.2 Circuit design. Differentiator (left) and filter (right).

Figure 3.3 shows the frequency response of the analogue anti-aliasing filter from a simulation carried out in LTSpice (simulation software from Linear Technology). The solid line shows the frequency, where the cut-off frequency (-3 dB damping) is at [redacted] Hz and the stop frequency with -20 dB is at [redacted] Hz. The dashed line shows the phase.

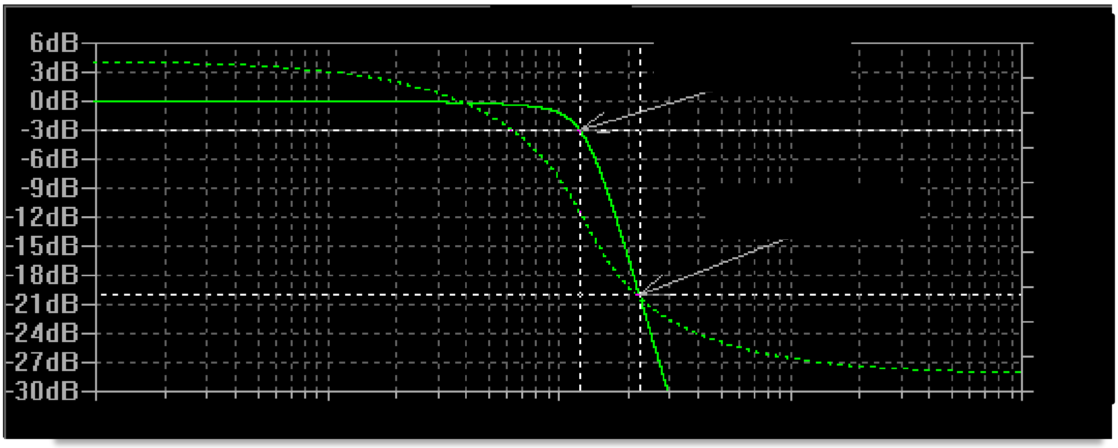

Figure 3.3 Simulated frequency response of anti-aliasing filter.

Figure 3.4 shows the analog anti-aliasing filter on a circuit board along with its terminal.

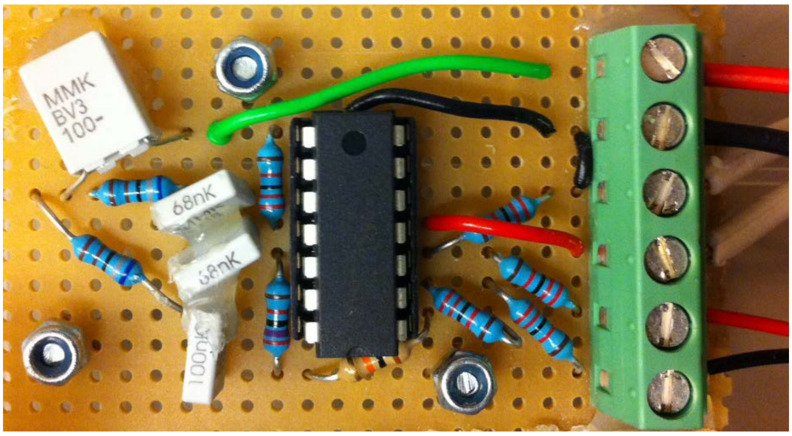

Figure 3.4 Analogue anti-aliasing filter.

The actual frequency response of the anti-aliasing filter was measured, and can be seen in Figure 3.5. The curve is constructed from manually measured values. The signal is sinusoidal and obtained from a function generator, where the frequency is measured with a digital multimeter and the voltage value is measured with the log equipment. For detailed description of equipment, see chapter 3.2.1.

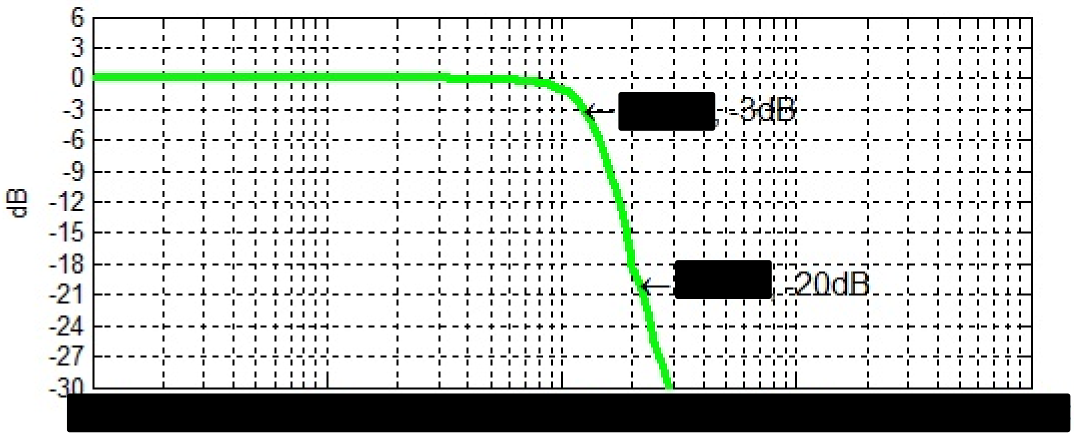

Figure 3.5 Actual real-life frequency response.

As can be seen, the actual cut-off frequency is [redacted] Hz, which is slightly different from the simulated one ([redacted] Hz). Also the stop frequency of [redacted] Hz also differs slightly from the simulated one ([redacted] Hz).

3.3 Signal characteristics

Following section contains a description of the voltage characteristics for each of the 4 stability systems when engaged.

The voltage ripple during an ABS engagement has a certain shape that needed to be analysed and recognized. Figure 3.6 shows the speed, acceleration, voltage and vehicle safety system activation (ABS, AYC, TC and SC) during a randomly chosen 1000 seconds long period containing at least one ABS engagement.

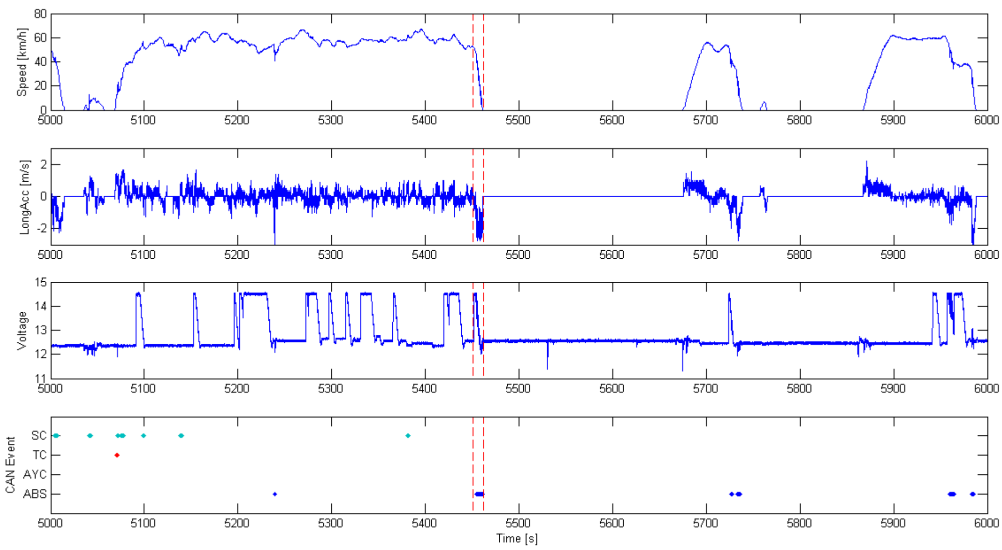

Figure 3.6 Selection of various signals.

3.3.1 ABS

The red markers around 5460 seconds in Figure 3.6 highlight an ABS engagement during normal braking. This section is displayed in close-up in Figure 3.7 to visualize the characteristics of the voltage drop during an ABS engagement.

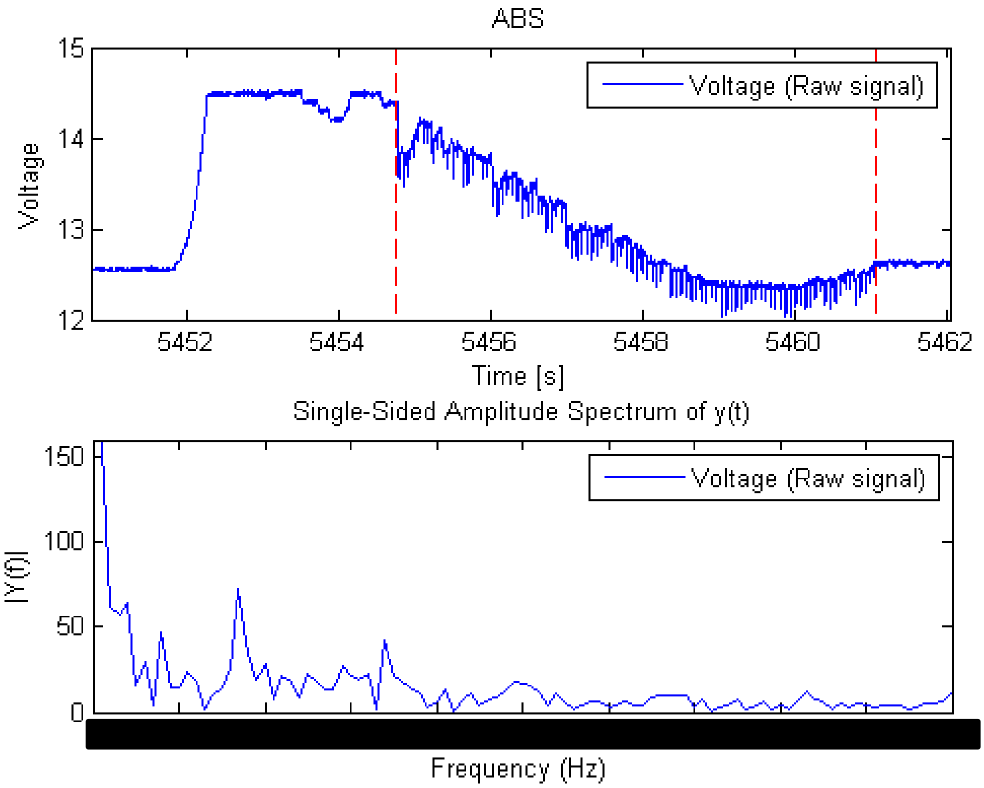

Figure 3.7 Voltage signal and power spectrum during braking with ABS engagement.

The voltage level change between approximately 12.5 volt and 14.5 volt, seen in Figure 3.7 upper, is due to the regenerative charging of the battery during braking. The ABS engagement is approximately 6 seconds long and is situated between timestamp 5455 and 5461. By visual inspection one recognizes that the fundamental frequency, from now on called 1st harmonic, is in the region of [redacted] Hz. This is confirmed by the power spectrum, Figure 3.7 lower, where the 1st harmonic is identified as [redacted] Hz. The voltage drop clearly has a continuous and repetitive characteristic though it needs to be cleaned up before it is put to use.

3.3.2 TC

Figure 3.8 shows the typical characteristics of a TC engagement (within the red dashed lines). It is recognize by two peaks with irregular time span between them. When examining the power spectrum, there is a significant peak close to 0 Hz is the DC voltage (which is not of interest, since it is later on filtered out). For the rest of the frequency span, there is a low frequency with multiple higher harmonics, making it difficult to recognize the first harmonics. In addition to this, the irregularity of the frequency from case to case makes it difficult to characterize it.

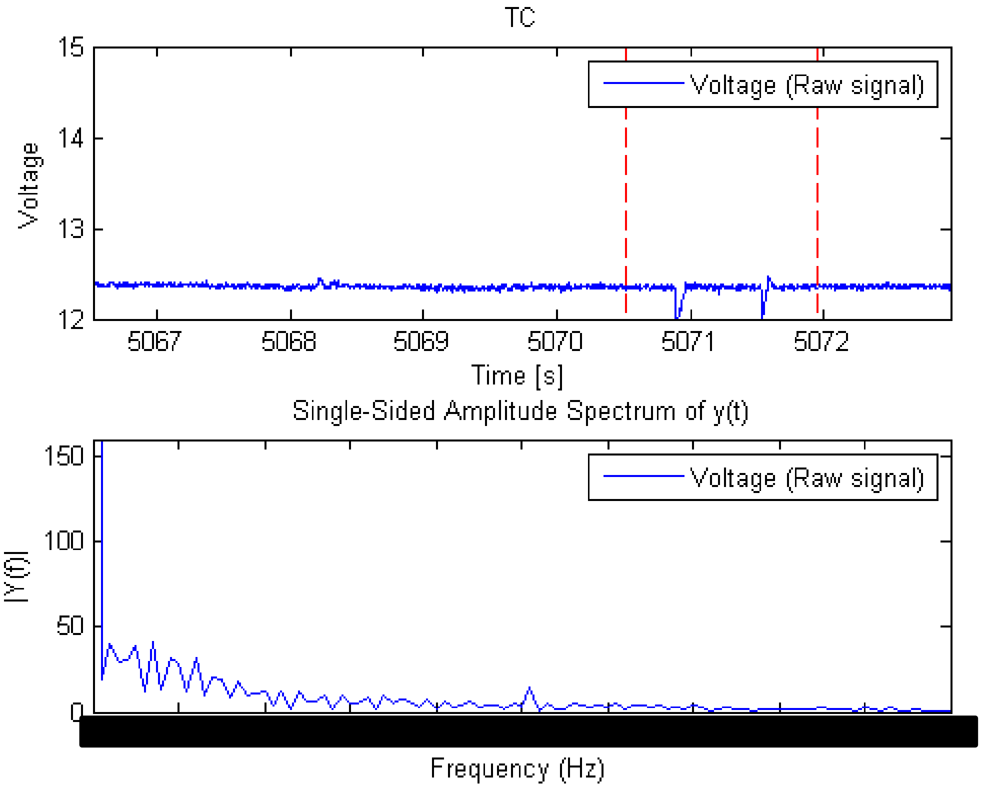

Figure 3.8 Voltage signal and power spectrum during TC engagement.

