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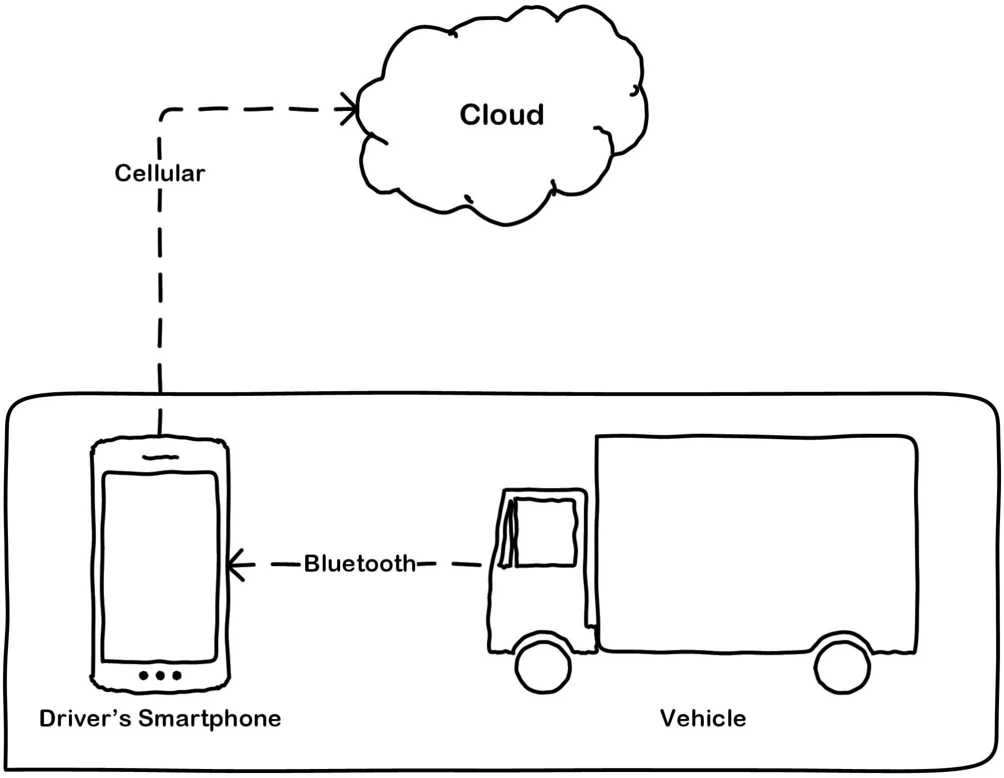

Road Condition Detection
using Commodity Smartphone Sensors Aided with Vehicular Data

Master's thesis in Computer Systems and Networks

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Gothenburg, Sweden 2016

Master's thesis 2016:NN

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Discovering Roadway Anomalies using Common Smartphones Wirelessly Connected to Vehicles

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Cover: Depicting the proposed system architecture for detecting and uploading the recognized road conditions to the cloud. Refer to Section 5 for more information regarding the suggested system.

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Abstract

Vehicles have become increasingly technologically advanced and have gone from being all mechanical to almost all computerized. Leveraging the digital vehicle and the many different sensors available, advanced vehicular systems have emerged that can intervene in critical situations, before the driver has a chance to react.

The technical advancement realized, is however not limited to vehicles, as similar technological betterment can be observed in smartphones. Smartphones have emerged from being basic devices into an advanced platform housing different communication channels, capable computational hardware and access to a diverse set of sensors to interact with the surroundings.

In this thesis, the problem of detecting a diverse type of road conditions is studied using data fusion between the available sensors, both from the smartphone and the vehicle. In the proposed system, the smartphone is the designated computational platform in addition of providing its build-in sensors to the detection algorithms. Positioning by the means of Global Positioning System (GPS) is used to tag detected events and by leveraging the accelerometer, vehicular shock and vibration information is inferred, all from the smartphone sensors. This sensory information is then complemented by the additionally available sensors from the vehicle such as speed, throttle position, motor revolutions per minute (rpm) and motor load.

The main challenge faced comprises of fusing the data from the two disjoint sensory platforms together, to be able to detect road conditions. In addition, different sensor characteristics, such as sampling rate, have to be taken into consideration, as well as the limited computational capacity offered by a smartphone. Furthermore, battery consumption also has to be minimized for the proposed system to be a viable solution. Also, unlike some other related work which uses expensive calculations to perform the detection, a lighter approach is leveraged, without any heavy operations applied.

The conclusions that can be drawn is that combining smartphone data with the vehicular sensors indeed helps in road condition detection. Not only does it help in determining the ground truth, which is a non-trivial problem to solve, but also to be able to detect different road conditions as well as to help reject false-positives. Moreover, the developed algorithms presented are signaling the simplicity of the approach taken by means of leveraging the available sensors, ensuing their applicability as real-time algorithms to be executed on commodity smartphones.

Keywords: road condition detection, vehicular sensor networks, On-board Diagnostics (OBD)

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Thank you.

Barnabas Sapan, Gothenburg, June 2016

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1

Introduction

"[...] no-one should be killed or suffer lifelong injury in road traffic."
—Swedish Transport Administration

In land transportation, recent focus has been on developing technologically advanced vehicles with an increased context awareness. They have been equipped with sensors to monitor their surroundings, and some vehicles also take appropriate emergency actions, even before the driver has a chance to react. While the vehicles have evolved, the roads that support the vehicles have staggered in development. New roads are built to meet the rising demands while most of the roads are left unmonitored. This thesis presents an ad-hoc system to fill the gap of unmonitored roads. With a better understanding of the road networks and their surface conditions, government entities have a better chance improving the routes before severe accidents occur, caused by lacking road quality.

1.1 Background

Last year, 2015, World Health Organization (WHO) estimated that around 1 million road traffic accidents had a fatal outcome [1]. Every year is an ongoing struggle trying to decrease, and eventually completely eliminate fatal road accidents. However, to be able to reach these goals, higher demands are not only placed on the vehicles, but also on the roads themselves. During the time while vehicles have seen a quick technical advancement in the terms of overall safety equipment, roads have been neglected. Road safety can only improve by a fixed amount through means of enhancing vehicles, before road quality quickly becomes an important limiting factor. Hence, it is of paramount interest to preserve high road condition, to be able to completely defeat lethal road disasters.

Roads continuously degrade over time because of several factors, such as severe weather conditions, tear from normal traffic and unexpected loads, ultimately increasing the accident proneness. To be able to improve and maintain the roads, they have to be continuously monitored. However, monitoring roads quickly becomes a non-trivial task to solve because of roads spanning wide geographical areas. Populating all pathways with Road Side Units (RSU) capable of monitoring and analyzing the roads, is a non-scalable solution. Generally, the infrastructure necessary to achieve good road coverage requires enormous investments, often not feasible. A distributed solution that has a low initial start cost and which can be retrofitted on existing hardware, would serve as a better transitional solution, or even as a permanent one.

On an abstracted level, the proposed system in this thesis consists of two different sensing components in an effort to detect road anomalies with greater context awareness. The first source of information is from sensors available in commodity smartphones. Sensors such as accelerometer and Global Positioning System (GPS) will be utilized to be able to detect events and to derive the road anomaly location. In addition of leveraging the smartphone as a sensory board, it will also serve as a computational platform, where the road analysis calculations take place. Besides, from the mobile device, a wireless connection is established to the second origin of sensory information, the vehicle. The vehicle provides sensors to complement the smartphone, such as motor revelations per minute (rpm), accelerator pedal position, et cetera. By utilizing commodity hardware found in everyday smartphones with sensors already available in vehicles, a distributed road sensing network is built. Thus, by means of letting every user with a smartphone connected to their automobile participate in road analysis, a vast amount of roads could be covered and analyzed cooperatively.

The major contributions of this thesis work are the discussion and development of a system capable of detecting a set of road conditions and events. Also, unlike previous work in the field of road condition detection, an emphasis is put on detection simplicity without heavy data-processing. Speed bumps are detected to disambiguate between potholes, which are detected by an adequate accuracy. Events such as triggering of Anti-Lock Braking System (ABS) are also observed, signaling slippery roads. Likewise, a form of traction loss is similarly detectable and discussed. Furthermore, miscellaneous events like the detection of door slams and engine stalls are additionally recognizable. While some of the aforementioned events have previously been detected in the context of a smartphone, others are unique to this thesis. However, to the author's best knowledge, no attempt has been made to leverage vehicular data to achieve a greater detection accuracy. Thus, in this thesis, the idea of leveraging vehicular sensors in addition to using commodity smartphone sensors is born. Therefore, further directed research is enabled with the possibility to extend the results achieved.

1.2 High-Level Motivation

Today, vast road networks exist which cover great parts of land. Furthermore, in the developed world, the most frequently used means of transportation is transportation on roads. Roads are the functional units of modern cities; it is the city's vessels. When heavy weather conditions infer with pathways, a widespread effect can be observed that immobilize parts of the civil area. In short, travel on roads has become a necessity for many people. Thus, given the frequent use of transportation on roadways, it is of great interest to keep the pathways in good condition for safer travels.

The work presented in this thesis makes use of the fact that a great deal of people travel on roads using various means of transportation. The vision is that each equipped vehicle will be part of the global sensory network, where each vehicular unit is capable of detecting road conditions on the roads driven. The individual contributions are then used to create a collective overview of the traveled and analyzed roads with road anomalies identified. The proposed system is thus suitable as an economically beneficial ad-on road analysis, which does not require any expensive Road Side Unit (RSU) hardware or infrastructure. Most of the hardware needed in addition to a vehicle, is already in hands of most of the people, even in developing countries, namely the smartphone [2]. Thus, based on the aforementioned observation, a large scale adoption of the presented system is feasible.

The motivation to utilize smartphones in conjunction with vehicular sensors is argued for in a multitude of ways. Firstly, the goal is to have as many users as possible passively participate in road condition analysis, and thus, smartphones provide a convenient platform. Secondly, it grants access to sensors not always found in vehicles such as GPS and an accelerometer. Thirdly, it provides beneficial networked connection to upload the road condition information. Finally, companies such as Combitech AB envisions smartphones and tablets as replacements for the vehicles dashboard and infotainment system using software platforms such as Automotive Grade Android (AGA) [3]. Hence, the use of AGA further provides incentive to utilize mobile devices and leverage the additional sensors available from vehicles.

1.3 Scope

The applications and benefits for a system such as the one proposed in this thesis are wide. For example, the possibility of saving human lives exist, as different road conditions and anomalies are set to be detected. Moreover, by using a system similar as to the one presented, diverse road parameters could effortlessly be collected concerning the different pathways, aiding in further road improvement work.

The deployment of a production ready system is, however, both time-consuming and a complex task. This thesis will only touch on the relevant scientific parts and disregard situations often required to be dealt with in a production ready system. Examples of such cases include handling of unexpected data connection unavailability, disambiguation between accelerometer reading of an uneven road compared to an accidental drop of the phone, et cetera. Likewise, while important in a production ready system, user privacy will not be analyzed. The focus is instead on showing the possibilities of the system suggested and to highlight the limitations, and not on producing a ready to use system which can be taken live without any modifications.

Moreover, to make the algorithms universally compatible, retro-fittable and to ease the development in this thesis, no attempt to access proprietary sensors will be made. The modern vehicle is a digitalized machine developed by different manufacturers, all containing vast amounts of interconnected computer nodes, each housing a diverse set of sensors. Moreover, some of the aforementioned automotive sensors are set to be utilized by the road condition detection algorithms. However, a different magnitude of vehicular sensors is available and accessible on the vehicle bus which connects the vehicular computer nodes. This is due to the fact that some communications protocols are standardized in different open protocols, while others are proprietary to the specific vehicle manufacturer. Additionally, some protocols are required to be implemented by the vehicle maker, as regulated by different laws in major parts of the word. To simply development, only the regulated sensors will be explored, and thus, the scope of research is limited to only the openly available sensors.

Three main phases exist in this thesis; a data acquisition phase, an analysis, and a testing phase. To be able to get confident statistical representing results of a road anomaly, a wide range of different hardware have to be tested on different vehicles, roads and conditions. However, due to both time constraints and resource limitations, only a limited subset of all available combinations will be evaluated. This fact should however not significantly alter the results of this thesis, ensuring thesis applicability.

1.4 Thesis Organization

To aid the reader orient the thesis, the available chapters are listed with their main content briefly mentioned.

Chapter 2	Firstly, to get an overview of the work done prior to this thesis in the field of road condition detection, the related work is presented.
Chapter 3	Next, the necessary background is described to enable the development of the road condition detection-system. The sensing data mechanism for both the smartphone and the vehicle is discussed and a short introduction to the platform is given.
Chapter 4	After a brief introduction have been given, relevant work and the fundamental background presented, this chapter describes the road events the system should be able to detect. The forthcoming detectable road events are exposed and their motivations for recognition is given. Moreover, the selected detection approach applied in this thesis is also motivated.
Chapter 5	In this chapter, the system architecture is presented. A high level overview of the system is given with all of its components. Likewise, the road anomaly detection-system is detailed with its associated cloud. The systems power-saving features are also discussed.
Chapter 6	To be able to do analysis, develop detection algorithms and later evaluate the systems effectiveness, sample data is needed. The data acquisition method is described and the test-aiding software is shown, enabling isolated, repeatable and deterministic testing.
Chapter 7	Each event that is set to be detectable is exemplified and means to detect the events and conditions are presented.
Chapter 8	The capability of the system is examined and the detected road conditions evaluated. Examples of items brought up for discussion are the effect of smartphone placement on signal quality, the battery saving techniques performance and, both general as well as detailed evaluation of all detected events.
Chapter 9	A conclusion is made summarizing the results and achievements of this thesis.

Chapter 10	Future work is noted, enabling further directed and continued research in the area of road sensing.

2

Related Work

There have been other efforts in analyzing, detecting and reporting different types of road conditions. While most of them share the same end goal, to be able to detect and report road anomalies to a central server, different approaches have been taken. Some work heavily relies on custom-made and tailored hardware, while others make the detection using commodity smartphones. In the past work, the sensor that has received the most attention is the accelerometer sensor capable of detecting accelerations, usually along three orthogonal axes. The majority of the relevant papers found and presented in this chapter deal with the accelerometer in a vehicular setting, while one paper focuses on cyclist experience mapping, leveraging a sensor fused approach. The last presented paper, unlike the others, instead presents the findings on how to perform ground truth marking in vehicular sensing experiments.

2.1 Accelerometer Based Approaches for Road Surface Sensing

J. Eriksson et al. [4] describes a system which uses a highly responsive accelerometer mounted to an embedded computer to detect potholes. Three different sensor placements were tried before determining that placing it in the dashboard proved to be convenient while producing adequate signals. The sampling rate of the accelerometer was 380 Hz from which the raw reading was passed through a set of filters. Each filter either rejected or approved the data for continued processing to the next set of filters. Example of filters were to reject data under a specific velocity to protect against spurious events, otherwise causing falsely detectable signatures, and to detect the deviation in z-acceleration as a mean to infer road surface level variations signaling potholes, et cetera. Testing showed that in an uncontrolled environment, 90% of the actual detected potholes truly needed to be repaired.

Another relevant paper discussing mobile road condition detection is by Mohan et al. [5]. In this paper, the authors performed experiments on mobile devices which wirelessly connected to an accelerometer. While the accelerometer peaked at a sampling frequency of 610 Hz, the experiments were conducted with it configured to 310 Hz. Challenges previously not dealt with but brought up for discussion in the paper was virtual reorientation of accelerometer, honking detection and the idea of triggered sensing. By utilizing the properties of Euler Angles and performing the calculations, the accelerometer could be placed in an arbitrary orientation while still reporting unison acceleration readings. Honk detection was used as a way to infer chaotic situations in road traffic to provide context awareness, complementing the accelerometer reading. Furthermore, triggered sensing was used as a mean of only enabling the GPS sensor when necessary to tag the detected road anomalies with positional information, thus, preserving battery by having the GPS disabled for the majority of the time. However, note that triggered sensing was never implemented, as it was deferred as future work.

There has also been work done on estimating road roughness with smartphones. International Roughness Index (IRI) is a metric which previously only could be measured by dedicated devices. However, Douangphachanh et al. [6] demonstrated that by utilizing smartphone accelerometers, the road roughness could be derived. The authors took accelerometer samples at the maximum of 100 Hz before passing it through a high pass filter and then through Fast Fourier Transform (FFT)[1]. The conclusions that could be drawn indicated that there was a linear relationship between acceleration data and road roughness. It was also noted that road anomalies often manifest themselves in the frequency range of 40-50 Hz.

2.2 A Sensor Fused Approach to Detect a Wide Variety of Events

The paper by Shane B. Eisenman et al. [7] examined the possibilities of fusing different sensors together to gather statistics about recorded rides in the context of bicycling. They developed a sensing system for mapping the cyclist experience using a diverse set of sensors, both from a mobile phone and a sensory board called Moteiv Tmote Invent. In the paper, the researchers utilized sensors such as GPS, pedal revolutions per minute (rpm), wheel rpm, road slope, sound, video, et cetera. The mobile phone served not only as a sensory platform, but also as a gateway to send the collected data from its own sensors, and other sensors mounted on the bicycle, to a central server. Different observations could then be drawn from the collected data, such as if the bicycle was braking or coasting at any given time and the overall vehicle density near the bicycle at different time periods. A health index was also derived based on car density, sound level and CO_2 level.

2.3 Ground Truth Collecting in Vehicular Sensing Experiments

The paper by Strazdins et al. [8] discusses how to perform accurate ground truth marking in vehicular sensing experiments. Marking of ground truth in a vehicle as driving past the anomalies is not recommended by means of several reasons. Reasons include GPS inaccuracy, lack of precisely defined methodology and the difference in perception of road anomalies between people and factors such as speed and the vehicle itself. Instead, the recommended way to mark ground truth is through the

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[1] Using Fast Fourier Transform (FFT), a signal can be transferred from its initial domain into the frequency domain, and the opposite way, aiding in some calculations.

medium of manual walking, which reduce the previously mentioned imprecisions, as stated by the authors.

3

Technical Background

THE background presented in this chapter is the theory required to enable development of road sensing. The reader will be familiarized with the different available sensors in both the smartphone and the vehicle, get an outline of the On-board Diagnostics (OBD) protocol and gather basic understanding of an open connectivity platform called Automotive Grade Android (AGA).

3.1 The Digitalized Vehicle

From the inception of automotive travel, vehicles have been all mechanical. However, lately, with the advancement of technology, many automotive systems have been replaced with digitalized counterparts. No longer are there a direct physical connection between the throttle and the engine. Sensors are instead placed on the accelerator pedal and electrical signals are transmitted to a small computer responsible to control the throttle by feeding an appropriate mixture of fuel and air into the engine. That is, mechanical controls have been replaced by force generated through signals made using electrical means.

The new digitalized scheme carries beneficial attributes. Electrical intervention can easily be achieved, enabling active safety systems to intervene in critical situations, before the driver has a chance to act. In addition to quick engagement and disengagement of safety systems, computerized vehicles empower a diverse type of knowledge to be transferred from the computer science domain into the transportation domain, enabling new possibilities.

3.1.1 The Open Connectivity Platform - Automotive Grade Android (AGA)

One of the platforms taking advantage of the digitalized vehicle is the concept of Automotive Grade Android (AGA). AGA enhances the open source Android mobile operating system with the intention to be used as an infotainment and dashboard replacement. The platform connects to the vehicular network and by means of easy to use functions, developers can provide applications augmented by vehicular data. Also, through AGA, sensors throughout the vehicle and the smartphone could be conveniently accessed, which this thesis takes advantage of.

3.2 Sensing Data Inside a Vehicle

To achieve road sensing, different sensors have to be utilized. One of the goals of this project is to utilize already available hardware. Hence, two types of sensory information will be used to get adequate context sensing, the smartphone and the vehicle.

Lately, smartphones have been equipped with different sets of sensors, often to aid user experience and to be able to adapt to a small set of physical conditions. Receivers to systems such as Global Positioning System (GPS) are used to provide location-awareness and accelerometers are used to accustom the interface to device orientation. While many different smartphone sensors exist, the background of the relevant sensors necessary to implement road sensing will be given in this section.

Vehicles in contrast, contain many sensors necessary for advanced functions such as traction control and airbag inflation upon impact, as allowed by the development of computerized vehicles. For the aforementioned vehicular functions to work correctly, a high degree of participatory sensing is required. Therefore, the different sensors available in the vehicle are connected via a common bus enabling inter-connectivity and shared sensing. Hence, tapping in on the bus by means of specialized protocols reveal the sensory readings, as utilized in this thesis for road analysis.

3.2.1 Relying on Third-Party Smartphones for Sensing

Modern smartphones house a diverse set of available sensors which can interact with the physical world. Sensors such as light meter, Global Positioning System (GPS), proximity sensor and accelerometer are all commonly found in smart devices as of late. This section discusses the necessary background of mobile sensors to enable road sensing, namely the accelerometer and the GPS.

3.2.1.1 The Accelerometer Sensor

The accelerometer is one sensor commonly found in many smartphones, both on low and high-end devices. An accelerometer measures, as its name implies, acceleration forces. These forces can be classified as either static or dynamic and be measured in either one, two or three orthogonal axes. Gravity that is always exercised on the smartphone is an example of a static force while dynamic forces manifest themselves more energetic, such as movements, vibrations or shock. Figure 3.1 exemplifies the directions the forces can be perceived in a commonly used coordinate system, such as in the Android mobile operating system.

While different types of accelerometers exist, the main features that has a relevance for the intended application of road sensing are bandwidth, resolution and noise. Bandwidth is the frequency the accelerometer operates in [9], measured by the hertz (Hz) unit. A higher bandwidth allows for a more accurate true-to-world sampling of events. However, a high bandwidth is not beneficial in itself. The sampling quality is also affected by the actual resolution provided, which is the ability to differentiate one reading from the other. Lastly, noise is the amount of unwanted fluctuation not part of the actual signal.

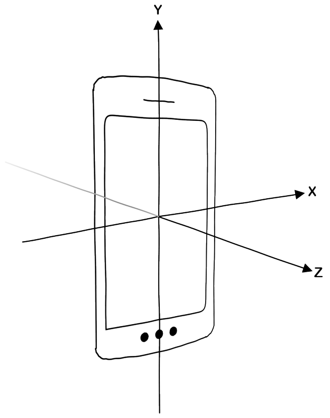

Figure 3.1: A typical accelerometer coordinate system with the x, y and z axes shown.

Based on the physical accelerometer and its features, different virtual sensors could be derived. Linear acceleration and gravity are two examples of derived sensors. Linear acceleration is the acceleration isolated from earth's gravity, measured as the acceleration minus the gravity. A gravity sensor is the opposite, gravity is returned without other influences. In the mobile operating system Android, the virtual sensors are available for developers to access in a similar fashion to as the physical sensors [10]. Equivalently, the Apple mobile operating system iOS also offers convenient access to these virtual sensors [11].

The application of accelerometers can be extended to numerous disciplines. Low bandwidth and resolution accelerometers are commonly found in smartphones. They are used to adapt the graphical interface to device orientation (by measuring gravity) and to provide control input possibility for games (by measuring linear acceleration). Sensors with high bandwidth and resolution are used in control and balancing applications. As an example, accelerometers could be placed on bridges to monitor the structure resonating behavior. In addition to the accelerometers already in wide use, recently, high impact resistant, single-axis accelerometer sensors that can measure high forces, have been employed in vehicles. These aforementioned special sensors are used as a reliable method of deploying airbags consequent to accidents [12].