3.3.3 AYC

The issue with AYC is exposed in Figure 3.9. AYC utilizes the ABS unit to brake the wheels individually, which is why a complete AYC sequence contains several short ABS engagements with irregular time intervals. As can be seen, the frequency of voltage drop is very irregular with no obvious 1st harmonic, which leads to an identification issue, just like the case with TC.

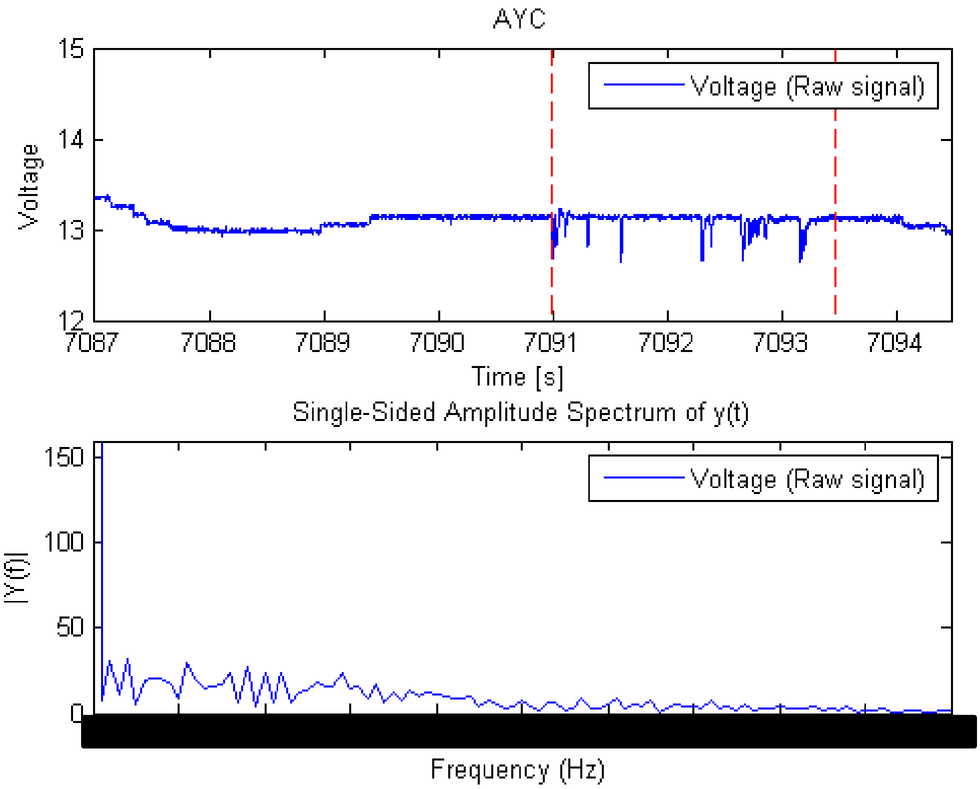

Figure 3.9 Voltage signal and power spectrum during AYC engagement.

3.3.4 SC

Figure 3.10 shows the characteristics of a SC intervention. Approximately 2/3 part of the engagement is a flat noisy signal, while the last third changes and looks somewhat similar to a square wave signal that in the very end starts to drop. The power spectrum reveals that the power density is low throughout the entire frequency span, which together with the random change of shape makes it difficult to characterize.

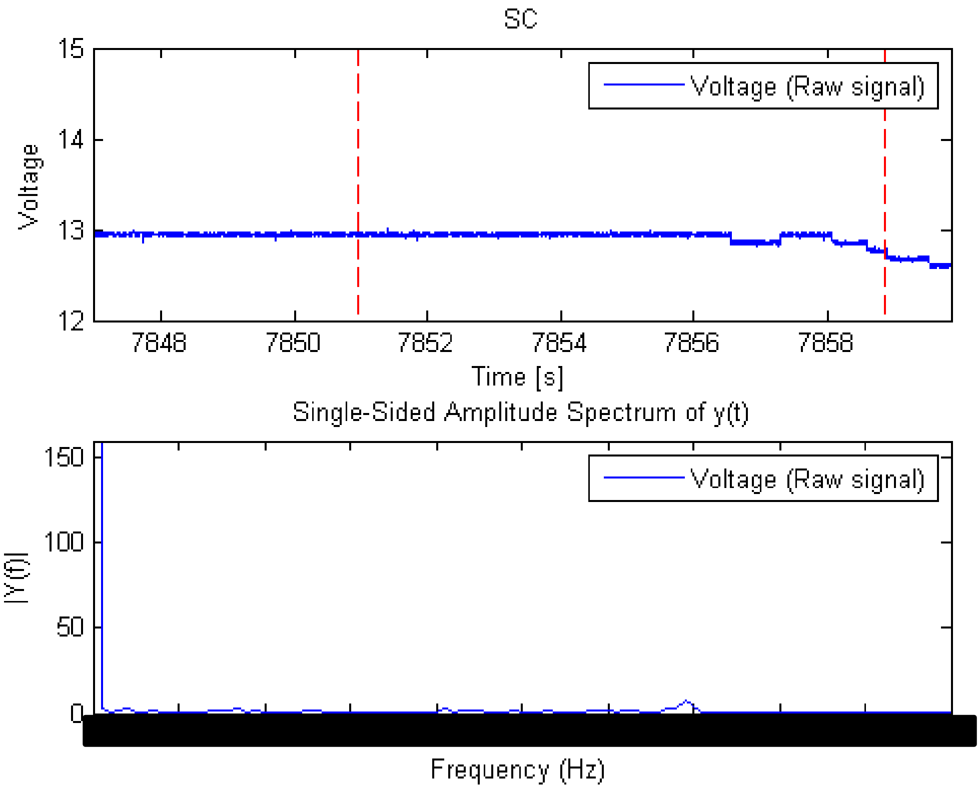

Figure 3.10 Voltage signal and power spectrum during SC engagement.

3.4 Signal processing

The regenerative charging is not always activated during braking since it's dependent on other factors such as battery voltage level and outside temperature and can thus not be used by the detection algorithm and need to be removed.

A 2nd order Butterworth high-pass IIR Direct Form II filter with an [redacted] Hz cut-off frequency is applied to remove the low frequency component, which may be considered as a DC-component. Order and cut-off frequency was selected to preserve as much as possible of the ripple characteristics while removing the DC component. A 30th order Butterworth low pass IIR filter with a [redacted] Hz cut-off frequency is applied to remove the high frequency component, which is considered as disturbances. The filters may of course be realized with a band pass equivalent; however, two filter steps are used for visualization purposes. The two filters are seen in Figure 3.11 and Figure 3.12.

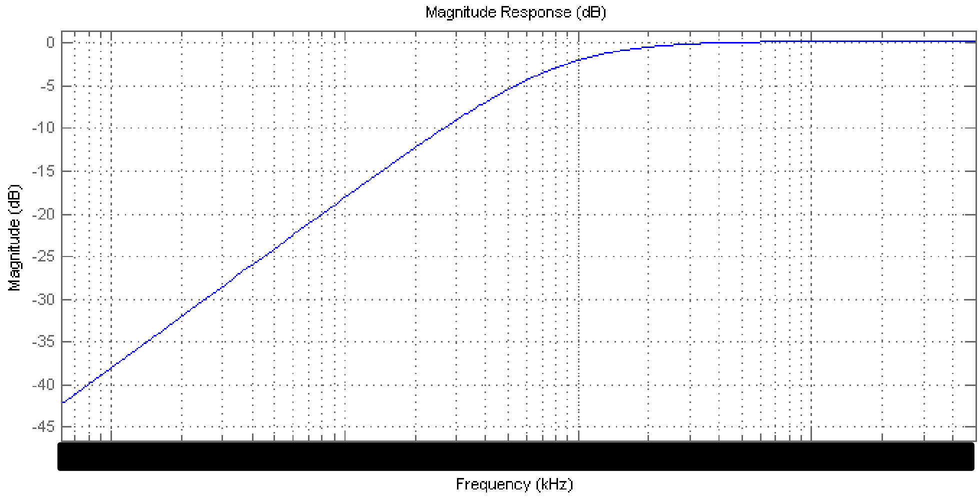

Figure 3.11 Frequency response of 2nd order Butterworth high-pass IIR Direct Form II Filter.

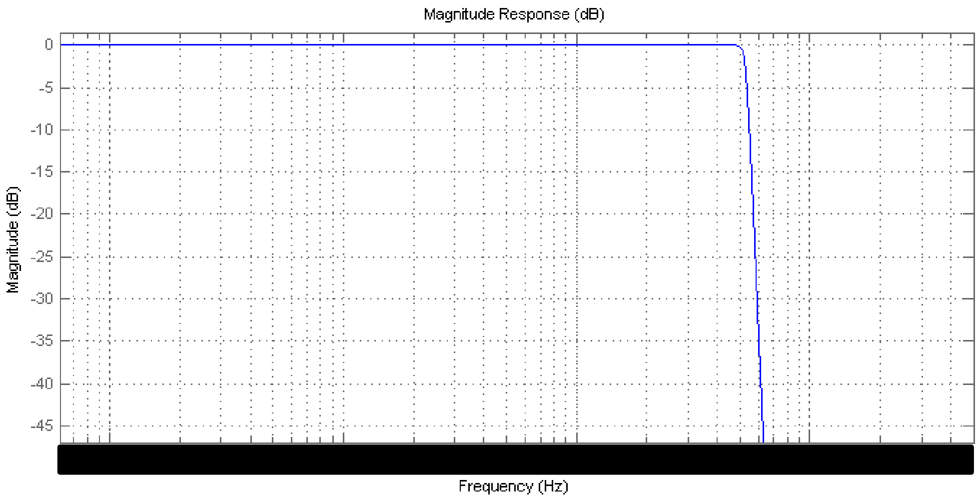

Figure 3.12 Frequency response of 30th order Butterworth low-pass IIR Direct Form II filter.

Figure 3.13 shows the voltage signal at the different stages; from the top, as original, low-pass filtered, high-pass filtered and band-pass filtered.

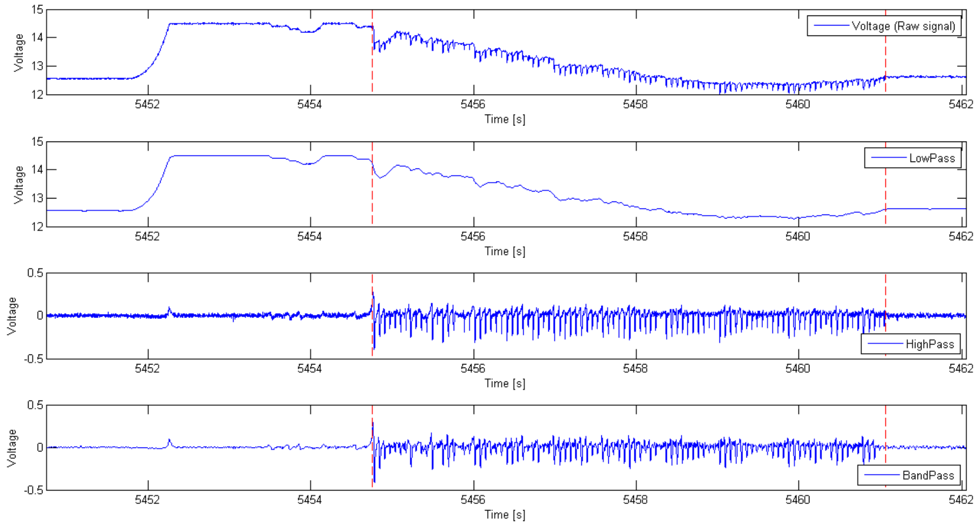

Figure 3.13 Voltage signal during an ABS engagement in the different filter stages.

The high-pass and band-pass filtered signals show clearly the ripple during the engagement of the ABS pump between 5455 and 5461 seconds.

Figure 3.14 show a 1 second long close-up of the voltage ripple during an ABS engagement before and after band-pass filtering.

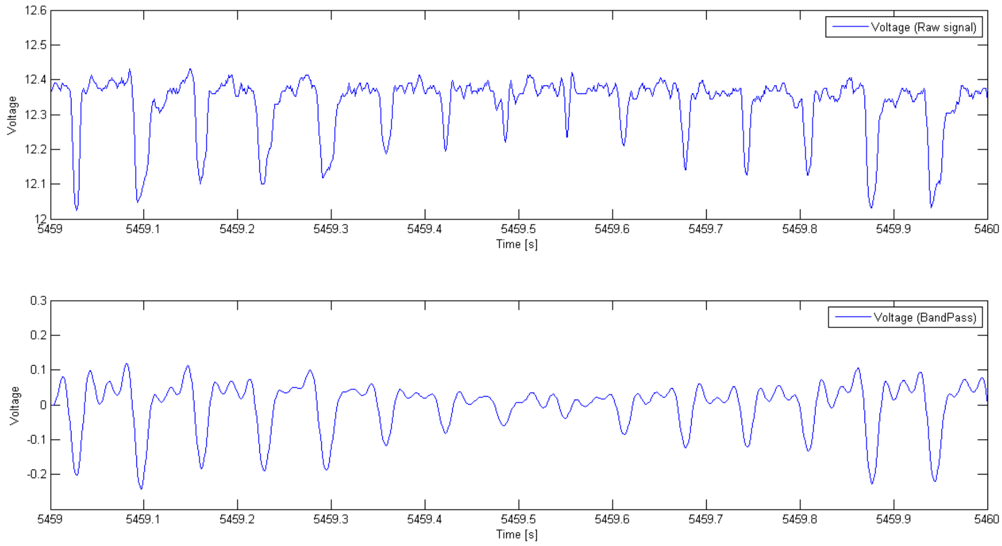

Figure 3.14 Close-up comparison between unfiltered and band-pass filtered signal during ABS engagement.

As one can see the signal is “normalized” around zero and the high frequency disturbances are removed while the general shape and area of the ripple is preserved.