3.2.1.2 The Positioning Sensor

Due to the rising popularity of navigation software, smartphones have been supplied with the ability to geo-locate by the use of different positioning strategies. While different location strategies exist, the American deployed Global Positioning System (GPS) is the most frequently supported system with myriad of end devices. The GPS provides world-wide, continuous three-dimensional positional information [13], which might be one of the reasons for its widespread success. As the rest of this thesis only discusses the GPS system, the reader interested in other alternative solutions to acquire a geo-location, should turn to the book by E. Kaplan [13] for more information.

Acquiring a GPS position fix is a one-way communication exchange with satellites building on the time of arrival of signals. Devices that are equipped with

GPS hardware listens and captures radio waves transmitted by satellites which contains the signal transmission timestamp. Based on the received signal and the encapsulated timestamp, the user's receiver can use the information to calculate a satellite-to-user range, dependent on device time. However, for a geo-location to be approximated, at least four satellites are necessary for triangulation. While in reality three satellites would be enough for triangulation, the fourth satellite is used for clock synchronization, as an accurate fix relies on highly synchronized clocks [13].

The time to get the first location fix is called Time to First Fix (TTFF). Fixing time can vary depending on the current information available. E. Kaplan [13] states that three conditions are needed to be able to receive a location in around 30 seconds; an up-to-date almanac, estimate of user position and and an estimation of user GPS time. If any of these conditions are not met, up to 12.5 minutes can be required for TTFF. While 12.5 minutes is the worst case, and even though it usually takes less then 30 seconds to acquire a fix, one has to plan beforehand when to activate the GPS receiver to get a fix in time while wasting minimal resources, such as the limited battery often available.

After the first fix is achieved, the GPS can continuously track the user's position by performing triangulations at a fixed refresh interval. The requirement is that the GPS receiver constantly have to be powered on and receive the satellite signals. However, on mobile devices running on limited battery capacity, battery can quickly be depleted as running the positioning sensor prevents the device from entering sleep mode. Together with the delay of TTFF, careful management is required to both have GPS enabled when needed, and to conserve battery when location from GPS satellites is not required.

Solutions to mitigate the drawbacks of the GPS's long TTFF and high battery consumption by its constant triangulations exist, such as [14] and [15]. These are alternative positioning strategies based on deriving an estimated location. Many smartphones allow for a quick, low power and approximate means of positioning usually by leveraging cellular or WiFi connectivity. They work by having an accessible global database containing the names (id) and locations of wireless access points. Then, based on which access points the smartphone can reach, an approximated location of the device could be derived as the access points location is known. This approximation, usually obtainable quickly, could be beneficial in many cases where the sheer accuracy of the GPS is not needed. Moreover, the alternative triangulation approach also has the added benefit of obtaining the device position in a battery friendly way, compared to the GPS sensor, making it the desired solution in some cases.

3.2.2 Dedicated Built-in Vehicular Sensors

Vehicles have quickly advanced from being only a mechanical construction, to housing hundreds of small computational nodes. Vast computational networks exist within modern vehicles with nodes handling both low and high critical operations. Low critical operations, which often offers increased comfort, are operations such as lowering the window and turning on the headlights. More critical tasks include the engagement of airbags upon collisions, maintaining stability using Traction Control

System (TCS) and more efficient braking by means of Anti-Lock Braking System (ABS).

For any of the aforementioned systems to work, different sets of sensors are required capable of detecting the events, allowing appropriate countermeasures to be taken. ABS for example, rely on sensors to report the wheel rotation speed. Only when it senses that one of the wheels have locked itself, does the system engage. Similarly, TCS activates exclusive when one of the automotive wheels are spinning faster than the others, signaling loss of traction.

While the sensors play a key role in many vehicular systems, the vehicular sensors available could also be extended into the diagnostics domain. By utilizing the vast amount of sensors that already exist, vehicle diagnostics and fault localization is also aided. The On-board Diagnostics (OBD) - the vehicle diagnostic interface - is often accessed using a Diagnostic Link Connector (DLC), as pictured in Figure 3.2. Thus, via this connection, sensory data could be read externally to the vehicle, as utilized in this thesis for road condition sensing.

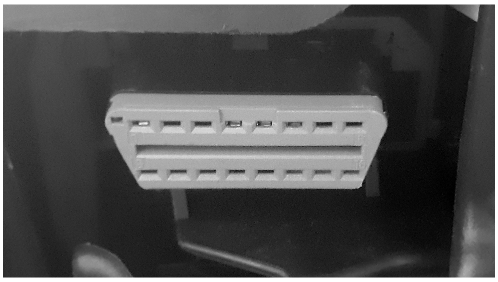

Figure 3.2: On-Board Diagnostics female link connector found under the dash on driver's side, enabling the retrieval of vehicular diagnostic data.

3.3 Vehicular On-Board Diagnostics (OBD)

On-board Diagnostics (OBD), or more recently the second generation interface OBD-II, offers standardization in vehicular self-diagnostics. Normally, numerous different sensory readings exist via the OBD connection depending on the vehicle and its conformance to the complete standard with all optional features [16]. However, all newly manufactured vehicles are required to have OBD, with a certain set of implemented sensors. In the European Union, all petrol vehicles have had the requirement since year 2001, and gasoline vehicles since 2004 [17]. In America, a similar standard was enforced already in 1996 [18].

The OBD system monitors a set of main vehicular system components and is able to report any internal anomalies. Because of the OBD system's monitoring of different set of sensors and values, the system is also functioning as an early warning system. If any value significantly deviates from its normal threshold, the Malfunction Indicator Light (MIL), or more commonly known as *check engine light*, gets lit up. Thus, the MIL indicates an internal vehicle inconsistency, such as overheating or general engine malfunction, more often than not needing further investigation. In such cases, leveraging the OBD connection allows the technician to access the vehicular sensors, assisting the specialist to locate the fault quickly. However, in this thesis, the sensory information in the vehicle is leveraged to aid in road anomaly detection, and not to locate faults.

Accessing the sensory information available on the vehicle requires means of connection, usually a dongle, a knowledge of the signaling protocol employed and the familiarity of the sensor id requested. Consequently, these aforementioned requirements are the topic of the forthcoming sections.

3.3.1 Accessing Automotive Diagnostics Data using a Dongle

The sensory values available on most of the vehicles are accessible using the Diagnostic Link Connector (DLC), which has to be located under the drivers dash on the driver's side on compatible vehicles. Once the port is found, there exist different ways of connecting, via a physical wire or wirelessly. However, because of the success and the versatility of Bluetooth, it is usually the preferred way, which is also the way of access in this thesis.

To be able to establish the wireless Bluetooth connection, a Bluetooth dongle is required to be inserted into the DLC port. A dongle is an extension which provides added functionality, in this case, wireless data transmission. Figure 3.3 depicts a OBD Bluetooth dongle capable of transferring diagnostics data to a wireless receiver.

Figure 3.3: On-Board Diagnostics male Bluetooth dongle which allows wireless diagnostic data to be transferred from the vehicle.

While different types of dongles exist, most provide the same core functionality and support the same set of vehicular protocols. Please refer to the next section, Section 3.3.2 for more information about the available vehicular signaling protocols. However, in terms of the OBD dongle, the difference often lies within the maximum transmission capacity. Some support a transmission bandwidth and hardware allowable to sample sensors at a few hertz (Hz), while others allow for a significantly faster rate during optimal conditions. If real-time data is required to be accessed, a high refresh rate is advantageous to capture the fine details.

The interested reader is referred to the reference guide for the OBD interpreter microchip ELM327 found in many OBD dongles. The document contains detailed information about the different mode of operations and provides a good insight of the general capabilities offered and expected in similar interpreter microchips [19].

3.3.2 OBD Signaling Protocols

In vehicular systems, Control Area Network (CAN) is a widely used communication protocol between the different vehicular computerized nodes. Originally, the CAN protocol was proposed as a direct application to automotive systems, but it have also been proved to be useful in different control systems as well [20]. Several reasons for its widespread success include its real-time and reliability guarantees, comparably high speeds to other similar protocols, while all being a cost-effective solution. A direct application of the CANs increased speed is that OBD data can be transferred quicker, which in many cases is beneficial.

The ISO 15765-4 protocol working on a CAN bus has quickly become the norm as an OBD signaling protocol, partly because of its speed. However, in addition to CAN, four other different signaling protocols are allowed as OBD data transferee, some considered legacy. Discussion of the alternative OBD protocols working on a variety of different automotive buses is beyond the scope of this thesis, they are just enumerated for the interested reader.

- SAE J1850 PWM (Ford vehicles)
- SAE J1850 VPW (General Motors vehicles)
- ISO 9141-2 (Asian, European and Chrysler vehicles)
- ISO 14230-4 KWP (Diverse vehicles)

3.3.3 Obtaining Sensory Readings from the Vehicle using Parameter IDs

After a connection is established by selecting a suitable signaling protocol, data transfer can commence. However, firstly, the mode of operation needs to be configured. The vehicular microcomputer responsible for the collection and analysis of the sensors' data have different possible working configurations. These modes are identified by a unique number in the range of one to nine, totaling of nine different modes. For this thesis, only Mode 01 is of significance, where the live data of the polled sensors is retrieved. Hence, by requesting a value for a specific sensor in Mode 01, a momentary snapshot of the real-time value is returned.

Moreover, accessing the automotive sensors also requires an unique item identification (ID). Each sensor in the vehicular system is designated a Parameter Identification (PID), which is used as the communication destination. These are standardized identifications listed in the J1979 Diagnostic standard [16]. While the vehicle is not required to respond to all PIDs, and thus all sensors, available and supported vehicular sensors could be determined by dedicated commands in the defined scheme.

Once the mode of operation is selected and the PID chosen, the access to vehicular sensors is via a polling mechanism. Sensor ID is broadcasted along with the designated mode of operation (Mode 01, Mode 02, etc cetera) on the vehicular bus using the OBD connection. The device who identifies itself as responsible for the PID, generates a response and sends it back on the bus. This response is then captured and sent to the technician via the OBD connection.

However, it is not possible to group sensor calls together and get an accumulated response. Access to the sensory data, is as mentioned, only strictly done in a sensor by sensor fashion. If multiple sensors are to be polled, separate sequential polling is required for each sensor. It is notable that this behavior might introduce some unexpected jitter between each response, causing the response rate for each sensor to fluctuate if polled periodically.

Values returned from the requests are interpreted in hexadecimal and have to be calculated using formulas defined in the standard to get meaningful data. The answerer returned from the vehicle for a sensory request is 4 bytes. Dividing the response into the four different bytes with the least significant bit to the right, calling each byte A, B, C and D, the formulas shown in Table 3.1 are achieved for calculating the results. The table also shows each listed sensors' PID and the description of the sensor value.

Table 3.1: Table showing a small subset of the available sensors in a vehicle, accessible through OBD. The formula tab illustrates the method of converting the received response to meaningful data.

PID [hex]	**Description**	**Unit**	**Formula**
04	Engine Load	%	$A \times 100/255$
0C	Engine Rpm	rpm	$((A \times 256) + B)/4$
0D	Vehicle Speed	kph	A
11	Throttle Position	%	$A \times 100/255$
46	Ambient Air Temperature	$°C$	$A - 40$

As a final remark on accessing the OBD sensory readings, it is noteworthy to mention that the J1979 Diagnostic standard mostly deals with conformance and testing of vehicle emission parameters (and implicitly fault localization), as required by various laws. Different proprietary sensors could be reached through other proprietary standards and communication means, not brought up for discussion in this thesis.

4

Road Event Selection and Approach Incentive

There exists a vast amount of road events that could be beneficial to detect in the pursuit to completely eliminate fatal road accidents. Moreover, many different actions can be taken to lower the risk of accidents with fatalities as outcome. Certainly, having advanced safety features built into the vehicles are advantageous. Furthermore, having adequate road quality is also influential. However, momentary costs aside, features such as the human factor also heavily contribute to the collision proneness. Based on the two identified contributing factors, road quality and the human factor, a general motivation on the incentive to detect road condition events is given. Then, based on the presented criteria, the road events subsequently explored in this thesis are highlighted and discussed. Additionally, in this chapter, the motive to utilize vehicular sensors is given as well as the strive to accomplish the detection by simple means.

4.1 Incentive to the Selection of Events to Detect

Leveraging automotive travel on pathways is a vital part in many people's daily life. However, taking on a journey is not entirely risk free. Recent vehicles have seen an advancement where vehicles come standard with usually several active and passive preventive measures, collectively working on to improve the odds of surviving in a severe collision. Nonetheless, while some mitigation is achieved with the forward movement of technologies in the automotive industry, other factors can still alter the risk of sustaining injuries, worth taking a closer look at. Examples of such altering risk factors which are often easy to forget, include the general road quality features [21] and the human factor [22].

The events that are set to be detectable by the proposed system should relate to the aforementioned facts regarding the road quality and human factor, and in a way provide further mitigation against the risk of accidents. If the events adhere to and affect the matter, a multitude of benefits can be derived from the detected conditions, affecting the collective good. An overview enumeration is presented highlighting some of the betterments that can be achieved if the detected events abide by the observed risk altering causes.

- The society – Saving lives by introducing road awareness based on conjoint detection of events.
- Road maintenance operators – Guiding them to the most urgent anomaly,

enabling quick repair.
- Research establishments – Giving access to anomaly data with their logged behaviours can open up for new possibilities.

4.1.1 Events set to be Detected

Based on the previously selected criteria (see Section 4.1), the events that are set to be explored and detectable are presented. Moreover, the chosen events are motivated and their benefit carrying attribute in the context of road condition sensing highlighted. The means of detection are given in Chapter 7, with each event respective evaluation presented in Section 8.4. Here-next, an enumerated list follows with the selected actions that should be recognizable by the system.

Speed bumps are an accepted solution in many parts of the world as a way of enforcing the speed limit on stretches of road, preventing over-speeding. According to Francis K. Afukaar [23], the speed factor alone contributed to more than 50% of Ghanaian road accidents in the years between 1998 and 2000. Independent studies also show that if speed reducing obstacles would be installed, the number of fatalities could be reduced by 60% [24], or if concentrating to Ghana only, by up to 72% [25]. Speed reducing obstacles are established to impose the speed limit, in an effort to reduce the risk of accidents. However, if the the driver fails to slow down and still passes over the speed hump, a reveres affect can result, as damage can be sustained to the body [26] and to the vehicle itself. Thus, by means of detecting speed bumps, the society could be helped. Moreover, there also exist reasons to detect speed humps as a way to disambiguate between other road anomalies, as similar sensory signatures can occur complicating accurate detection.

Potholes, cracks and general surface variations in the road profile do not only increase the discomfort during driving, increment vehicular tear, but can also impair the vehicle maneuverability. Government entities have a strong interest in the smoothness of a ride, as it reduces fuel consumption and provides a safer driving experience [27, 28]. However, specially configured vehicles are needed to take road surface measurements, which is both a time consuming and a discontinuous process. Road anomalies can thus be unnoticed for a greater amount of time. Therefore, it is of great interest to promptly detect and report any unlisted road surface inconsistency, in a distributed fashion, relying on commodity hardware in hands of majority of people. Furthermore, quick detection allows road maintenance operators to fix the anomaly, before severe accidents occur in favor of the collective good.

Traction loss can occur during bad weather conditions, such as heavy rain or snow, causing severe consequences. Loosing traction implies severely dampened automotive maneuverability, making it likely that an accident will follow. Anna K. Andersson et al. [29] summarizes numerous studies indicating that a large portion of accidents occurring during the winter season can be attributed to snow or ice on the pathways. However, slippery surfaces are not always immediately apparent, especially during nights where the temperature is hovering around the freezing point. Therefore, by detecting the loss of traction, nearby vehicles could be notified in addition to letting the road maintenance operators know, enabling them to implement preventive measures, such as graveling or salting. To the best of found knowledge, traction loss is previously unexplored from a detection perspective in the context of smartphones.

Anti-Lock Braking System (ABS) is a system that enables the driver to remain in control of the vehicle during heavy braking. Traditional systems without ABS, simply apply the amount of braking force requested. Thus, during slippery conditions, the wheels could lock, impairing controllability of the vehicle. This phenomenon is mitigated with the use of ABS which more intelligently applies the braking force, without locking of wheels as a result. Moreover, the ABS system have clear characteristics that probably could be detected. If the event is recognized, it could be used as a mean to warn other drivers of the slippery condition ahead. Similarly, road maintainers could also be notified, allowing precautionary measures to be applied. As far as this author knows, the task of undertaking ABS and detecting it from an external entity, such as a smartphone, have previously not been conducted.

Engine stall can arise if the engine is not fed with the appropriate levels of features necessary for the engine to run. Often, the inducer is the human factor, however, engine malfunction could also be the contributing factor. The danger with engine stalls lies in that fact that the motion is interrupted, causing the vehicle to halt. If the rear driver notices the just stopped vehicle too late, a rear-end collision is a fact. Detection of the event is therefore beneficial. To the author's best knowledge, no attempt has been made to detect engine stalls through a smartphone. However, there exists many patents dealing with apparatuses built-in or around the motor to enable detection, warning or circumvention of halting engines. Examples include [30], [31] and [32].

Door slam is an event that stands out from the rest by its convoluted connection to road safety. However, detection of door slams has beneficial attributes. For example, by detection of the event, a knowledge could be obtained of when people leave the vehicle. Thus, the detection-system could be put into a low-power mode, prolonging its use and maximizing its effectiveness. To the best of author's knowledge, door slams have previously not been attempted to be detected.

4.2 Rationale of Leveraging Supplementary Sensors from the Vehicle to Aid Event Detection

The sensor that has received the most previous attention among the published papers regarding road analysis, is the accelerometer. It is not without merit, as the sensor is particularly suitable for the task. Placing an accelerometer in the vehicle enables a fateful capture of the road deviations caused to the encompassing vehicular chassis. Moreover, as road anomalies have specific signatures, these road inconsistencies could be detected, as shown later in this thesis. However, leveraging the accelerometer only gives one, while important, image of the situation at hand. Taping in on the vehicular bus using the OBD connection, opens up to a wide variety of additional sensors provided by the automotive. While there is a heavy emphasis on emission testing on the provided sensors, which the OBD standard is mostly used for, a few are seemingly useful. By utilizing the supplementary sensors, an improved awareness could be achieved. Not only are the extra sensors accurate in their measurements, but also provide the information on how the driver is utilizing the vehicle, which is undetectable with the accelerometer sensor alone. The benefits of utilizing vehicular data become apparent in the way the detection methods are developed in Chapter 7 and then confirmed as viable in the evaluation chapter, or more specific, in Section 8.4 which discusses the event detection rates.

4.3 Striving for Event Detection Simplicity as a result of a Constrained Environment

Regardless of the event, the detection emphasis is placed on accomplishing the recognition by simple means. No time-consuming or heavy operations should be leveraged, by reason of the detection taking place in a constrained mobile setting with strict power and computational requirements. The developed algorithms should be capable to execute in real-time on common smartphones, and as a mean of the operating context, battery usage has to be low, prolonging the detection endurance. As an example, each detected event need to be tagged with a positional location and therefore, methods to decrease the highly battery consuming sensor is needed. The proposed methods to decrease the battery strain is described in Section 5.1.1.4 and evaluated in Section 8.5.2.

5

System Overview and Architecture

The problem of detecting road anomalies can be approached in a multitude of ways. One possible solution is to use custom tailored devices, placed alongside thoroughfares, capable of constantly analyzing the roads. However, this approach depends upon significant infrastructure requirements and a has constant upkeep cost. The approach argued for and taken in this thesis is instead using a distributed solution consisting of a smartphone, a vehicle and a way to interconnect the two sensory platforms. The benefits of the proposed solution are multifold, such as that the solution is economically feasible, it eases the deployment in developing countries and that the system can be retro-fitted on commodity hardware with ease. Many of these benefits stem from that everyday people is expected to contribute to the analysis and data gathering. Any driver equipped with a low-cost commodity hardware, together with a smartphone and a vehicle, can passively take part in the road analysis on every drive for the collective good.

5.1 System Overview at a High-Level

One can imagine different ways of achieving the end goal - to be able to infer different types of road conditions. Solutions can be built upon the idea of utilizing tailored and dedicated devices, or on the idea to maximize the re-usability of devices already in service. The former approach enables the development of customizable devices within a tightly integrated environment, made to exact specification and requirements. While the just mentioned approach has inherited benefits, it also carries a significant drawback. Deploying such custom solution would be economically demanding, especially in developing countries because of the significant cost associated, such as installation and upkeep. Instead, the approach proposed here is to exploit devices in hands of almost everyone, specifically, the smartphone and the vehicle.

The proposed road condition detection architecture is comprised of two main components, the sensing part and the cloud. The first part, the detection part, is additionally a merge consisting of two sensory platforms. Sensors in the smartphone will be utilized in conjunction with the diverse available sensors in the modern automotive vehicle. To perform sensor fusion, interconnection between these two distinct components are made wirelessly using Bluetooth technology. More specific, a connection is established from the smartphone to the vehicle using an OBD dongle connected to the vehicles diagnostic port. The fused and analyzed sensory data from both the vehicle and smartphone can then opportunistically be sent to a central server for decision making of detected conditions to prioritize, leveraging the connectivity options available on smartphones. Thus, the aforementioned central server, the cloud, is the second part in the two-parted architecture arrangement, complementing the detection sub-system. However, note that all data processing is done locally on each smartphone to achieve a distributed road analysis network. Only the actual detected events are uploaded to the central server. Therefore, with this smartphone-oriented approach with analysis performed on each partaking smartphone, the large data volume otherwise required to be exchanged between the cloud and the detection sub-system is diminished.

An overview of the system can be seen in Figure 5.1. As observable, the detection-system refers to both the smartphone and the vehicle carrying out the detection, excluding the cloud. Moreover, as the cloud is considered an external entity, it is limited to only brief discussions in this thesis.

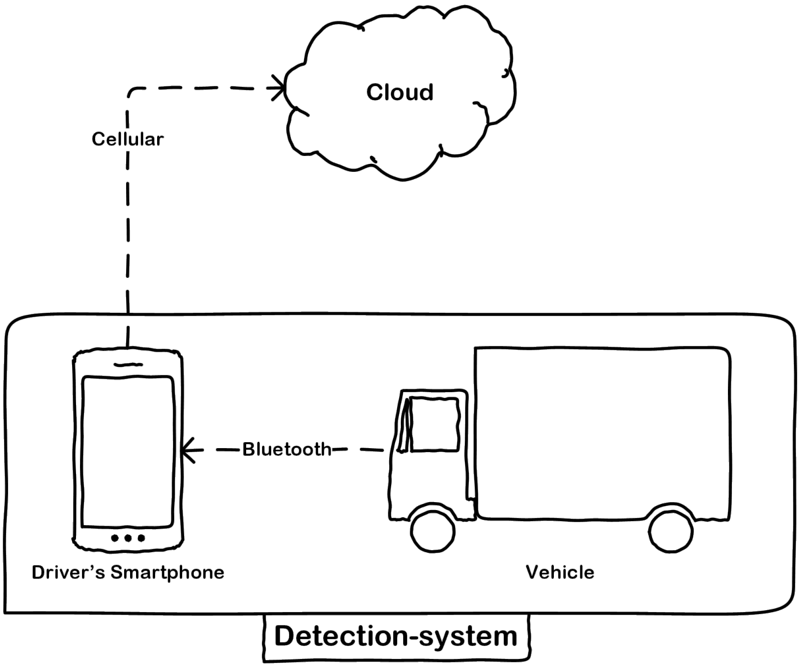

Figure 5.1: Overview of the proposed road condition detection architecture with the main system components.

In the proposed system, the OBD dongle responsible for the connection between the vehicle and the smartphone, is the only required upfront hardware cost, necessary to be able to gather vehicular data. These dongles can be acquired cheaply[1], and thus, a large scale adoption is feasible. The drivers participating are assumed to already have a vehicle and smartphone to take part in the road analysis, making the dongle the only extra requirement, which is not an unrealistic assumption. Smartphones are becoming a more prominent device even in emerging and developing countries [2], similarly to vehicle owning.