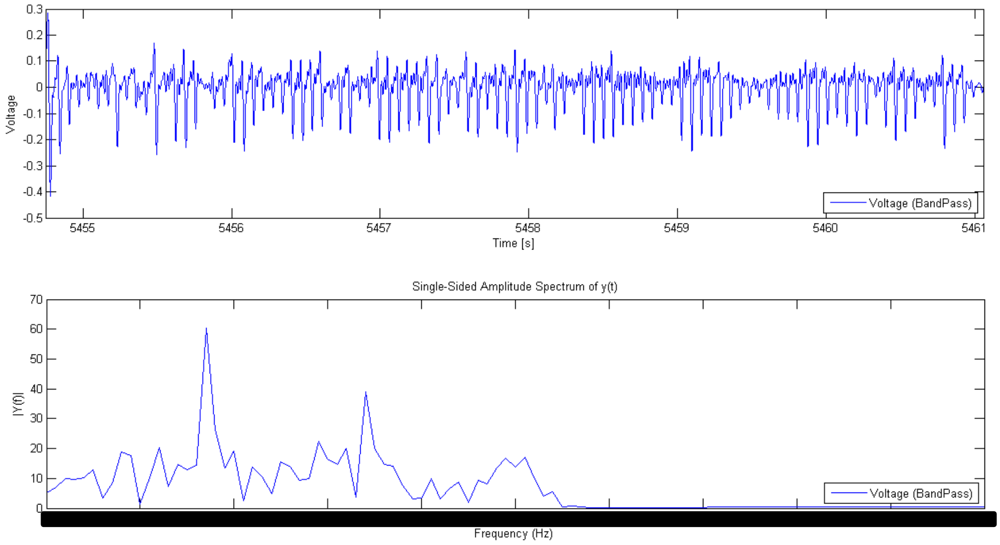

Figure 3.15 Band-pass filtered signal and its frequency spectrum during ABS engagement.

Figure 3.15 shows the band-pass filtered signal during the ABS engagement. The ripple has clearly a repetitive characteristic. The frequency spectrum shows that the 1st harmonic is [redacted] Hz; the 2nd harmonic is [redacted] Hz and the 3rd harmonic at [redacted] Hz. All examined ABS engagements show the same characteristics, what differs of course is the length of the engagements.

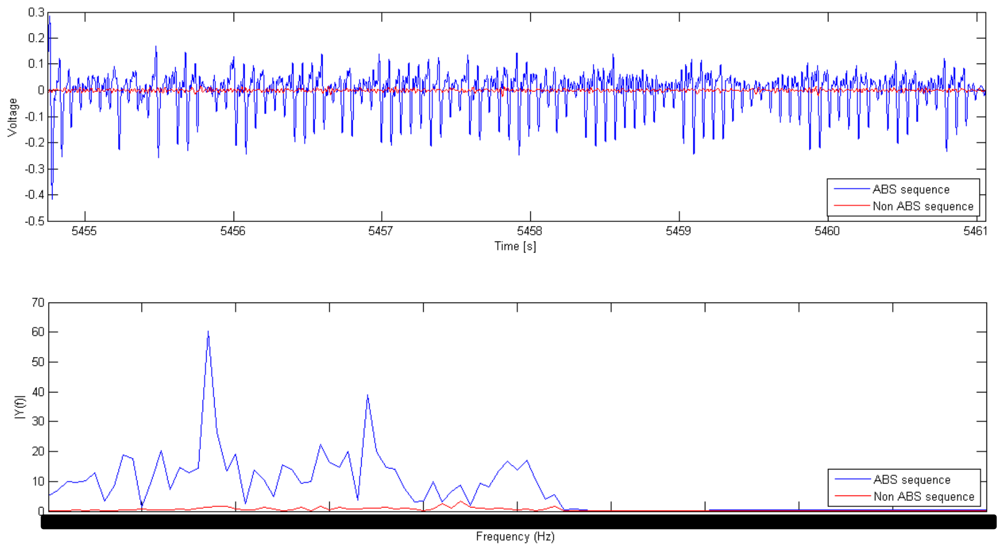

Figure 3.16 Band-pass filtered voltage and Power spectrum for ABS active/inactive.

Figure 3.16 shows the comparison between the power spectrum of the voltage signal when the ABS is engaged and during a sequence 10 seconds earlier, where no safety systems are active. The signal from a sequence without ABS being active (red line) shows that the power density is low throughout the frequency range compared to the blue signal (ABS active) described earlier.

3.5 ALGORITHM DEVELOPMENT

Following subchapter describes the three algorithms that were developed for detecting the ABS engagement.

3.5.1 ALGORITHM 1 - ANALYSIS OF DERIVATIVE

This subsection is a description of an algorithm for detecting voltage ripple using the derivative of the voltage and longitudinal acceleration of the vehicle. This algorithm will from now on be referred to as Algorithm 1. The algorithm has the following procedure, as can be seen in Figure 3.17.

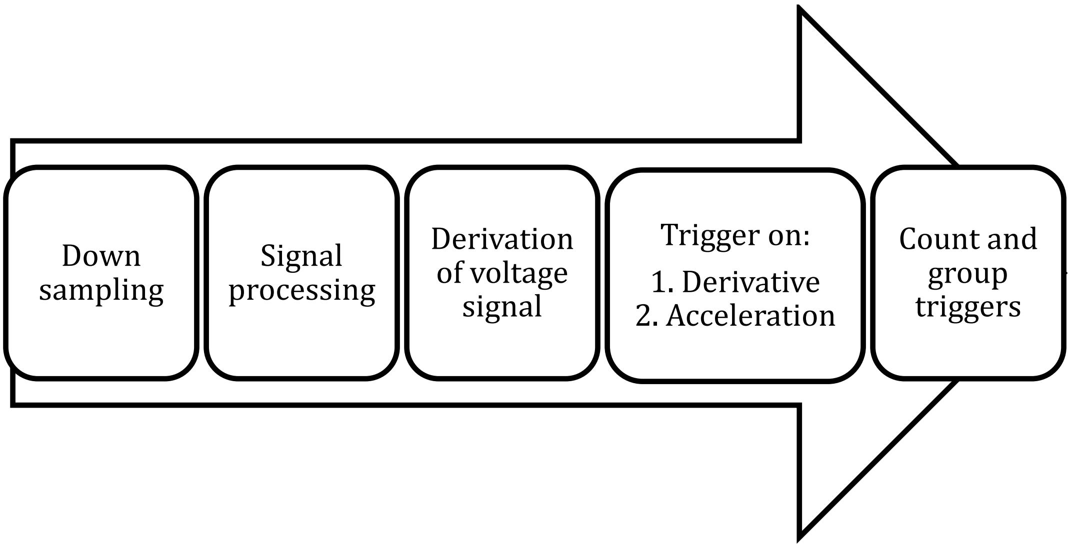

Figure 3.17 Flow chart of Algorithm 1.

Step 1 – Re-sampling

First step is to down sample the voltage signal [redacted] Hz to [redacted] Hz by simply selecting every 5th element in the original signal and discarding the rest. The downsampling is done in order to obtain a signal where the algorithm demands less computational power.

In case the acceleration has a different sampling rate (as was the case), up sampling of acceleration signal, using interpolation in order to match voltage signal is performed. The interpolation is done with linear interpolation method. Linear interpolation creates a straight line between two known points in the signal. For the two known points (y_0, x_0) and (y_1, x_1), the value y in point x between the known points is estimated with Equation 3.1:

$$y(x) = y + \frac{(y_1 - y_0)}{(x_1 - x_0)} \cdot (x - x_0) \tag{3.1}$$

Step 2 – Filtering

The voltage signal is band pass-filtered ([redacted] Hz) according to the method described in section 3.4. This is done in order to filter out all frequencies that are not of interest for the signal detection.

Step 3 – Derivative

The band-pass filtered voltage signal is differentiated through the standard method, where the slope s is described in the following equation:

$$s = \frac{\Delta y}{\Delta x} \tag{3.2}$$

That is, the change in y divided by the change in x.

This is done in order to analyse sudden changes (fluctuations) in the signal.

Step 4 – Detection using threshold

The detection used thresholds of the two signals: voltage and longitudinal acceleration. The acceleration is added to the detection in order to confirm that the vehicle is actually braking.

The voltage signal is searched through in order to find where the negative derivative is below a given threshold and the instances are saved. The threshold for negative derivative is [redacted] V/s.

On the same instances, the mean longitudinal acceleration is calculated and compared with a certain negative threshold to ensure that the vehicle is actually braking. The acceleration threshold is set to [redacted] m/s^2. To detect TC, another threshold can be added that also passes through all instances with acceleration above [redacted] m/s^2. All other instances that do not fulfil these criteria are discarded.

If the signals pass through the thresholds, it is considered as a valid indication of activated ABS or TC system and passed on to the next processing step.

Step 5 – Grouping of indications

In this step, the several indications are merged in to only one indication per ABS indication activation. This grouping is carried out in two stages:

- **First round of grouping**
  In the case of a continuous series of indications, erase all except the first one in the series and thereby grouping them.
- **Second round of grouping**
  If two grouped indications from the first run are less than [redacted] samples apart, these are consider to be one and the same event and the last one are removed. Otherwise, these are considered as two separate events.

These five steps of processing deliver indications where the ABS and/or TC have been active. The algorithm is easily configurable to detect mainly ABS or both ABS and TC, by adding or removing one of the acceleration thresholds.

3.5.2 ALGORITHM 2 - PEAK COUNTING AND VOLTAGE DROP AREA

This section describes an algorithm, which in short detects ABS engagements by counting the number of voltage drop peaks and the area of these peaks. The workflow of the algorithm is visualized in Figure 3.18.

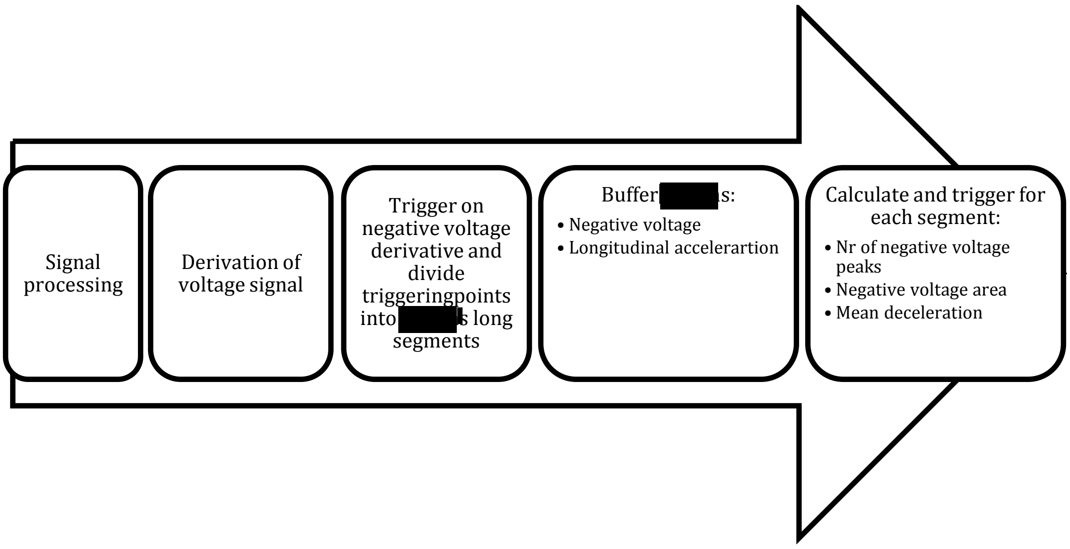

Figure 3.18   Flow chart of Algorithm 2.

Step 1 – Signal processing (band-pass filtering)

The voltage signal is filtered with the band-pass filter described in section 3.4. The band-pass filter removes the DC component of the signal while the shape and area of the voltage ripple, which occur during an ABS engagement, are preserved.

Step 2 – Derivative

See previous description in Algorithm 1.

Step 3 – Voltage derivative trigger

The algorithm is triggered by a threshold at [redacted] to the voltage derivative. If two or more triggering events occur within [redacted] s of each other then all these events will be considered to be the same event.

Step 4 – Buffering signals

Two signals are buffered in [redacted] s segments when the algorithm is triggered in step 1:

1. The negative band-pass filtered voltage.
2. Longitudinal acceleration.

Step 5 – Calculate entities and trigger

Three entities are calculated and used by the decision function:

1. The negative voltage peaks mean voltage, i.e. the area of the voltage drop, per second is calculated for each segment and the triggering threshold is set between [redacted] V.
2. The negative voltage is thresholded at [redacted] V. The thresholded signal is then differentiated to localize and count the edges of the negative peaks. Trigger thresholds are set between [redacted] and [redacted] peaks per second. In the ideal case there should be exactly [redacted] peaks per second but in reality this differs due to chance, how well the derivative triggering in step 1 is synchronized with the actual event, and the length and continuity of the ABS sequence.
3. The mean acceleration/deceleration is calculated for each segment and the triggering threshold is set to less than [redacted] m/s.

All criteria must be fulfilled to be deemed as an ABS engagement.

3.5.3 ALGORITHM 3 – POWER SPECTRUM ANALYSIS

This section describes an algorithm, which detects ABS engagements by analysing the signal power at the 1st and 2nd harmonics that are associated with the ABS system. The workflow of the algorithm is visualized in Figure 3.19.