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[1] As of writing in 2016, many OBD dongles can be acquired for less than $10.

5.1.1 The Road Condition Detection-System

The proposed road condition detection-system is the principal part of the two-parted system. It consists of a smartphone, a compatible vehicle and a mean of establishing a connection between the two sensory platforms. This section presents more details about the proposed detection-system with the employed sensors and the interconnection necessary.

5.1.1.1 Smartphone and its Sensors

Phones have evolved from carrying out basic tasks such as placing phone calls to becoming devices with a significant broader appeal. In the proposed road detection-system, the smartphone carries an important role with key functionality. It functions as a sensory platform, computational platform and as a gateway for detected events waiting to be uploaded to the cloud. The mobile platform of choice in this thesis is an Android device running the AGA platform[2]. AGA allows convenient mean of sensory data access, as well as enabling beneficial access to Internet using built-in Android calls, easing in prototyping and development.

The broader smartphone appeal could partially be attributed to the deeper engagement provided by the diverse set of sensors available in the modern smartphone. By the sensors, the device is capable of interact with its surrounding, augmenting the experience. Henceforth, the most common found sensors are itemized, excluding derived virtual sensors.

- Light meter (photometer) – Light intensity.
- Accelerometer – Three dimensional acceleration.
- Positioning (GPS) – Continuous positional fix.
- Magnetometer – Patches of magnetic materials.
- Gyroscope – Angular position.

Out of the sensors available, the ones deemed to be applicable to road condition detection are the GPS and the accelerometer sensor. Positioning using GPS is used to tag the events with location coordinates while the accelerometer is used as the main road condition sensor, enabling vehicular vibration capture. The magnetometer sensor which measures magnetic field distortion, have shown to be useful in detecting dense patches of vehicles [7]. However, as it is already a partially explored sensor, and as it does not add any benefits in the proposed system, it will be disregarded. Another commonly found smartphone sensor is the light meter. During the work of this thesis, the light intensity as measured by the sensor could not be found to carry any beneficial attributes in the context of detecting road conditions. Thus, the light sensor will be neglected from further discussion as well. The last common available sensor is the gyroscope. Lately, the gyroscope sensor has gained traction in smart devices, nonetheless, it is still not as common as the other aforementioned sensors. A gyroscope can augment the accelerometer and provide further dimension of sensing, namely rotation or twist. However, this type of additional information is not directly needed in the road analysis context, and the sensor is therefore omitted.

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[2] Noteworthy is that the choice of employing an Android smartphone is only for convenience, as the author have previous Android experience. Using an arbitrary mobile operating systems would have been equally possible, given the opportunity exist to access sensors.

In this discussion, however, it is important to note that some derived virtual sensors rely on multiple sensory sources, such as the derived linear acceleration sensor. The linear acceleration sensor is in some implementations employing both the accelerometer and the gyroscope sensor fused together in a software layer, while some provide direct hardware access. Thus, even if a sensor, such as the gyroscope is disregarded, it might augment other sensors implicitly.

The Accelerometer Sensor

The accelerometer sensor is the primary road condition characterization sensor. During automotive travel, the vehicle is subjected to different types of groundwork containing different textures and road conditions. These vibrations and shocks are then manifested and transferred to the vehicle, which by an accelerometer, could be picked up as acceleration deviations. There exist multiple ways of determining the acceleration, and thus, the vibrations. The accelerometer reading can be done either as is, with the earths gravitational force applied ($\approx 9.82\ m/s^2$), or with the gravitational force removed, often called linear acceleration. In the context of road sensing, the gravitational force does not carry any bearing. Hence, the choice is to use one of the virtual sensors for road sensing, specifically, the linear acceleration sensor - acceleration without the gravity. Hereafter, all discussions related to the physical accelerometer also applies to the linear acceleration sensor, as both share similar set of physical hardware components.

On closer inspection, the rationale behind detection of road anomalies, is that all different types of road conditions cause a noticeable deflection in the vehicle movement compared to its normal operation. Hence, by placing a smartphone with an accelerometer in the vehicle and keeping it there for the duration of the driving, a close mapping of the actual vehicle shock and vibration could be captured. However, because of different material characteristics, accelerometer placement might affect the captured signal quality. Based on experiments Eriksson et al. determined that placing an external accelerometer on the dashboard and on the windshield yielded similar signal quality results [4]. While they did not have the accelerometer built-in, such as in the smartphone as in this proposed system, it serves a good indication of placement. In this system, similar experiments were conducted before determining that placing a smartphone on an empty seat versus having it fixed stationary on the floor had small, but significant differences. Mounting the smartphone on a solid, non-damped surface, such as the floor, produced sharper and better signals with more details. By this fact, the smartphone containing the accelerometer is recommended to be placed on a hard surface for the duration the road condition sensing.

All recently developed smartphones have an accelerometer built-in, and differences between the employed hardware can be found, possibly affecting the detection of road events. Hence, other factors than smartphone placement and accelerometer reading type is of relevance for achieving a clear signal quality, such as the employed accelerometer hardware. The most significant quality carrying attribute for road sensing is the sampling frequency of the accelerometer. Having a high sampling frequency ensures that as many details as possible for any given event can be captured. In addition to having a suitable sampling frequency, it is also advantageous if each sample returns as little noise as possible which later aid in the signal processing and analysis. In total, three different smartphones were tested, all with different accelerometers. Out of Samsung Note 4, Samsung Galaxy SIII and Nexus One, the highest averaged update frequency achieved were around 133 Hz with the Samsung Note 4, which is also the reason why it was the chosen device for the system evaluation. Table 5.1 summarizes the tested smartphone accelerometer update frequencies.

Table 5.1: Accelerometer update frequency per tested smartphone. The showed refresh rate is the averaged speed as measured during a minute interval.

Smartphone	Accelerometer Refresh Rate
Samsung Note 4	133 Hz
Samsung Galaxy SII	102 Hz
Nexus One	100 Hz

The Positioning Sensor

The positioning sensor is the second chosen smartphone sensor, employed to mark the detected road anomalies with their position. By utilizing GPS and tagging the events, future repairs of the anomaly in question is aided as the location could be sent to authorities responsible for road maintenance.

Similarly to the accelerometer, the positioning sensors using GPS satellites also have a defined update frequency, depending on the underlying hardware and software. The GPS refresh rate as measured on a Galaxy Note 4 averages at 1 Hz. Although it is far from the accelerometer rate, 1 Hz is still capable of delivering near real-time positional tracking with a high accuracy, usually with an error margin of 2% [33].

Compared to the accelerometer sensor, the GPS sensor is a heavy energy consuming sensor, indicating that careful power-management is necessary for prolonged road condition detection. The GPS should quickly be brought online and get a positional fix to be able to tag the occurring event accurately, while it should be in a standby mode when not actively used. The challenging aspect is managing the Time to First Fix (TTFF) and the subsequent positioning requests. The proposed solution to mitigate the energy consumption by the positioning sensors and other parts of the system, is discussed in Section 5.1.1.4.

5.1.1.2 Vehicle as a Sensory Platform

Means of transportation utilizing machines have quickly grown into an indispensable way of communication, and thus, a significant effort has been made to evolve and digitize the vehicle. The once simple vehicles have become advanced systems housing different set of sensors capable of diverse functions. However, the vehicle to be utilized as part of the detection-system only has one requirement to fulfill for it to be compatible. Particularly, the precondition is that an On-board diagnostics (OBD) capable port should be present, which is found in all recent vehicles as a result of different regulations.

The OBD port availability is required, as it is via the standardized OBD connector sensory values are read from the vehicle. Sensory values are transmitted from the vehicle to the smartphone using a different set of standard defined protocols. The attribute of large importance in this context is the speed that the sensory values could be polled and transferred to the OBD port for transmission to the smartphone. The quicker the sensor values reach the smartphone, the better correlation and analysis could be carried out.

In Table 5.2, the tested vehicles are listed and their respective observed maximum update frequency per vehicular sensor shown, as acquired via the OBD connection. As can be seen, the signaling protocol employed significantly affect the sensor update frequency. Therefore, as a faster refresh rate aids in the correlation to be performed with the smartphone sensors through its finer detail capture, the vehicle used is a VolksWagen Golf.

Table 5.2: Vehicular sensor update frequency per sensor. The update frequency presented is averaged during a minute interval.

Vehicle	**Mdl. Year**	**Prot.**	**Upd. Freq./5 Sensors**
VolksWagen Golf	2015	15765-4 CAN	2.5 Hz
VolksWagen Passat	2013	15765-4 CAN	2.5 Hz
Toyota Avensis Verso	2003	ISO 9141-2	1.4 Hz

Based on numerous open vehicular sensors accessible via OBD and defined in the standard, five have been identified as useful for road condition detection. The identified vehicular sensors are listed in Table 5.3, with their choices motivated in the next coming paragraphs. However, note that in addition to complying with the standard OBD protocols, vehicular manufacturers often implement proprietary protocols aiding in diagnosing the vehicle at pre-approved service points. As the aim of the proposed system is to have a system that is not dependent on the vehicle in use, the adoption of non-standard protocols is not allowed. Discussion of the alternative sensors is therefore beyond the scope of this thesis.

Table 5.3: Identified vehicular sensors useful for road condition detection.

Sensor Name	**Description**
Engine Load	Absolute engine load reported [%]
Engine Rpm	Engine revolutions per minute minute [rpm]
Vehicular Speed	Current vehicle speed [kph]
Throttle Position	Accelerator pedal position [%]
Ambient Air Temperature	Ambient air temperature measured [$°C$]

By polling the vehicular speed sensor, an instantaneous and accurate representation of the current travel speed is acquired. Speed information is advantageous as many different event characteristics are altered when experienced at different speeds. In addition, the actual event intensity also heavily depends on the vehicular speed, making machine detection cumbersome if not accounted for. Hence, the speed variable is inputted into the detection algorithms and detection thresholds are modified accordingly. It is worth noting that the vehicle speed also could be derived from the positioning sensor by calculating the difference between two subsequent position fixes. However, the accuracy and speed achieved would be lower than by determining the speed from the vehicle itself, making the former approach more suitable.

Engine load and throttle position are used as a complementary mean of analyzing on how the driver is utilizing the vehicle. The throttle position sensors often give an indication of the wanted speed increase before the actual speed sensor gives any indication. This latency is due to the fact that the vehicle has to overcome the forces acting upon it, before the velocity is reflected of the accelerometer pedal position. Similarly, a deceleration intention is clearly indicated by a sudden release of the accelerator pedal, even before the speed sensor revel the driver's aim.

A sudden spike in engine rpm without a corresponding increase in the vehicle speed, is a good indication of traction loss. This condition is useful to detect as a precautionary measure, alerting other drivers of the lowered friction ahead. Moreover, the event is also beneficial for road maintenance operators to help prioritize roads which are the most slippery to apply preventive measures, such as salting and graveling.

Additionally, some events could also be benefited by having a knowledge of the surrounding ambient air temperature. For example, some events have a higher tendency to happen at temperatures below the freezing point. Hence, the ambient air temperature sensor is also polled at regular intervals.

Only a small subset of sensors has been selected out of the many available. The selected ones are the ones that are deemed to be beneficial for road analysis. The majority of the unselected sensors have a more prominent diagnostic emphasis, not found to be applicable in this context. Examples include engine coolant temperature, fuel injection timing and fuel system status.

5.1.1.3 Interconnection Between the Smartphone and the Vehicle

The intercommunication between the two sensory platforms, the vehicle and the smartphone, is made using a Bluetooth connection. The connection initiator is the smartphone and the endpoint is an OBD dongle connected to the vehicle's diagnostic port. Making the requested connection requires an initial pairing with the smartphone, before subsequent connections can be made automatically.

No restriction is placed on the OBD dongle except that it should be using a command-set understood by both the vehicle and the road detection smartphone application. While different models and makers of OBD dongles exist, almost all provide the same basic functionality. In this thesis, two different dongles were tested. The main observed difference is their refresh rate in polling the vehicular sensory PIDs. In this context, a higher polling rate is preferred to enable capture of finer details and a more convenient processing and correlation of the data-streams. For more information regarding the achievable OBD dongle poll rate, refer to Section 8.7 which evaluates two common OBD dongles.