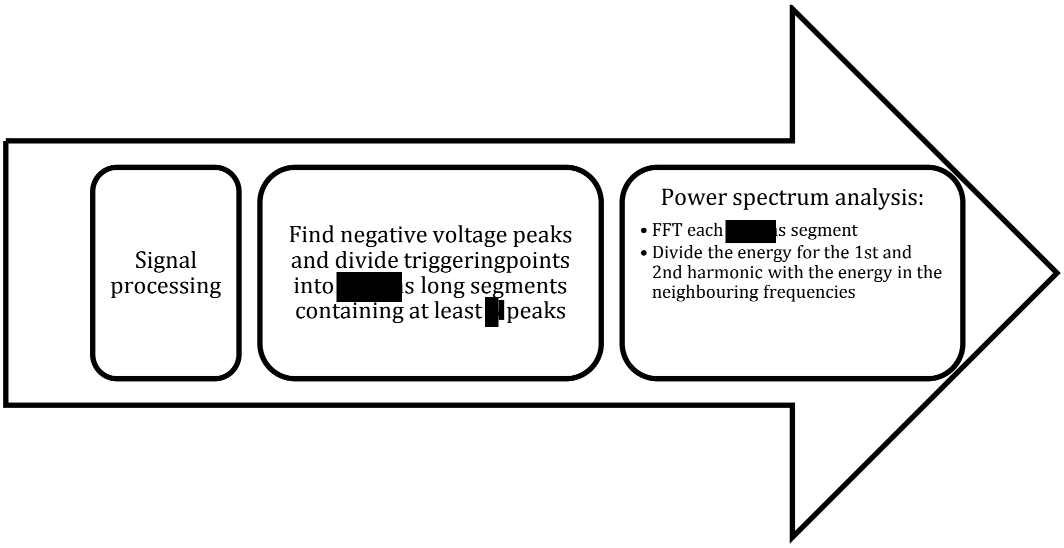

Figure 3.19 Flow chart for Algorithm 3.

Step 1 – Signal processing

Signal processing carried out according to section 3.4.

Step 2 – Voltage derivative trigger

The algorithm is triggered by a threshold at [redacted] to the voltage derivative. The triggering events are divided into [redacted]s long segments and must contain at least [redacted] negative derivative events. Note that the event counter is not a peak counter, which is the case in algorithm 2.

Step 3 – Power spectrum analysis

Each [redacted]s segment is transformed using Fast Fourier Transform (FFT) defined as:

$$X(k) = \sum_{j=1}^{N} x(j) e^{\frac{-2\pi i}{N}(j-1)(k-1)} \tag{3.3}$$

The sum of power in the 1st and 2nd ABS harmonics together with each ones closest neighbouring frequencies are divided with the sum of power in the frequencies in between the 1st and 2nd harmonics and frequencies below the 1st harmonic, resulting in equation 3.5.

$$P(k) = 2|X(k)| \tag{3.4}$$

$$\frac{\sum_{k=xx}^{xx} P(k) + \sum_{k=xx}^{xx} P(k)}{\sum_{k=xx}^{xx} P(k) + \sum_{k=xx}^{xx} P(k)} \geq$$ [redacted] (3.5)

3.6 VALIDATION

The algorithms were tested with the data obtained from Logging Session 2 and 3 (section 3.1.2 and 3.1.3) for cross-validation. An evaluation script was created in Matlab in order to validate the performance of the developed algorithms.

3.6.1 VALIDATION METHOD

The evaluation script compares the algorithm results with the reference signals gathered from the vehicles CAN-bus and returns the type of event and its position in time. The script has the algorithm results and time vector, CAN-bus time vector, ABS, AYC, TC and SC as input.

Inputs:

1. Trigger and time vectors from detection algorithm
2. Event data and time vector from CAN data

Step 1

Group both Trigger events and CAN events into segments with the maximum length of 3 seconds per event. Events that are situated within 3 seconds of the first event will be considered to belong to that first event and so forth.

Step 2

For each trigger event, search for CAN events that are situated within +- 3 seconds of the first index for each Trigger event. The CAN events uses a hierarchy system as follows; ABS, AYC, TC and SC. Are two different types of CAN events situated within the set time window to a Triggering event then the one with highest rank will be chosen to classify the event.

Step 3

Summate all signed Triggering events and calculate the number of true positive, false positive and false negative events. Outputs true positive, false positive and false negative events for each event type and their timestamp.

Figure 3.20 show the evaluation results for one logging session performed in the highlands north of Östersund. First 3000 seconds consists of driving in Östersund city and on dry highways. Rest of the session consists of a combination of mud, snow and ice together with steep variations in altitude. The safety systems are frequently activated due to the rough conditions.

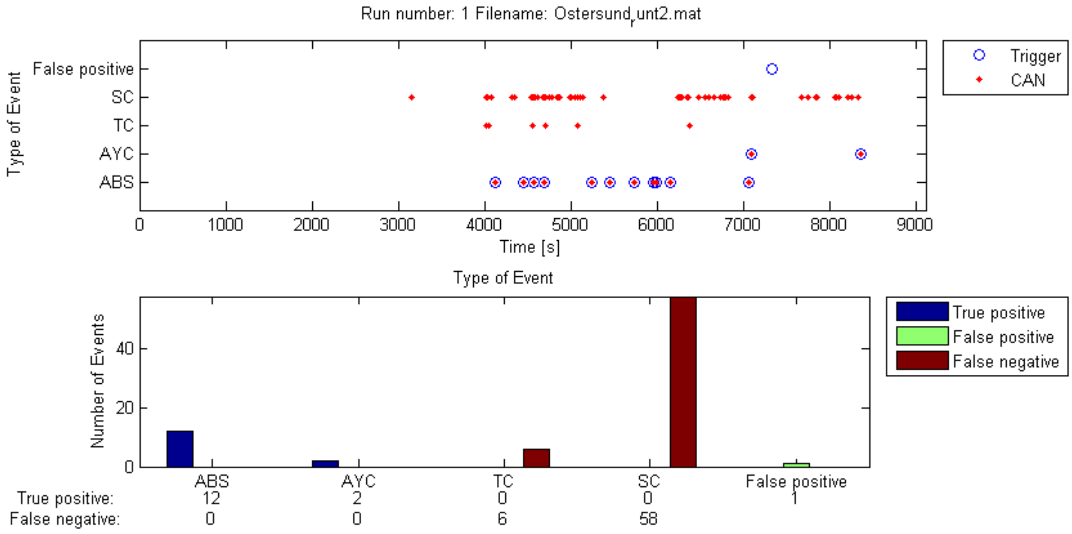

Figure 3.20 Graphical representation of the evaluation results. Upper: type of trigger event over time. Lower: Number of true positive, false positive and false negative for each type of event.

4 RESULTS

This chapter presents the result from the measurements carried out and the performance of the different algorithms that were developed. It also states the advantages and disadvantages of the three algorithms.

4.1 DISTURBANCE SOURCES

The disturbance test showed that none of the power-consuming units inside the vehicle caused any noticeable voltage ripple that would in any case cause false triggers of the algorithms. However, it should be mentioned that the vehicle did not have all available additional equipment such as sunroof or electrical seats, which could be a possible disturbance source.

The external light bar on the roof of the vehicle was found to disturb the voltage level in the vehicle and create a ripple that was similar to the voltage ripple created by the ABS. Since the algorithms require, among other factors described earlier, negative acceleration values in order to consider a ripple as valid instance, the light bar will not generate false triggers when the vehicle is standing still with the light bar activated, but only in case the vehicle is decelerating. The light bar has two blinking modes, with quite similar characteristics after band-pass filtering, which is why only one of them will be described.

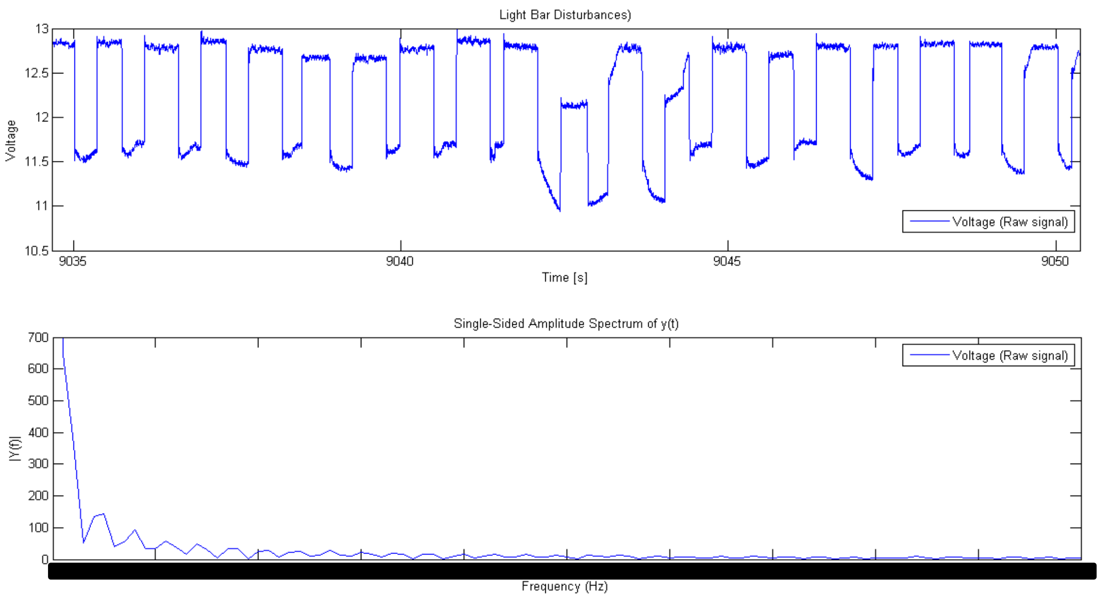

Figure 4.1 Light Bar raw signal.

Figure 4.1 shows the raw voltage signal and its amplitude spectrum for one of the modes. As seen in the plot, the signal is a square wave and at a first glance it does not seem to be similar to the ripple caused by the ABS pump. However, when looking at the band-pass filtered signal, the character changes (see Figure 4.2).

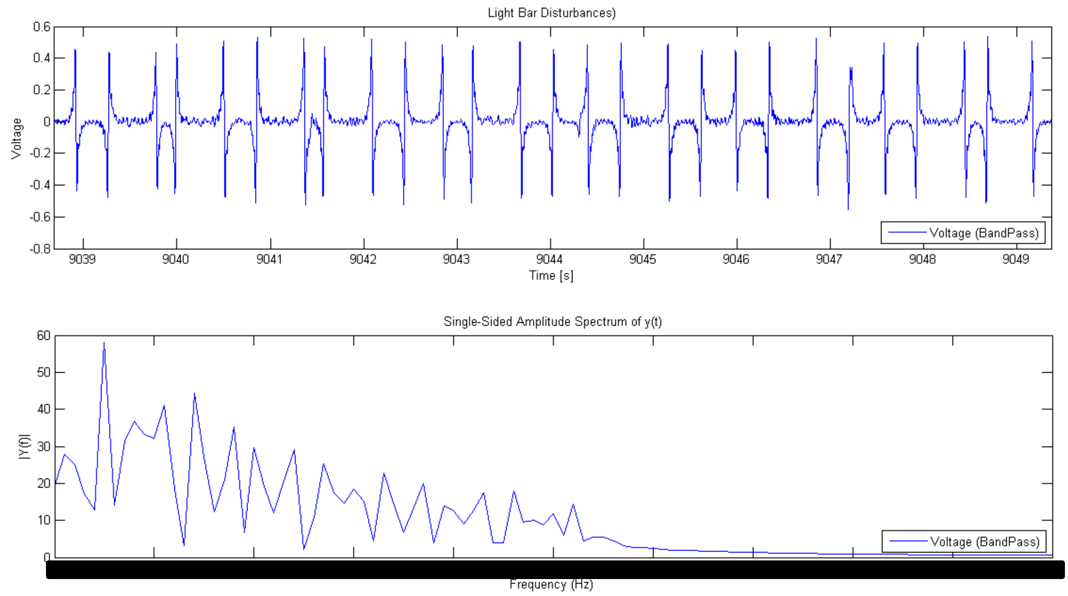

Figure 4.2 Light Bar band-pass filtered signal.

The issue with the band-pass filtered signal is that several of the harmonics are very close to the 1st harmonic of the ripple that is desired to be detected. Because the algorithm is tuned to be more ‘sensitive’, the amplitude peaks in nearby frequencies cause issues since they are not filtered out.

4.2 Algorithm Performance

The three algorithms where tested on the data from Logging Session 2 and 3, which includes 30 hours of varied driving (see chapter 3.1). The result is measured in number of true positive and false negative per total number of actual ABS engagements and the number of false positive for ABS, AYC, TC and SC.

The total number of activations for each system in the test runs was:

- ABS: 52
- AYC: 12
- TC: 38
- SC: 161

There are two results presented in this subsection; the first result for each algorithm is based on data including the sequences where the aftermarket light bar was activated and the second the result based on data where the sequences have been cut out.

4.2.1 ALGORITHM 1

Algorithm 1 managed to detect 51 out of the 52 ABS activations (see Figure 4.3) tested on data containing the light bar sequence. This means that the algorithm has 98 % detection accuracy for the available data that it has been validated against.

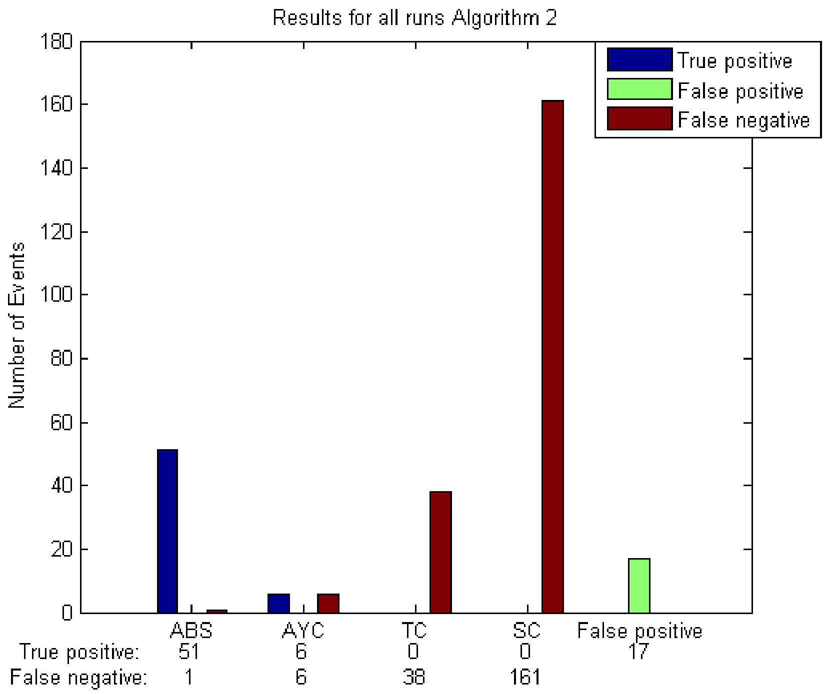

Figure 4.3 Results for Algorithm 1 for validation data including light bar.