5.1.1.4 Triggered Sensing as a Mean to Save Battery

The proposed system foundation is that it enables road detection by commodity smartphones, which unfortunately, contain a finite battery capacity. Hence, taking steps to conserve battery is of a paramount interest, enabling prolonged use. Out of the selected smartphone sensors, namely the GPS and the accelerometer, the GPS is the most battery consuming sensor. Therefore, the priority is to lower the GPS usage before mitigating the accelerometer battery utilization. However, other components could also benefit from applying battery saving techniques, such as the the interconnection between the vehicle and smartphone, which likewise will be considered.

Lessening the battery strain as caused by the GPS sensor is of great importance. However, completely disabling the sensor is not possible, as the positioning system is required to be able to tag events with location information upon event detection. Moreover, to be able successfully and accurately (within GPS limits) label the events, the GPS inherit location fix latency has to be considered when enabling the sensor, as it is not an instant-fix system. Having the positioning service always on is the simplest solution, which however, is not advised because of its high battery usage. Instead, a method similar to the one proposed by Mohan et al. [5] is employed, which was deferred by the authors to future work. The GPS remains powered off during normal operation and upon a detected event, triangulation is carried out by low-power means, such as cellular or WiFi, to derive an approximate location. This rough location is then uploaded into the cloud using the smartphone Internet connection, before the positioning information is pushed to other devices in the estimated location vicinity. When those detection systems then approach the same road anomaly, the GPS is turned on a few minutes earlier to ensure a location fix ahead of the probably same road anomaly to be encountered again. The rationale is that first an approximate location of the event is acquired, before gradually a better location fix could be obtained by other vehicles approaching the same anomaly. The most prominent advantage of this GPS usage is that most of the time the GPS could remain in a powered off state, ensuring longevity of the battery compared to having the GPS always on. The Figure 5.2 showcases the just mentioned event tagging procedure.

Steps can also be taken to minimize the accelerometer battery impact. As the accelerometer is considered to be the main road condition sensor, it however, always has to be turned on. Nonetheless, the accelerometer offers a higher degree of customization, enabling intermediate states between full power and being turned off. Smartphone accelerometers can often be given a hint on the desired sampling frequency wanted. For example, the Android mobile operating system offers four discrete steps ranging from slow to fastest sampling speed [34]. Furthermore, the Apple mobile operating system iOS, also offer the option to specify the update speed of the accelerometer, here however, in Hz intervals [11]. To conserve battery, the idea is to let the accelerometer vary in the samples taken per second depending on a set of conditions. For example, if during one sample the speed is zero as sampled from the vehicular sensor, then the vehicle is in no motion and it is deemed that the accelerometer sensor update speed could be lowered, conserving valuable battery. Similarly, if the vehicle remains stationary and passengers leave the vehicle, which

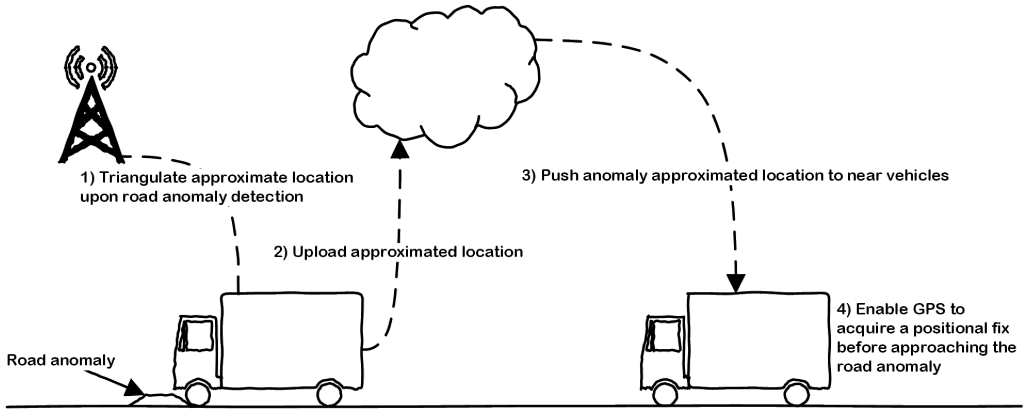


Figure 5.2: The anomaly position tagging system based on triggered sensing. Note that the smartphone is omitted from the figure for simplicity.

could be detected, the accelerometer sensor or even the whole system could be put into a power-save mode until further notice.

Here-next, the Bluetooth connection between the vehicle and the smartphone is studied, allowing the application of battery saving techniques by means of regulating the wireless usage. However, the possibility of preserving the power available is complicated by the fact that the wireless connection has to be established for the duration of the road condition sensing. Data is constantly fetched from the vehicle to the smartphone, permitting road analysis. Connection teardown and initialization take considerable amount of time, making it necessary to keep the connection alive betwixt the platforms. What instead can be done to lower battery strain, is to selectively poll the vehicular sensors, i.e. to only poll sensors that are needed at the specific moment. For example, during a traffic light while the vehicle is not in motion, no other sensors are of interest except to periodically check the vehicle speed to decide when to yet again start sampling the other sensors. As a result, the vehicular bus gets less congested and less data has to be transferred over the wireless connection to the smartphone, conserving scarce power.

Another battery saving example akin to selective polling, is the regulation of sampling speed associated with the ambient air temperature sensor. As the ambient temperature is not expected to change frequently, much less frequent polling is needed compared to other vehicular sensors. However, if an accurate and up-to-date information is nonetheless needed, the current temperature could be retrieved in less than a second anyhow.

To summarize, the aforementioned selective (triggered) polling techniques offer a smaller battery saving impact by means of its already lowered battery strain compared to the GPS. However, selective polling is still beneficial in addition of performing triggered sensing on the GPS sensor, which only enables the positioning sensor when necessary. Collectively these methods help to lengthen the maximum road condition sensing period achievable on portable commodity smartphones.

5.1.2 Cloud Considerations

In the proposed system, the cloud is constituting the second part of the two-parted architecture, complementing the detection-system. However, the cloud is considered as an external entity, and is therefore limited to only brief discussions, limited to this section.

The cloud in the road condition context is an abstraction of a central server to which all detected events gets uploaded to. Each road detection unit processes the local road information, and if an event is detected, a tuple is uploaded to the cloud. The tuple consists of `<timestamp, event_type, lat, long>` describing the detected event based on a timestamp, in addition to positional information such as latitude and longitude coordinates.

During system usage, false-positives are likely to occur as many variables can affect the detection of road conditions, many of which are challenging to protect against. As false-positives, in this case defined as events reported which in reality are false, are unwanted and costly for road operators to investigate, mitigation strategies are needed. Therefore, it is recommended to let the cloud do data aggregation. A simple and yet efficient countermeasure is to implement an algorithm that grade the certainty of detected events based on the number of reported incidents in the vicinity. Further influences can also be considered, such as the road usage level. With a high traffic intensity, there is a larger probability that different detection systems consisting of different vehicles will detect and report the same anomaly. The more systems that report an anomaly in a specific region, the greater the indication is that an actual event of interest have been detected and that it is not a random noise disturbance. In addition, further improving the accuracy of reported events, connecting the cloud to other sources such as a Geographic Information System (GIS), could enable exclusion of events known to be non-relevant. An example could be to dismiss rail-road crossings, with otherwise could be reported as a pothole by the detection-system because their signal feature similarities.

Concluding, having a cloud with the aforementioned data aggregation features permits an overall greater true-positive rate to be outputted by the system. In Figure 5.3, the cloud with its proposed capability is detailed. Consequently, note that multiple events are uploaded and that they are aggregated into a perspicuous list of road anomalies.

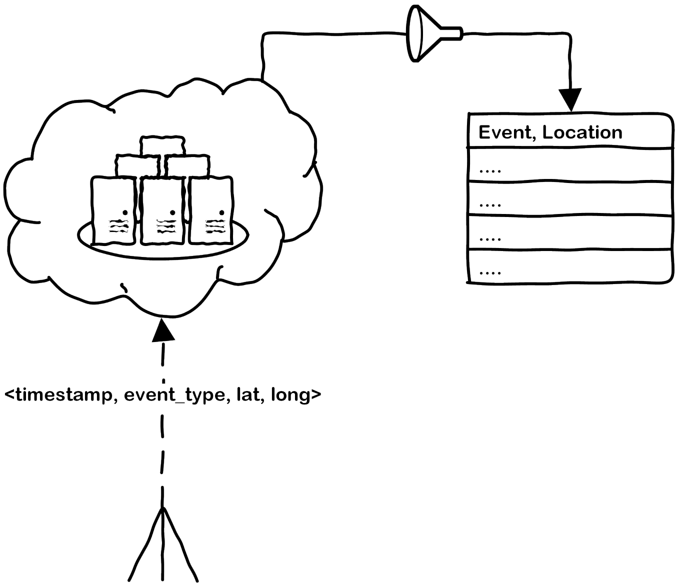


Figure 5.3: Overview of the proposed cloud for the detection-system with its ability to do data aggregation.

6

Data Acquisition and Test-aiding Facilities for Road Analysis

To be able to develop and evaluate road anomaly detection algorithms, sample data has to be acquired. Moreover, the collected data has to be manually analyzed before correlations techniques could be applied and methods of automated detection built. A custom data acquisition solution is developed and predefined test-tracks are selected. These test-tracks include events such as potholes, speed bumps and during driving, Anti-lock braking system (ABS) is triggered. Furthermore, ground truth collection is also to be employed post-data collection to identify the actual events in the set of collected data by means of manual marking. After the data is collected, the third step includes development of a software solution aiding in testing the later proposed event detection methods. The test-aiding software can replay the collected data, to enable verification of the different detection approaches in a controlled environment, without physically taking a test-drive.

6.1 Objective

Before the data analysis can begin, sample data has to be collected. The hypothesis that stand is that more events are identifiable using the proposed system, which fuses sensory information from the vehicle and the smartphone, compared to other solutions which only rely on one source of sensing, such as a smartphone. The road anomaly that have received the most previous attention is the detection of potholes. As such, this proposed system should be able to detect a wider variety of anomalies, or more thoughtfully classify potholes. The objective of the data acquisition is thus formulated as 1), to log data containing diverse events such as potholes, speed bumps, et cetera and 2), to mark the ground truth in the collected data accurately.

After data acquisition and when the data-set has been marked with the ground truth, detection of the captured road events by computerized means will be approached. However, to repeatedly test the implemented detection algorithms by performing a test drive on each iteration, is neither scalable nor efficient. To have the means to accurately perform repeated tests systematically while conserving a deterministic testing approach, a replay functionality of the gathered data would be desirable. Therefore, a test-aiding solution is needed to be developed with a data repeat component. Ultimately, the test-aiding solution should adhere to the following listed objectives: 1), it should exhibit deterministic data replay functionality and 2), it should aid in prototyping of the detection algorithms by shortening the testing time compared to manual test-driving.

6.2 Data Acquisition for Road Analysis

A special software solution is needed to fulfill the previously laid out objectives of data gathering (see Section 6.1). In this section, the data acquisition method is presented and exemplified by showing an excerpt from the collected data. In addition, a presentation and discussion about the selected test-tracks from where the data is collected, is also made.

6.2.1 Employed Software, Hardware and Means of Data Gathering

Different data acquisitions software solutions exist that are tailored to collect vehicular diagnostics data, with different levels of offered adaptability. Examples include software solutions that can be run on both personal computers, and now also frequently on smartphones. However, the drawback of the existing solutions are that they are only customizable to a limited extent. The data logging format is usually not modifiable lessening the flexibility offered. Similar drawbacks can be found in sensor data gathering software to log smartphone sensors, which is also commonly available. A universal solution logging the pair of sensory platforms, the vehicle and smartphone, is however, missing.