One TC and one SC activation was detected, while 6 of the 12 AYC activations were detected. The number of false positive indications is 14.

Regarding the data not containing the light bar; Figure 4.4 shows that all results remain the same, except for the false positive. It shows that the light bar being switched on causes 10 out of the 14 false positive indications.

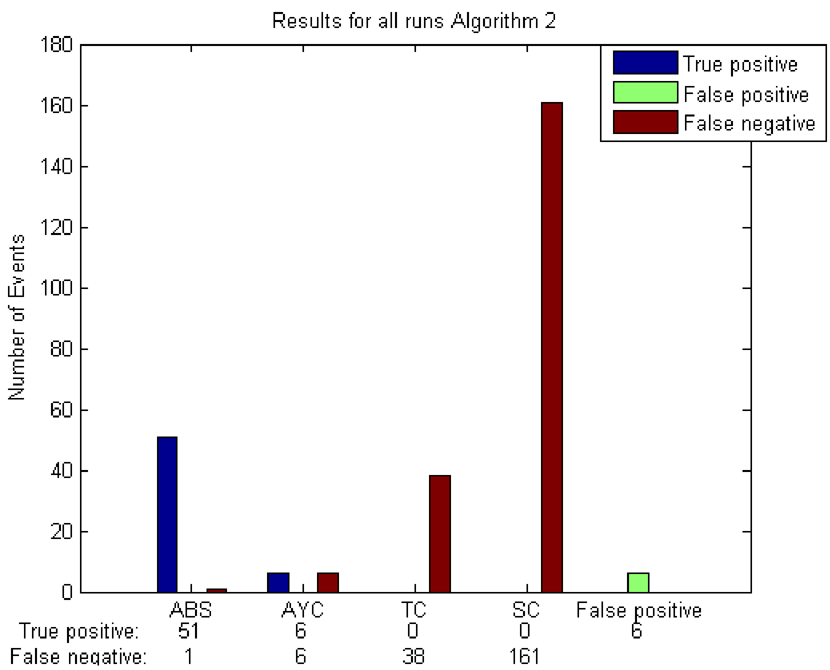

Figure 4.4 Results for Algorithm 1 for validation data excluding light bar sequence.

When configuring the algorithm to also detect TC, the results are slightly different (for validation against data without light bar). ABS, AYC and SC remain the same, while 20 out of 37 TC activations are detected and the number of false positive increase up to 9 (see Figure 4.5).

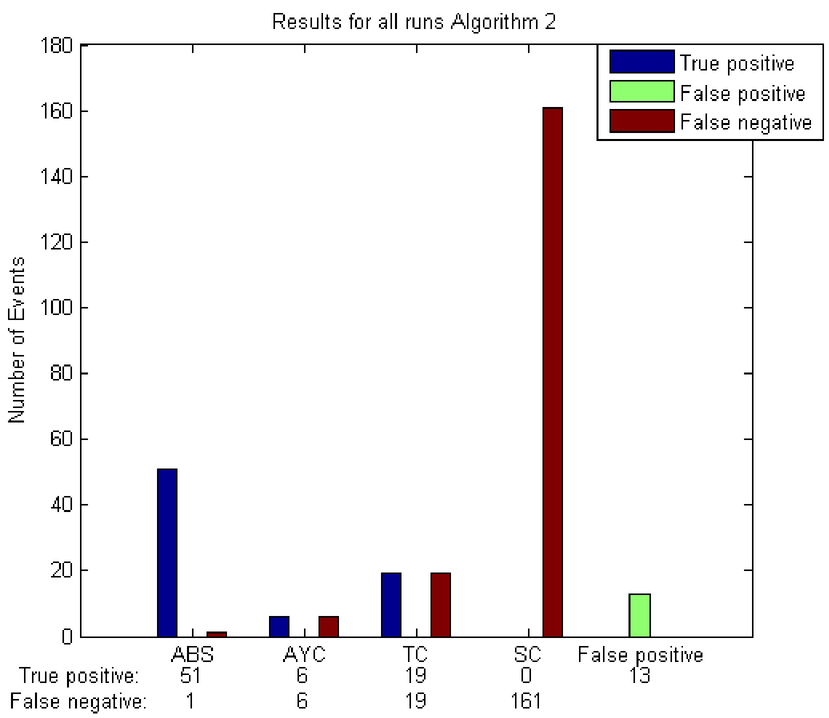

Figure 4.5 Results for Algorithm 1 with 'TC detection configuration' (validation data excluding light bar sequence).

4.2.2 Algorithm 2

Algorithm 2 is the best performing algorithm of the three. It manages to detect all of the 52 ABS instances that were present in the data. It detects 4 out of 12 AYC engagements, but none of the other systems (SC and TC). The light bar causes the one false negative.

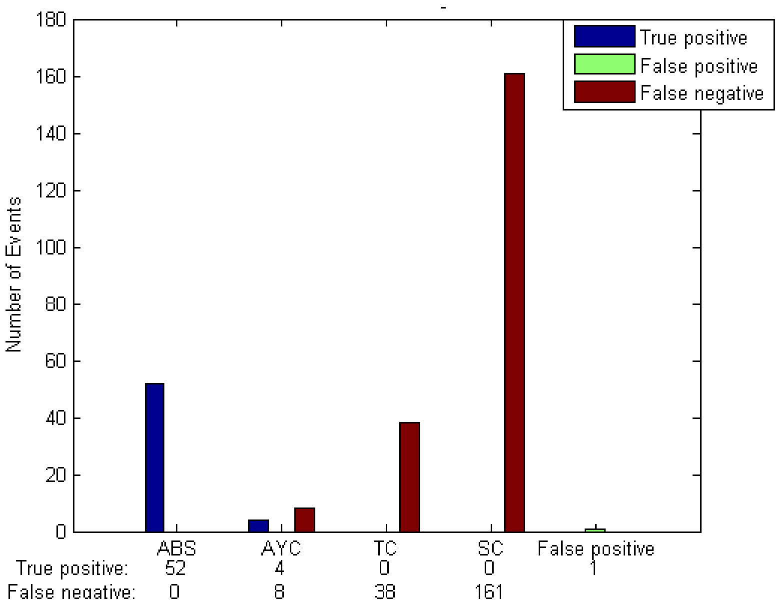

Figure 4.6 Results for Algorithm 2 for validation data including light bar sequence.

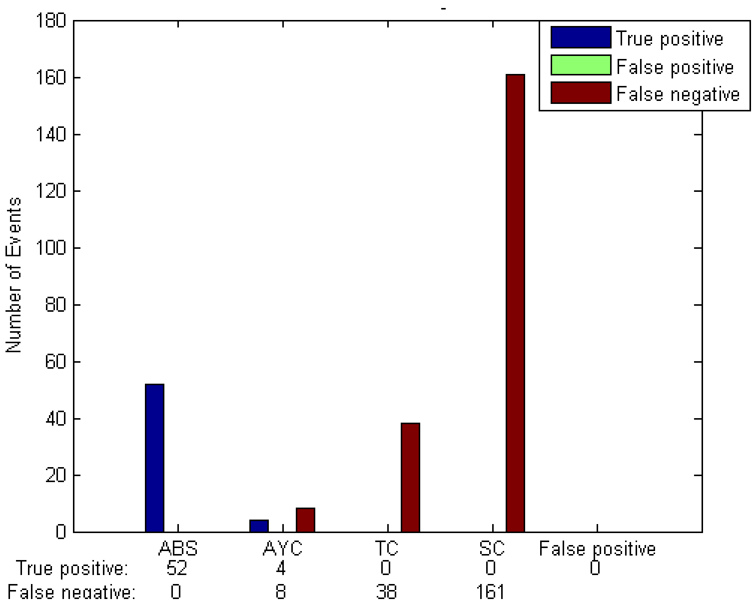

Figure 4.7 Results for Algorithm 2 for validation data excluding light bar sequence.

4.2.3 ALGORITHM 3

Algorithm 3 detects 51 out of the 52 ABS engagements, 4 of the 12 AYC engagements and none of the TC activations. The one single SC detection is considered to be false positive, as the trigger is within the time span when the SC is activated simply by coincidence, although the voltage ripple is identical to an ABS engagement. It produces 1 false positive, which is not caused by the light bar like in the other algorithms.

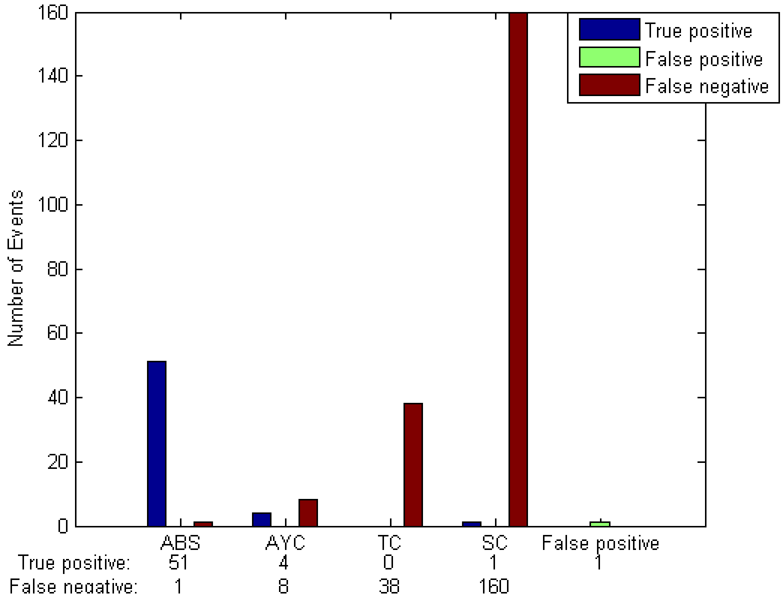

Figure 4.8 Results for Algorithm 3 for validation data including light bar sequence.

4.3 FALSE POSITIVE AND FALSE NEGATIVE EVENTS

The false positive trigged and false negative events are described in this subchapter.

4.3.1 ALGORITHM 1

Closer examination of the 6 false positive was performed by looking at the available CAN signals in the vehicle. This was done in order to identify the cause the false positive triggers. Two of the false positive triggers are most likely caused due to the electrical power steering, as the steering angle is increased rapidly; in one case during a gearshift with disengaged clutch and in the other case when the engine is idling. One false positive have been investigated, and found out to be caused by a sudden voltage drop, but no reason for this drop could be identified. The last false positive is caused by the same phenomena causing the two false positives for Algorithm 3, described in section 4.3.3.

The false negative is caused due to the relatively low acceleration during the ABS activation. The incident is trigged on the derivative, however the longitudinal acceleration is too low to pass through the given threshold. The threshold could be lowered, allowing the algorithm to pass this certain instance, but this will instead result in several new false positives.

4.3.2 ALGORITHM 2

Algorithm 2 has only one false positive and it occurs at the end of a braking sequence while the fast mode on the light bar is activated. Due to the transition between regenerative charging and no charging there is some additional ripple close to the negative voltage threshold which is registered as peaks by the peak detector and causes the false positive result.

4.3.3 ALGORITHM 3

Algorithm 3 has 2 false positive and 1 false negative.

False negative is due to the length of the event that is only [redacted]s long and contains [redacted] peaks. As explained in section (algorithm 3) the algorithm uses [redacted]s long windows when performing the analysis and in the worst-case scenario is the event split in to two different windows each [redacted]s long and this is too short a time for an accurate analysis and is therefore missed.

Both the false positive events occur when driving on a combination of snow, ice and mud with deep tracks, which rocks the vehicle back and forth and quite large corrections to the steering wheel are necessary to stay on track. SC is constantly activated and a voltage drop containing [redacted] respectively [redacted] peaks occur. These voltage drops are identical to an ABS engagement though no anomalies are found in the CAN data that can explain these events that occur during almost identical circumstances. It might be AYC that is engaged, considering the physical measurements in the CAN data this would be the most likely explanation though it's not reported over the CAN bus while the SC is engaged.

5 DISCUSSION AND CONCLUSION

This chapter covers issues which were discovered during this Thesis and conclusions regarding the results.

5.1 LIGHT BAR

As was discovered, the auxiliary light bar that was mounted on the vehicle had an impact on the performance of algorithm 1 and 2. It was decided to also present the result validated against the data without the light bar sequences. These results are considered to be a valid measurement of the algorithm performance, since it is assumed to be very unlikely to be present on a 'normal' vehicle. An exception for this would be maintenance vehicles of different kinds, which very often possess light bars of some sort. However, these algorithms and the complete system are expected *not* to be used on such vehicles.

5.2 THE SAFETY SYSTEMS

The ABS, which is activated by the driver braking, created a distinct character of the voltage ripple. However, AYC and TC, which is activated automatically, acting with irregular time intervals depending on the physical conditions present in the situation at the moment. This creates a ripple that differs from case to case, and is therefore difficult to characterize. This is the main reason why there is an issue to detect AYC and TC in particular. Since SC does not even use the ABS unit, it is even more difficult to detect because of the barely noticeable voltage fluctuation. The focus has been to detect ABS activation only, due to the statement made by Pär Ekström saying that ABS was the best indicator in the SRIS project (see section 1.1.1.).

5.3 VALIDATION DATA

Due to unusual warm winter conditions and the limited time frame for the thesis restricted the possible amount of time for data collection for algorithm validation to 30 hours. Making a judgment whether the amount of data is sufficient to confirm the performance of the algorithms is complicated. However, the varieties of road surface and road types covered were extensive, and all of the systems were activated comprehensively, which is why the confidence of the result is considered to be satisfying.

As stated earlier, the algorithms were developed based on one vehicle model and ABS OEM (ATE). There are at least 4 more large OEM:s (Honda, Bosch, Bendix, Lucas Girling) supplying car manufacturers with ABS systems that work differently and most likely have different impact on the voltage level in the vehicle than the one that has been tested. Other factors such as no regenerative charging, battery capacity or even engine power can influence how the voltage ripple occurs in the vehicle. These different ABS types and factors could not be investigated due to lack of the availability, but should most certainly be investigated in order to develop a more robust algorithm.

5.4 ALGORITHM PROPERTIES

Since the goal was to detect ABS-engagements this has been the priority during the development of the algorithms and thus is the main priority in the evaluation of their performance.

The advantage with algorithm 1 is that it is generic, i.e. it is not specified to suit only a certain car model where the ABS pump generates voltage ripple with a specific frequency. Another attribute is the fact that it works on a signal with lower sampling rate and thereby the computational power and time can be lowered. This could be an important aspect if it were to be implemented into a device with less powerful processor. Algorithm 1 is possible to easily configure to detect TC, with the punishment of adding 5 more false positives. In order to judge whether this is better or worse performance, one must take in to account the application area and many other aspects, such as the negative effect of an extra false positive versus the positive effect of an extra gained true positive. The disadvantage of Algorithm 1 is the slightly worse performance and the generated false positives compared to the other algorithms.

Algorithm 2 is very generic since it can operate at different sampling frequencies and allows for quite large variations in both frequency and magnitude of the voltage drop caused by the ABS system. The algorithm can function without acceleration sensor though one must then compromise between accuracy and sensitivity. ABS engagements that are continuous and have duration of at least [redacted] second are easily detected via the voltage signal alone. Shorter events are harder to detect due to difficulties to perfectly synchronize the algorithm with an actual event and fill the whole [redacted]s long window with a continuous ABS engagement.

Algorithm 3 is tailor-made for our particular vehicle and considers only the exact frequency, which that particular ABS unit works at. The performance is really good though and relies on the voltage signal only.

5.5 CONCLUSION

A complete easy to use recording equipment that records voltage, GPS position and vehicle CAN data to time synced CAN-protocol log-files has been assembled. These files are easily exported to other common file standards for further processing. The equipment were later used to collect necessary data for signal analysis and algorithm development and finally for algorithm validation.

This project has provided results showing that it is possible to detect ABS system activation with only the use of external sensors which was the goal with this Master's Thesis. It is possible to accomplish the detection through signal analysis of the vehicles electrical system alone, although better results are achieved if the longitudinal acceleration is also measured.

All three algorithms that were developed during this Master's Thesis, showed satisfying performance with high degree of both accuracy (more than 90 %) and sensitivity. One of the algorithms showed exceptional results with the available set of naturalistic driving data, scoring perfect detection results and zero error rate (100 % accuracy).

One of the algorithms also showed promising possibilities to detect Traction Control (TC) engagement. However, further development is needed to increase the accuracy of the algorithm in order to achieve fully satisfactory TC detection performance.

5.6 Future work

Next step from this point would be a complete implementation of the algorithms into the BiFi hardware which could be used to collect data to the SRIS-project. This would mean some additional programming in C-language and extra hardware configurations. All vehicles equipped with the BiFi-hardware could with minor hardware-upgrades and a software update be used to collect and report event data to the SRIS-database. A first step to make this information available to potential end-user could be graphical representation on roadmaps on the web, similar to an already existing application in the BiFi-project. The concept could be expanded further with a two way communication and a user interface delivering current local road surface conditions information in real-time to the end-user.

If the algorithms were to be applied, one should consider validating against more data in order to guarantee its performance.

Another aspect is to investigate whether the algorithms are applicable to other vehicle models and ABS types.

Extend the functionality of the algorithms to also detect TC and AYC with better accuracy.

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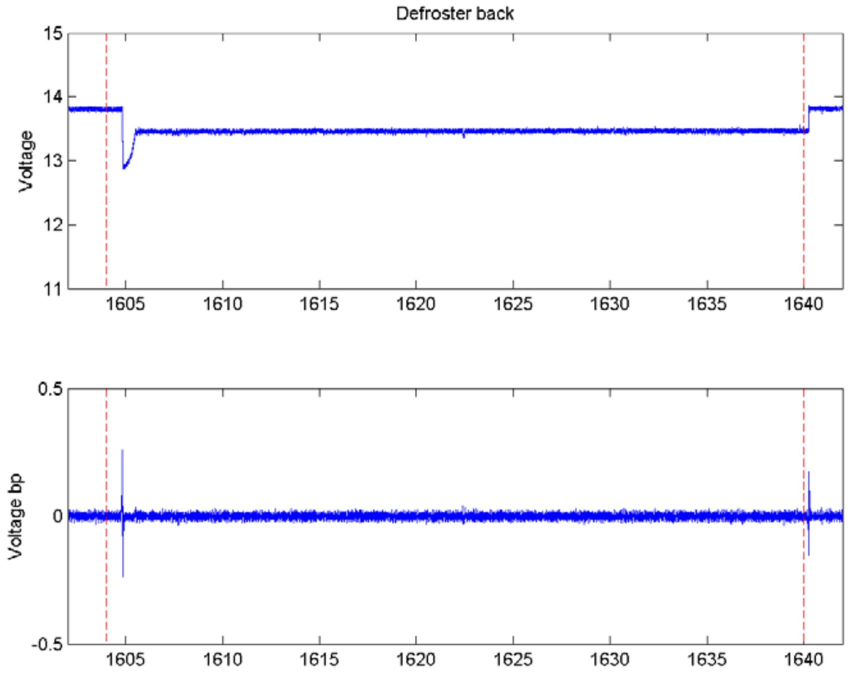
7 APPENDIX A: DISTURBANCE TESTING

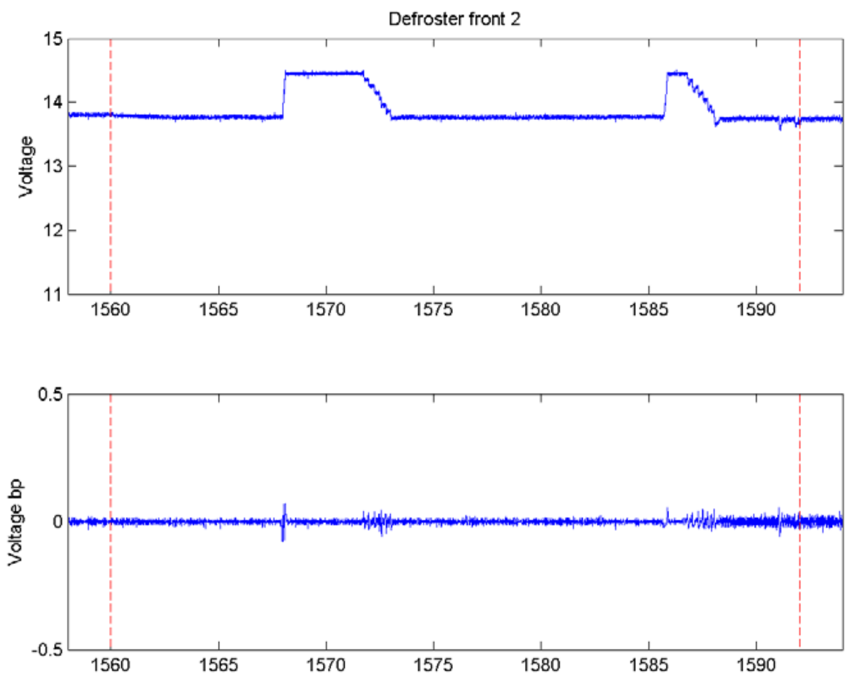
This section presents the most significant results of the disturbance tests that are described briefly in section 3.1.3 and more in detail in Appendix B. Some of the performed function tests didn't generate any measurable or at least noteworthy disturbances to the vehicle electrical system and are not presented in this section.

Note to the reader: for each test, two voltages over time graphs are presented; raw voltage signal on top and band-pass filtered in bottom. The events are situated between the two red lines.

7.1 DEFROSTERS

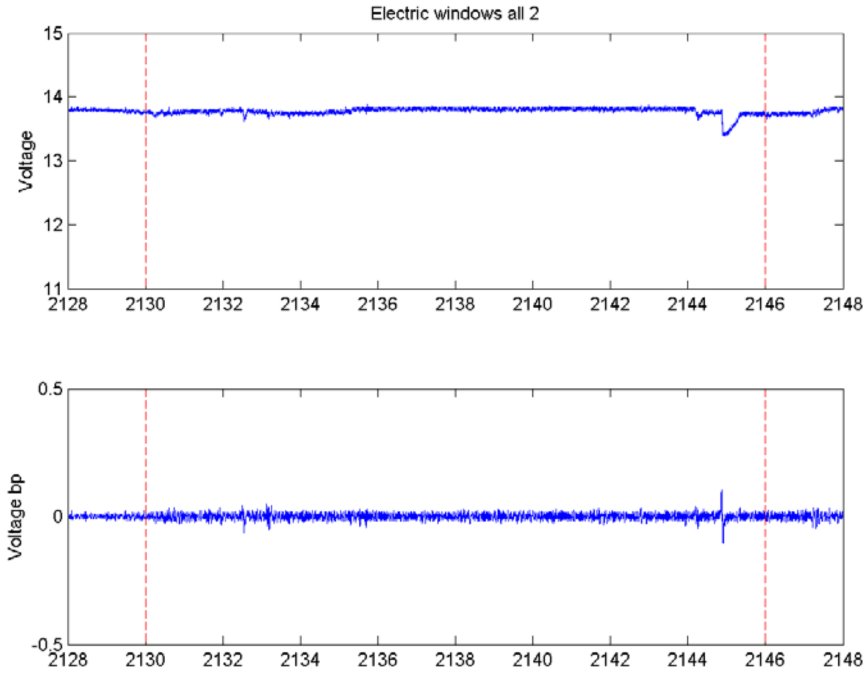


Rear view window defroster. The heater consists of electrical wiring and is quite power consuming as can be seen in the figure.

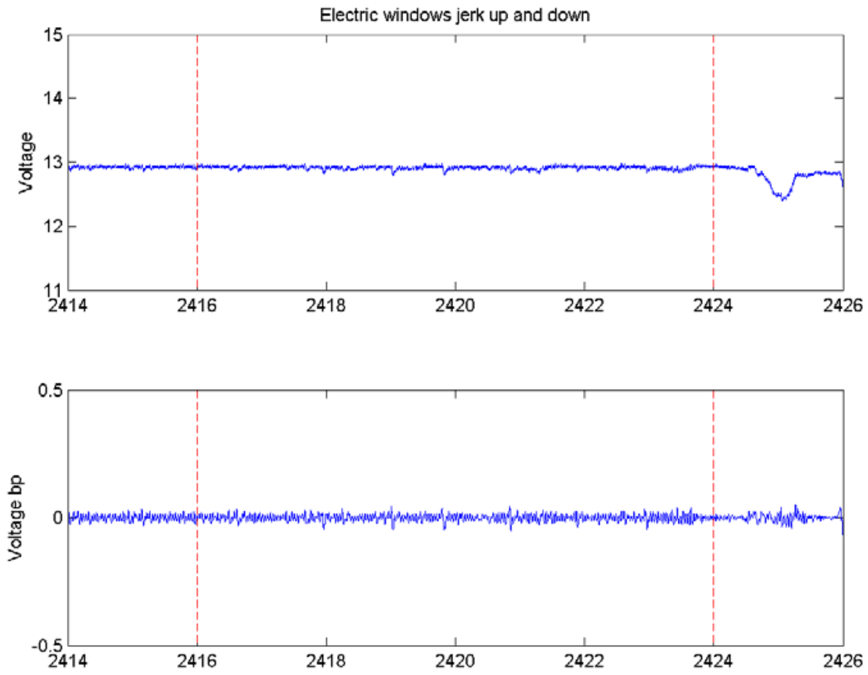


Windshield defroster. The defroster uses hot air from the climate control and is not that power consuming. The main power consumer is the fan that moves the air.

7.2 ELECTRIC WINDOWS

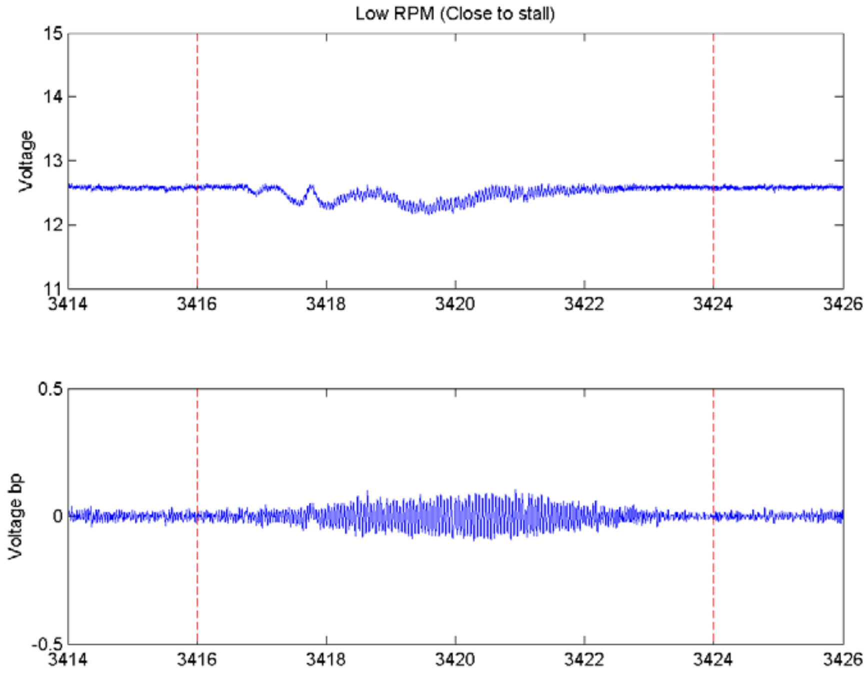


Opening all windows at once causes a very small voltage ripple. Closing them on the other hand causes a much larger drop which occurs when the windows reaches the final position and the load on the DC-motors increase significantly.