The means whereby no software package exist to log sensory data from both the vehicle and the smartphone, a custom solution is developed. The alternative would have been to utilize two different software, one to log vehicular data and one to log smartphone data to finally post-process, sync and merge the readings. However, in this project, a mobile application is instead built capable of logging the required information in one log file for convenience. The chosen way to save sensory data is in the simple Comma Separated Values (CSV) format.

The custom software persisted sensory data can be seen in Listing 6.1, with the information structure given with sample data. The logged information seen in the listing is from the previously discussed sensors with a timestamp attached. As can be observed, the timestamp displayed is the relative elapsed time since the logging started. Thus, it serves as reference of when the logged values were captured.

Listing 6.1: Excerpt from the data acquisition log file with masked location coordinates.

```
time;lat;long;x;y;z;ignition;throttle;rpm;speed;engine_load;amb_air_temp
0.012;lat;long;-0.112;0.159;-0.4885;1;0.13;1099;0;34.1176;2
0.013;lat;long;0.532;-0.028-0.1679;1;0.13;1099;0;34.1176;2
0.014;lat;long;-0.465;-0.1903;0.6602;1;0.13;1099;0;34.1176;2
```

The logging software is configured to capture sensory data at the highest possible sampling rate. In the test system, the fastest configuration achieves taking accelerometer samples at around 133 Hz and sampling the selected smartphone sensors at around 2.5 Hz per sensor using a VolksWagen Golf vehicle. During the entirety of the data acquisition, the smartphone is placed on the floor to receive as unaltered vibrations as possible, and thus obtaining clearer and more accurate accelerometer readings. Refer to Section 8.2 for a more detailed evaluation of the smartphone placement. The Bluetooth dongle enabling interconnection between the vehicle and the smartphone is an OBD Link made device called MX.

As an additional remark regarding smartphone placement, it is important to note that the accelerometer sensor is orientation sensitive. If the smartphone is not placed in a horizontal position, the reference origin will not be zero in all axes. To account for different possible mounting placements, before the data gathering can begin, the accelerometer sensor is calibrated. This is done by placing the smartphone in the desired location and keeping it still for a few seconds. During that time, a displacement average is calculated which is then used to adjust the subsequent recordings, to ensure that the reference is as close to zero as possible. For road anomaly detection, the phone must not be moved during driving to maintain the calibration.

6.2.2 Test-tracks and their Features

Test-tracks are selected containing a mixture of both urban traffic and stretches of rural roads. The itinerary chosen contains the usual city obstacles such as railroad crossings, speed-bumps, potholes and traffic lights. During a few rounds, Anti-lock braking system (ABS) is also engaged by performing a sudden braking movement. In addition, the chosen routes are not only traveled once, but multiple times to collect different sensory traits from the same event sources. Different prevailing traffic conditions can affect the speed during the event data collection, which possibility could alter the perceived event characteristics. Thus, capturing the sensory data multiple times at different speeds enables a more accurate digitization of the forces in action.

Totally around 100 kilometer of road is traveled and five hours of raw data logged, capturing the essence of the different types of road conditions and anomalies set to be detectable. All data is gathered using the custom developed smartphone application, which logs the previously discussed and selected sensors deemed to be beneficial for road condition sensing (mentioned in Section 5.1.1). The driven routes are summarized in Table 6.1, where each route is labeled with the set of events referred to as probable detectable road anomalies.

Table 6.1: Summary of the data acquisition routes listed with their main features of interest.

Location	Events
Skovde Centrum	Pothole, Speed Bump, Engine Stall
Skovde Rual Area	Pothole, Speed Bump, ABS, Traction Loss

In addition to the highlighted and potentially detectable road anomalies, each route contains other diverse road irregularities. The data gathered from the drives are thus supplemented with several other inconsistencies. Factoring in that some anomalies can cause similar sensory readings as other events, detection inherently needs to be rigorous to achieve a sustainable false-positive rate. An inclusive list of identified road features in the collected routes follows.

Manhole Covers. It is not uncommon to have manholes on roads to enable inspection of the public utility, such as sewers underground. However, the covers covering the holes, known as manhole covers, are often depressed into the ground as they are devalued due to use. The result is the formation of uneven surfaces which the detection-system has to take into consideration. Disambiguation between similar irregular surfaces akin to manhole covers, such as potholes and speed bumps, has to be made to enable adequate detection accuracy of the respective events.

Pothole Clusters. Rough roads because of many potholes in unison cause a different sequence of sensory responses compared to a single pothole. Consequently, this event either has to be rejected altogether, or accepted as a pothole or pothole cluster.

Thick Paint Markings. Crosswalks can have a variable amount of paint applied causing different noticeable fluctuations on the smartphone accelerometer reading when driven over. Likewise, thick paint drawn orthogonally on the road used to warn drivers of an upcoming crosswalk or intersection, can cause unwanted deviations in the accelerometer. Such cases have to be disregarded, as they do not constitute an event to be detected by this system.

Raised Intersections. Similar to other speed control details, raised intersections emphasize the current speed requirement. However, because of their similarities with speed bumps, disambiguation between the two items would be favorable. Nonetheless, as they provide the same consequence as speed humps, causing the drivers to slow down, disambiguation is not strictly necessary.

Heavy Braking. Depending on the traffic situation, heavy braking might be necessary to avoid collisions. However, the maneuver does not necessarily dictate that ABS is triggered, even if similar forces can be observed. As heavy braking might influence the false-positive detection rate of the ABS event, countermeasures have to be taken.

Sharp Turns. Similarly to heavy braking, sharp turns can in the right condition apply comparable forces on the sensors as other events. Hence, if not counted for, sharp turns might trigger false detection of other events.

Stretches of Varying Road Surfaces. Each road surface is different from the other, even if the same material is used. Factors such as age and wear level can heavily contribute to the perceived road smoothness. It is therefor important to consider that the baseline, i.e. during normal driving without any events, might be slightly different depending on the prevailing road surface characteristics.

Varying Speeds. Each event's signature characterization depends on many factors, although, the most prominently contributor excluding the event itself, is the speed of the vehicle. Therefore, it is of great importance to collect data from different events at various speeds, to be able to thoroughly classify events.

6.2.3 Ground Truth Marking and Labeling

After successful data gathering, the collected log files are transferred to a computer for manual analysis, plotting and ground truth marking. A small program is written in Matlab which parses each file and persists the data-points in separate charts, aiding in the analysis. Levering the plot, the events are identified and clearly marked with the ground truth.

However, to be able to accurately mark the plot with the ground truth, a non-ad-hoc methodology is needed. Strazdins et al. [8] states that ground truth collection is a non-trivial problem to solve. The recommended way is manual marking by walking alongside the road to both get an accurate location fix of the anomaly, and a possibility to judge the anomaly without other influences. On the other end of the spectrum, manual marking can be employed at the time of data gathering in the vehicle by means of noting the time and event experienced.

While walking is the preferred labeling method, it is also the most time consuming, and therefore, alternative solutions must be used. In this work, the roads traveled are well known and hence, the employed method is marking during data capture by having a passenger manually marking the events and noting the time. These road inconsistency markings are then transferred to labels on the generated graphs at event coordinates, aiding in the analysis. An example of such labeled section of a graph can be observed in Figure 6.1, plotted by the Matlab program.

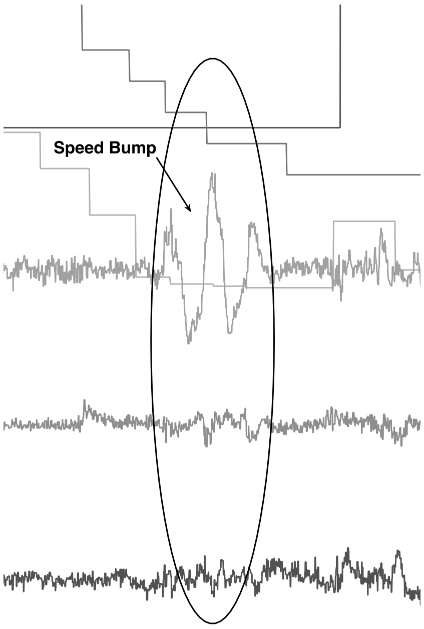


Figure 6.1: Example of a labeled graph with the ground truth marked to aid in the analysis. In the figure, a speed bump event is identified in the set of sensory data.

As concluding remarks regarding the ground truth, please refer to Section 8.3 for more information respecting the validity of the markings and labels. In that section, an argumentation is made to why the ground truth method chosen is not influencing the obtained results, ensuring a creditable data-set.

6.3 Data Replay Software to Aid in Testing

To test the developed algorithms on each iteration by performing a full test-drive over the same event, is not feasible. Means to accelerate the development and prototyping is needed, and thus fulfilling the previously laid out objectives of testability (see Section 6.1).

As mentioned in Section 6.2, the logged data is saved in a portable fileformat containing all the samples with timestamps from a zero-reference timeframe, allowing for a data reiteration to take place. In other words, leveraging the mapping of the traveled route, a replay of the route is possible by re-playing the information from the collected sensors at a correct timestamp interval, as dictated by the logged file. This achieves a true to time, one-to-one replay of the drive.

Furthermore, taking advantage of that the file contains all sensory readings from the complete drive, a fast-forward functionality could also conveniently be accomplished, by re-playing the stored values as fast as possible. A five-minute drive could then be re-created in less than 30 seconds on a Samsung Note 4 smartphone, a raw testing speedup of about 160%. Moreover, as each timestamp is re-played by the software, no matter if re-played at real-time or at a faster phase, the sensory data is fed into the developed detection algorithms in a way ensuing correct simulated time-reference. Thus, the same detection results are achieved independent of the re-play speed used. Therefore, utilizing the aforementioned feature, enables the implementation of more convenient, fine-grained testing capabilities, such as rewind, skip and to pause the simulation, without affecting the outcome.

During simulation, the detection algorithms continuously process the stream of data, producing a log of events detected with various characteristics. The constructed log file can then be crosschecked against the ground truth to determine the algorithm success rate. An example output as produced by the test-aiding software, can be seen in Listing 6.2.

Listing 6.2: Example output of the test-aiding simulator showing detected events and additional classificatory information, such as the true-positive probability.

```
[H]-Close Door detected [12.134:12.941]@Duration 0.87s
[L]-Pothole detected [41.2:41.863]@Duration 0.663s
[H]-Speed Bump detected [136.534:137.164]@Duration 0.63s
[M]-ABS detected [284.748:289.958]@Duration 3.21s
```

An important benefit of the test-aiding software, in addition to be able to perform rapid detection algorithm prototyping, is the realization of determinism. By utilizing the data replay software, deterministic testing behavior can be achieved. This would otherwise not be possible by manual test-driving because of several obvious contributing factors making each drive unique, such as traffic and a slightly different driving style on each run. Hence, by utilizing the test-aiding software, the detection approaches could be isolated, tested and improved in a controlled fashion.

7

Road Event Detection

The incentive to the events set to be detected have previously been given, as well as the system architecture and the data acquisition method. In this chapter, each event motives are briefly mention before their detectable signatures are exemplified. Moreover, the detection methods are presented which captures the core aspect of the signal characteristics, enabling event detection.

7.1 Road Anomaly Detection and Classification

During the course of this thesis numerous data have been derived from the routes driven. The routes contain a diverse set of events from which a subset have been selected for further discussion and analysis. The ones listed under this section are the ones that can be beneficial to detect in the context of road sensing. Firstly, speed bumps are discussed, before potholes and Anti-lock braking system (ABS) detection are presented. While speed bumps are not strictly a road anomaly, it is discussed as if not considered, might wrongly be classified as potholes on some elementary detection implementations. Therefore, it is not without reason to detect speed reducing obstacles.

As a final remark, this chapter describes the detection methodology of the events in a textual approach. However, the provided Appendix A lists the developed algorithms pseudocode in a short and concise way, allowing the reader to use it as a future reference.

7.1.1 Speed Bumps

The speed bump is a common speed reducing obstacle many drivers face. A speed bump is a ridge on the road, designed to force the drivers to lower their speeds temporarily. Different designs and shapes exist even though they share common attributes. One such common attribute is the swelling in the speed bump, commonly often referred to as the actual speed bump. The swelling, as can be seen in Figure 7.1, is usually a short stripe causing the vehicle driving over it to move in a specific, and sometimes uncomfortable pattern.