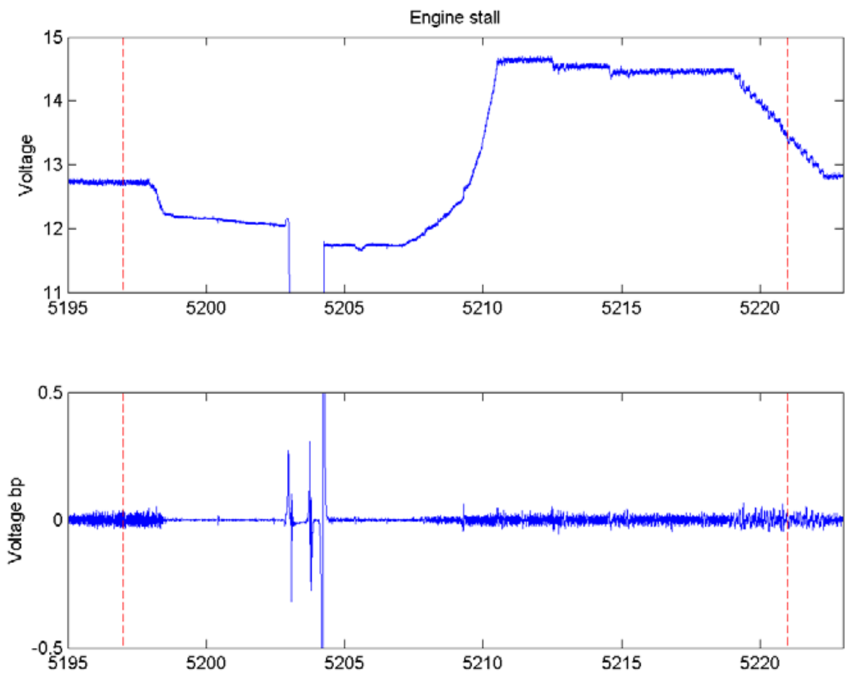


Rapidly change between roll down and roll up of the windows causes small continuous voltage drops. The large voltage drop behind the second red line is when the window closes.

7.3 ENGINE STALL

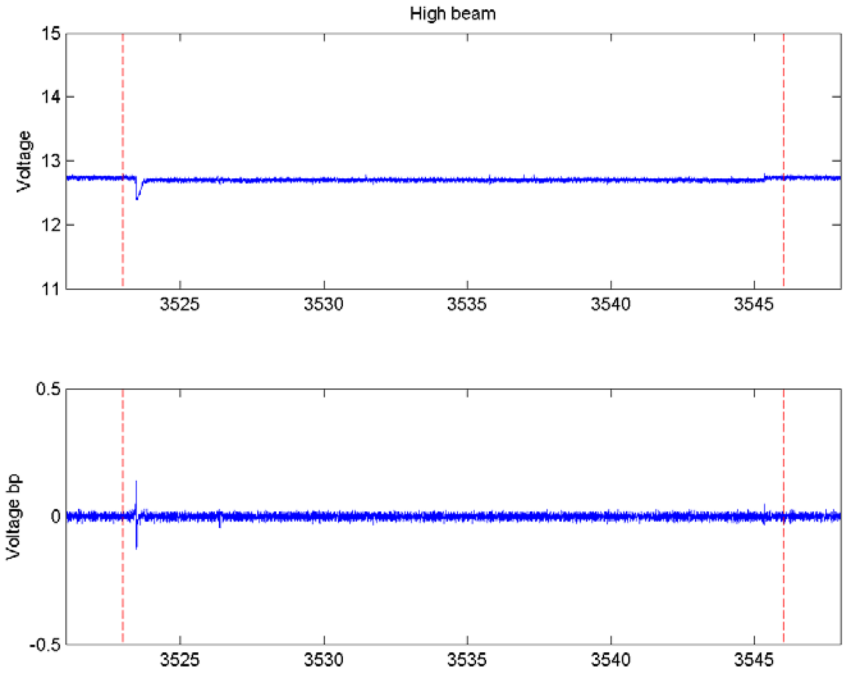


The vehicle is driven close to the engines stall rpm. This causes significant high frequent voltage ripple.

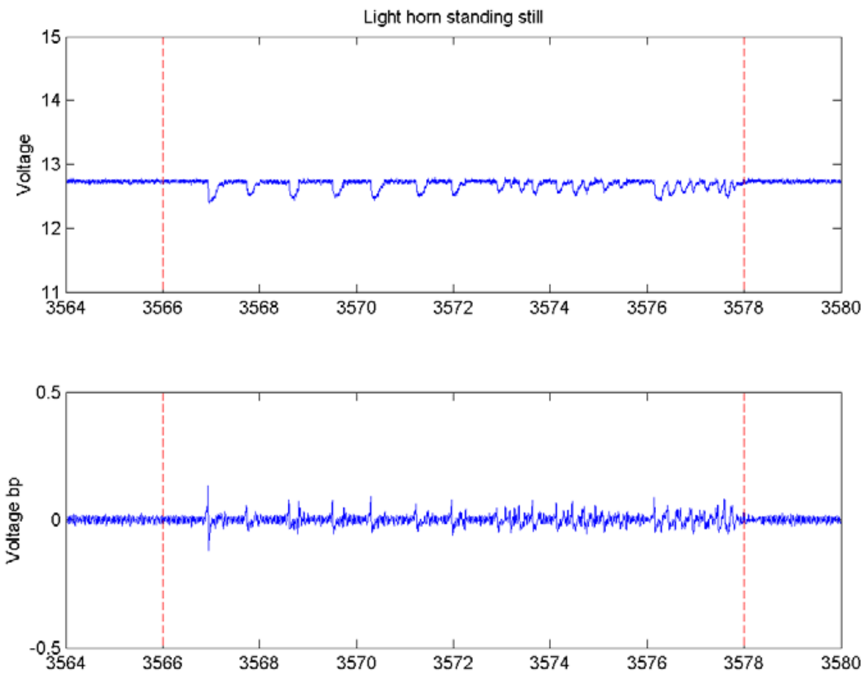


Engine stall causes both large low frequent voltage drop as well as a high frequent ripple. The steep decrease at 5203 is when the engine shuts down followed by an immediate restart.

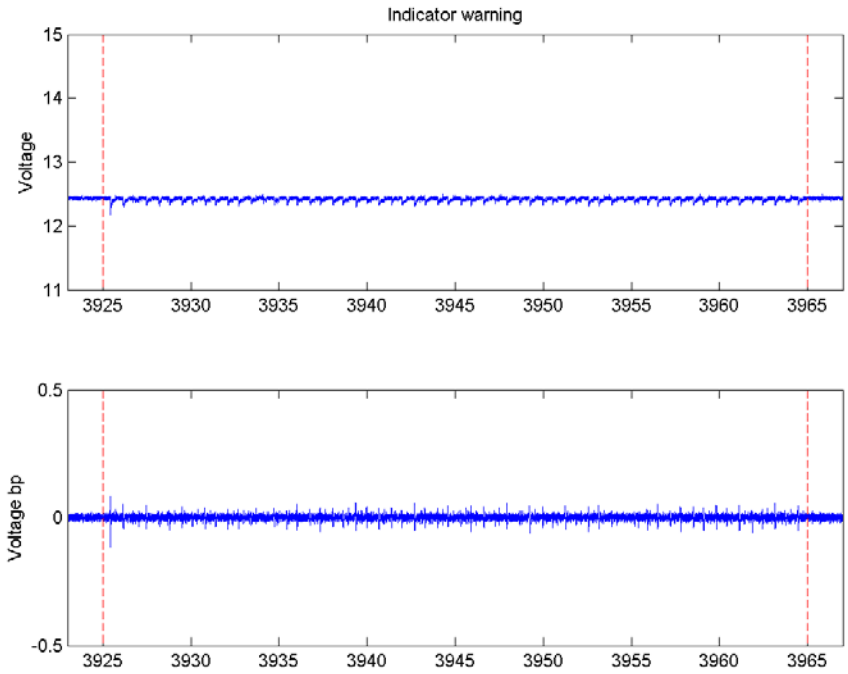
7.4 LIGHTS



Activation of the high beam causes a sudden voltage drop which quickly dissipates and stabilizes at almost the same level as before activation.

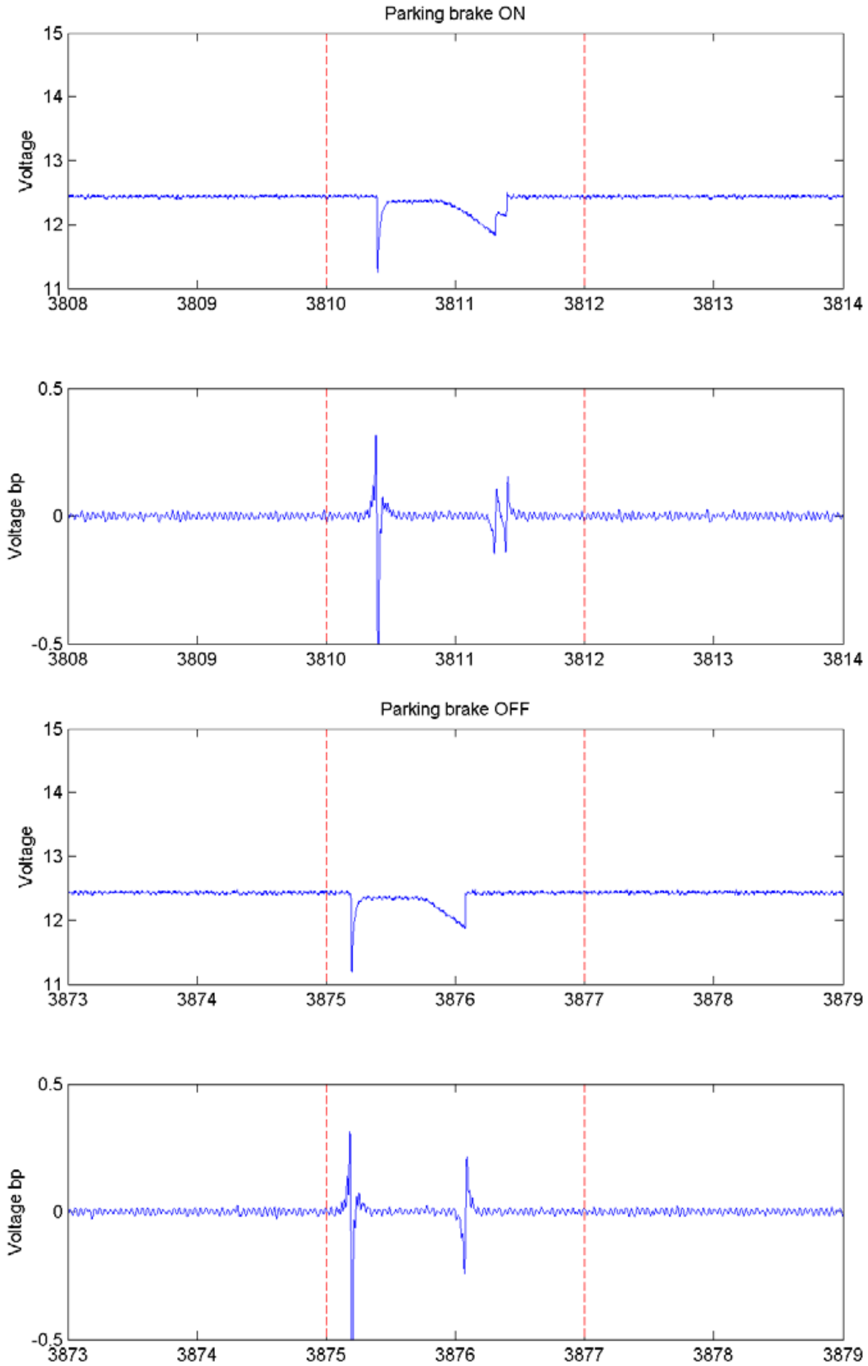


Repeated activation of the light horn causes sharp voltage peaks upon activation.



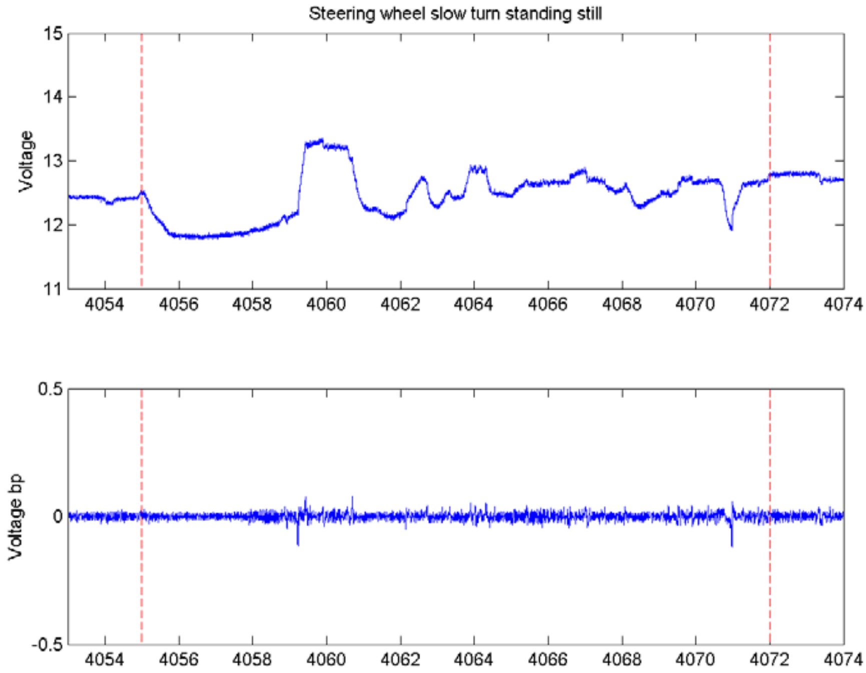
The warning lights operate at 8 Hz and causes a clearly characteristic and continuous voltage ripple.

7.5 ELECTRICAL HANDBRAKE

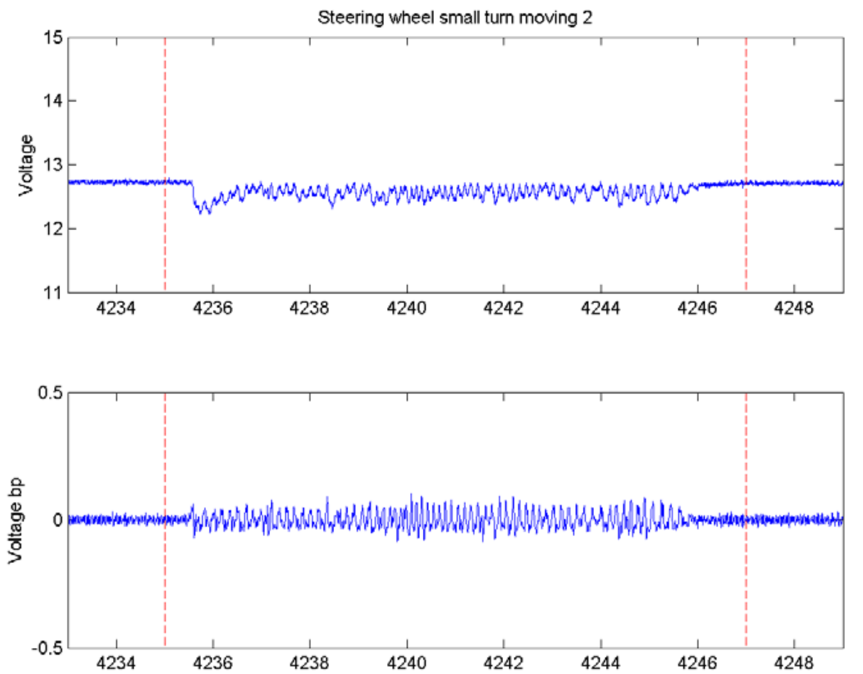


Both handbrake on and have a very distinctive characteristic.

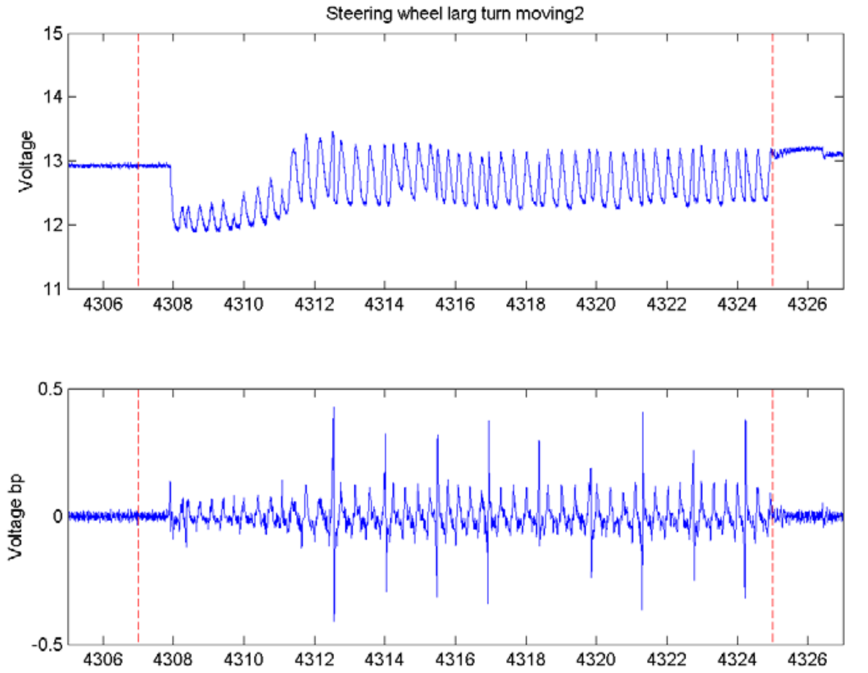
7.6 STEERING WHEEL (ELECTRICAL POWER STEERING)



Slowly turning the steering wheel while the vehicle is stationary. The voltage drop is quite significant since the vehicle is equipped electrical power steering. The motion is so low frequent that it's almost completely filtered out by the high-pass filter.

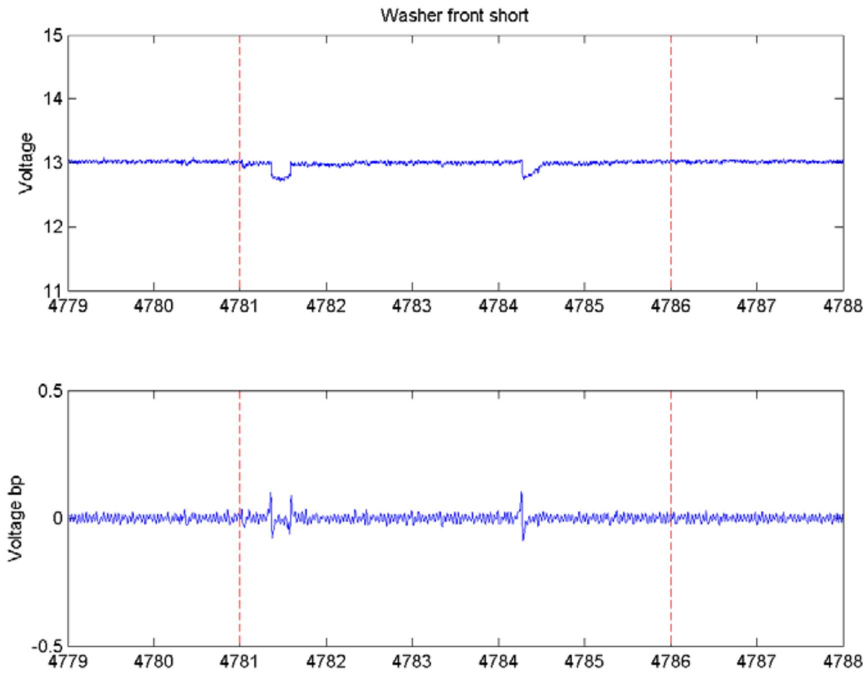


Rocking the steering wheel back and forth with small degree changes while moving causes a voltage ripple, which mirrors the rocking motion.



Same situation as previous test though the degree changes are increased causing an increase in amplitude of the ripple.

7.7 Windscreen and headlight washers



The first peak is caused by the high-pressure windscreen washer. The second triangular shaped peak is caused by the headlight washer. The windscreen wipers are only causing minor low frequent ripples, which change with the speed of the wipers.

8 APPENDIX B: TEST MATRIX

Steering servo	Turning rate	
	Slow	Measurement Nr: Time: Comment:
	Fast	Measurement Nr: Time: Comment:
	Small	Measurement Nr: Time: Comment:
	Big	Measurement Nr: Time: Comment:
High beam		Measurement Nr: Time: Comment:
Light horn		Measurement Nr: Time: Comment:
Fog light		Measurement Nr: Time: Comment:

Indicators		
	Left	Measurement Nr:
		Time:
		Comment:
	Right	Measurement Nr:
		Time:
		Comment:
	Warning	Measurement Nr:
		Time:
		Comment:
Climate control		
	Cold	Measurement Nr:
		Time:
		Comment:
	Warm	Measurement Nr:
		Time:
		Comment:
	Auto	Measurement Nr:
		Time:
		Comment:
Entertainment		Measurement Nr:
		Time:
		Comment:

Defroster

Front

Measurement Nr: ______

Time: ______

Comment: ______

______

Back

Measurement Nr: ______

Time: ______

Comment: ______

______

Washer

Front

Measurement Nr: ______

Time: ______

Comment: ______

______

Back

Measurement Nr: ______

Time: ______

Comment: ______

______

Activate all disturbance sources at once

Velocity: 0

Measurement Nr: ______

Time: ______

Comment: ______

______

Velocity: ______

Measurement Nr: ______

Time: ______

Comment: ______

______

Wiper

Front
Measurement Nr: __________
Time: __________
Comment:

Interval
Measurement Nr:
Time:
Comment:

Spd 1
Measurement Nr:
Time:
Comment:

Spd 2
Measurement Nr:
Time:
Comment:

Back
Measurement Nr:
Time:
Comment:

Low speed
Measurement Nr:
Time:
Comment:

High speed
Measurement Nr:
Time:
Comment:

Engine stall
Start:
Stop:
Measurement Nr:
Time:
Comment:

Electric windows			
	Normal		
		Measurement Nr:	
		Time:	
		Comment:	
	Jerk up and down	Measurement Nr:	
		Time:	
		Comment:	
Cruise Control			
	Cruise	Measurement Nr:	
		Time:	
		Comment:	
	Accelerate	Measurement Nr:	
		Time:	
		Comment:	
	Decelerate	Measurement Nr:	
		Time:	
		Comment:	
Seat heater	Nr ON		
	driver	Measurement Nr:	
		Time:	
		Comment:	
	passenger	Measurement Nr:	
		Time:	
		Comment:	

Normal Driving, no added disturbances		
Velocity: ___	Measurement Nr:	________
	Time:	________
	Comment:	________
Velocity: ___	Measurement Nr:	________
	Time:	________
	Comment:	________
Velocity: ___	Measurement Nr:	________
	Time:	________
	Comment:	________
Rev loss, start from idle	Measurement Nr:	________
	Time:	________
	Comment:	________
Electric rear view mirrors	Measurement Nr:	________
	Time:	________
	Comment:	________

9 APPENDIX C: CONTROLLER AREA NETWORK (CAN)

The Controller Area Network (CAN) is a serial communication protocol, which is designed to be used in real time control applications, which operates in harsh environments and demands high reliability. The CAN protocol was originally developed by BOSCH during the eighties to replace the wiring harness which connected the rapidly increasing number of Electrical Control Units (ECUs) inside vehicles with each other [**15**].

The CAN bus is based on the multi-master, or multicast, principle which means that there is no host computer that controls the traffic on the bus. All nodes (ECUs) are able to send, receive and request information from any node on the CAN bus. Instead of assigning each node with an address each message are assigned with a unique predefined identifier (ID). The nodes operate by listening, message filtering, on the bus for messages of interest. This reduces the load on the bus since multiple nodes, which make use of the same information, can receive the same message simultaneously since the messages are open to all nodes. Conflicts on the bus are avoided through the use of a message priority system, arbitration, which is based on the message ID value, the lower the identification number is the higher priority. Since the protocol use binary data for communication this results in 0 (low) being the dominant and 1 (high) the recessive. When multiple nodes are trying to transmit simultaneously the node transmitting the message with a higher ID will cease to transmit when it detects a dominant bit on the bus and the higher priority message will continue to transmit without delay. The message ID is determined based on the importance of the function, for example safety functions such as ABS has higher priority than the electric windows [**15**].

9.1.1 FRAMES

There are 4 types of messages (Frames) defined in the CAN protocol:

- Data Frame: carries data from transmitting node to receiving node(s).
- Remote Frame: request for a message with a unique ID to be transmitted.
- Error Frame: any node that detects a bus error will transmit an Error Frame and the previous message will be transmitted again.
- Overload Frame: when overload is detected a delay will be introduced between frames.

The Data frame will be described in detail to give the reader a good understanding of the robustness that is built in to the CAN protocol.

Data frame (Standard format)

The Data Frame consists of 7 fields: Start Of Frame (SOF), Arbitration Field, Control Field, Data Field, Cyclic Redundancy Check (CRC) Sequence, Acknowledge Field (Ack), End Of Frame (EOF). Figure 9.1 shows graphically how a CAN Data Frame on Standard Format is formatted.

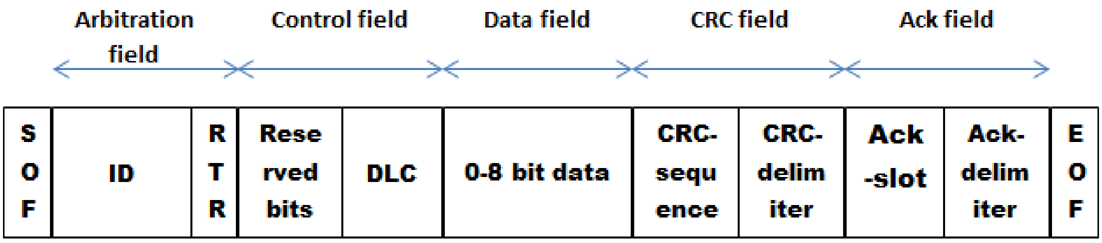


Figure 9.1 CAN Data Frame on Standard Format.

Start Of Frame: Consists of a single dominant bit to mark the beginning of a transmission and enable for leading edge synchronization between the nodes.

Arbitration field: Consists of the message identifier (ID) and Remote Transmission Request Bit (RTR) which is used to determine if the frame is a Data Frame or a Remote Frame.

Control field: Consists of 2 reserved bits and the Data Length Code, which tells the receiver the number of bytes the Data Filed contain.

Data Field: Contain 0-8 bytes of data.

CRC Sequence: The CRC Sequence is 15 bit + 1 recessive bit (Delimiter) and is calculated for the 15 lowest coefficients included in the stream with start from the SOF to the Data Field.

Ack Field: Consists of Ack Slot and a Delimiter. The transmitter writes two recessive bits to the Ack slot followed by all receivers writing a dominant bit if the received message passes the CRC Sequence check.

EOF: Consist of a 7 Bit long Delimiter.

9.1.2 ERROR DETECTION

The CAN protocol utilizes multiple communication safety technics to ensure low error rates:

- Stuffing errors: When either five consecutive dominant or five consecutive recessive bits are transmitted will the transmitter insert either a recessive or dominant bit and thereby a leading edge to maintain a correct synchronization. If this isn’t detected by a receiving node it will transmit an Error Frame.
- Bit error: The transmitting node is always listening to the bus and compares the transmitted bit stream with the actual bit stream on the bus to ensure there are no Bit Errors. Arbitration and Ack bits are excluded from this check.
- CRC error: When a checksum error is detected at a receiving node, an Error Frame will be transmitted.
- Frame Error: Several predefined dominant and recessive bits are present in the transmitted frames. All errors at these predefined bits except during the EOF will result in a Frame error.
- Ack error: If the transmitter isn’t detecting any dominant bits in the Ack Slot, i.e. the message wasn’t received by any node, an Ack error is flagged.