There exist multiple reasons to detect the speed enforcing obstacles and act accordingly. The movement caused by the hump provides the drivers with the incentive to reduce their rate of travel, enabling positive effects. As an example, the reduction of speed has decisive benefits, for instance, lowering the number of fatalities by as much as 60% [24], or in Ghana by up to 72% [25]. Therefore, the

Figure 7.1: A typical round-topped speed bump with a height of 6 *cm* and a length of 2 *m*.

affect could possibly further be increased by notifying the drivers of the upcoming anomaly, reinforcing their effects. However, if the automobiles fails to comply with the speed reduction, disadvantages also exist with installing speed bumps, such as the possibility of injury if passed over the anomaly at excessive speeds [26]. Moreover, on elementary detection algorithms, speed reducing obstacles could also falsely be detected as potholes. Therefore, based on the aforementioned possible outcomes, it is beneficial to detect speed reducing obstacles.

7.1.1.1 Detection

Upon passing over a speed obstacle and when the front wheels of the vehicle hit the hump, the vehicle moves up, before quickly moving down when the front wheels pass the bump, as they yet again touch the regular road surface. Similar movement could be observed when the rear wheels hits the deformation. Hence, by this observation, the vehicle will be experiencing exactly two bumps, one from the front wheels and one from the rear wheels. Evaluating the features in finer details reveal that a bump can be observed as consisting of one upward motion followed by a downward motion. These are characterizing features that then could be picked up by an accelerometer, and hence, these details lay the detection foundation of the speed bump event. Consequently, the fact that the deviation pattern causes a motion either upwards or downwards, could be detected by simple means. Leveraging the area beneath the graph as an indication of a deviating motion enables the detection of the bump pattern, without any signal-processing applied.

In addition to the detectable humps indicating a potential speed bump, another detection possibility straightening the detection of the event could be observed. As the wheel pairs receive the speed bulge in concordance, only minimal deviation is expected in the x-acceleration (lateral acceleration). As will be shown, this is not true for all events, such as potholes (see Section 7.1.2), which can affect only one side of the vehicle. Therefore, assuring that the x-acceleration average does not marginally increase during a possible speed bump event, the speed bump could be disambiguated from potholes in an uncomplicated way.

The behavior of the vehicle driving over a speed bump was recently discussed. Next, a closer look is taken on events just prior and after a speed bump. The main objective of a speed bump is obviously, to cause the drivers to slow down. Hence, prior to the hump, as the drivers are approaching it, the expected behavior is a deceleration. As the proposed system is polling a set of vehicular sensors, a deceleration could be noticed in many ways, including by checking the speed meter, the motor revolutions per minute (rpm), throttle position or even the engine load. Conversely, an acceleration will most probably be occurring right after traveling over a speed bump, to recover the speed lost. Moreover, this speed change would be observable by the proposed detection system's various sensors. Leveraging the vehicular sensors is therefore a simple mean of further assuring the occurrence of a speed reducing obstacle.

Furthermore, an additional effort is made to reduce the possibilities of erroneous events to a greater extent. As observed from the acquired data, a typical speed bump normally spans the range of 2-3 m. Consider traveling over a speed bump at 20 kph, or around 5.5 m/s. Then, a hump of 2.5 m, should be passed in approximately 0.5 s. Measuring the length of the hump can be achieved by deducing the time-span from the first bump in the graph, indicating when a set of wheels have completely passed over it. To reject spurious speed bump events, a comparison of the the acquired value to the expected value can be done, dismissing erroneous events.

To summarize, a few main features are needed to accurately detect speed bumps; deceleration, bump detection and then acceleration. A deceleration is expected before a noticeable deviation in the z-acceleration would be picked up as the vehicle passes the bump. However, note that only minimal x-acceleration is anticipated. Then, after the detected accelerometer deviation signature of two bumps, an acceleration is likely as the vehicle moves away from the hump, and continues on the road. The aforementioned features are clearly visible in Figure 7.2, showing a plot of data logged over a typical speed bump.

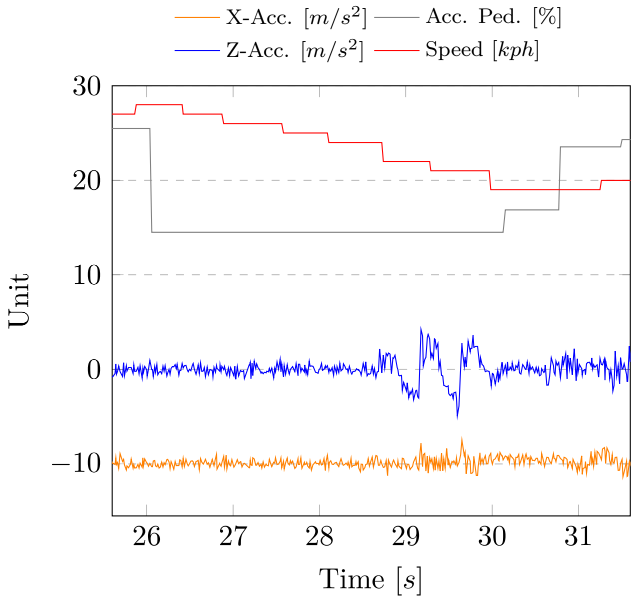


Figure 7.2: Plot showing a selection of the logged sensors when driving over a speed bump. The main features; deceleration, bump and then acceleration are visible. Note that no significant deviation is captured in the x-acceleration (——) as the wheels receive the bump in unison. Moreover, observe that the x-acceleration is relocated to a baseline of -10 instead of 0, to ease in displaying the plot.

7.1.1.2 Approach Constraints

Based on the prime features of speed bumps, automated methods capable of detecting them are possible. While the expectation is that all the stated aspects will occur, situations can nonetheless arise where the discussed chain of events does not happen in the stated order, or some events not at all. Till now, it has been assumed that deceleration before a speed bump occurs, and acceleration afterwards. In some cases, for example in heavy traffic conditions, deceleration might not occur because of already low speed. In such cases, polling the accelerator pedal could be conducted, often returning a hint on the intended speed despite the speed meter indication. Thus, the detection method could be fallen back to relying on another vehicular sensor. While these scenarios might impact the overall detection accuracy slightly, it is not a major issue as the main speed bump detection sensor is still the accelerometer. However, by detecting all of the discussed features of a typical speed bump, a high degree of certainty is ensured.

Moreover, as a final note regarding detection of speed bumps, note that the analysis of two consecutive humps (see Section 7.1.1.1) implies that the vehicle is approaching and moving over the speed bump at a ninety-degree angle, i.e. head on. The same analysis would not hold true otherwise, as each set of wheels would not receive the bump in unison, causing a different movement pattern. This non-head-on case is considered as an uncommon special case, and is not dealt with in this thesis. Similarly, while different shapes of speed ramps exist, only round-topped ones will be considered, as they are the most common speed reducing obstacles in the tested area.

7.1.2 Potholes

Potholes are disruptions on the road surface which are usually caused by surface weakening, because of its continuous usage alongside with wear and tear. These road disturbances are commonly manifested as carvings, causing an uncomfortable vehicular movement if driven over. Because of its uncontrolled nature, potholes could also be dangerous if not noticed priori, as they could be deep and lead to unexpected maneuver, or even severe automotive damage. Hence, it is of great interest to detect them, enabling quick repair. An example of a larger pothole, which should be avoided if traveling at a faster rate of motion, can be observed in Figure 7.3.

7.1.2.1 Detection

Potholes can be evinced in different sizes ranging from small to large with different depths. However, upon driving over a pothole, the given characteristics as perceived by the sensors share similar features, namely an unexpected deviation from the averaged accelerometer reading in the past. This is due to the fact that the pothole is at a different level compared to the road, causing a vehicular hump. Therefore, taking into account the acceleration spike that is caused, potholes could be detected.

Naturally, the size of the fluctuations generated and picked-up by the detection-system when passing a pothole depends on the specific pothole details. An example

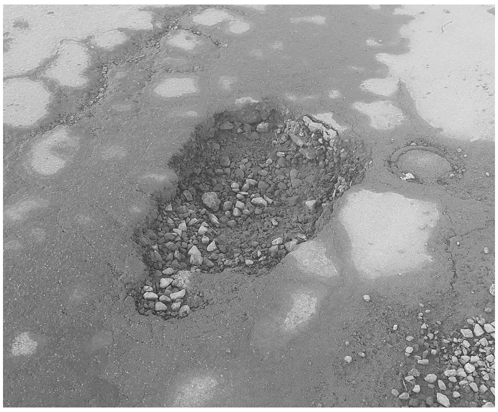
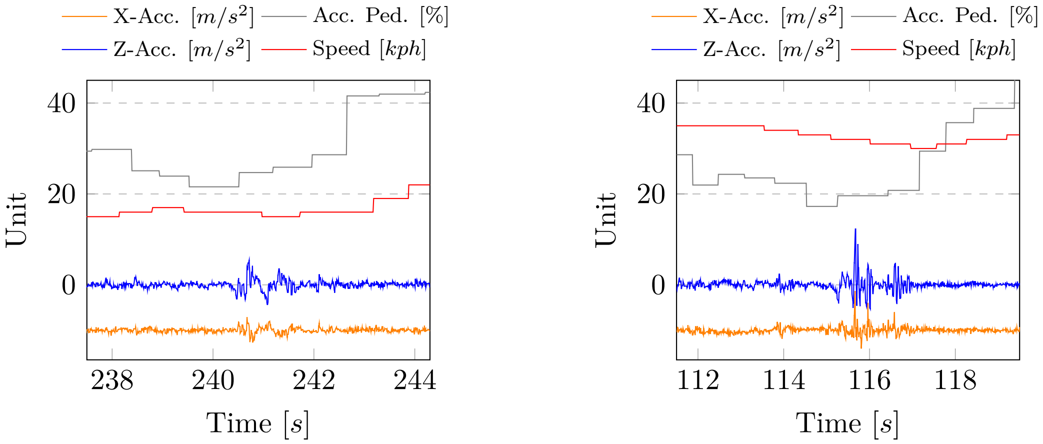


Figure 7.3: An example of a large pothole, around 7 *cm* deep.

highlighting the differences between collected potholes traits is depicted in Figure 7.4. In the left graph, Figure 7.4a, the vehicle passes over a comparable small pothole in comparison to the right chart, Figure 7.4b. As also shown in the figure, different speeds could be observed because of the various prevailing traffic conditions near the potholes during data acquisition, also effecting the sensory data captured.



(a) Small pothole with a limited accelerometer fluctuation.

(b) Large pothole with a significant accelerometer fluctuation.

Figure 7.4: Recordings of a vehicle passing two potholes. In (a), a small pothole is passed which causes smaller accelerometer fluctuations compared to (b), in which a larger pothole is driven over. When studying the graphs, note that the x-acceleration (——) is shifted downwards to ease in plotting. In reality, the baseline is at 0, similarly to as the z-acceleration (——).

The detection of potholes is primarily done with the accelerometer sensor. As observable from the Figure 7.4, potholes could be classifiable by the accelerometer and complemented with the vehicular sensors. In each figure's center, the accelerometer readings brake the surrounding pattern, indicating a possible pothole. The acceleration in the z-direction, that is the vector pointing straight out of the smartphone screen, obviously gives an indication of a just passed irregular road surface because their different surface levels. Thus, leveraging the knowledge of a typical pothole event trait, pothole could be detected. Therefore, based on the acceleration spikes caused, the employed recognition approach builds on two simple methods; determining the difference in subsequent z-acceleration readings to get the acceleration magnitude, and on an increased z-axis moving average compared to previously calculated values, indicating a road inconsistency.

In addition of leveraging the observation of a sharp deviation in the z-axis by the accelerometer, further means could be taken strengthening the detection procedure. As an example, potholes are only expected to hit one side of the vehicle, as they do not span all the way across the road. Hence, the accelerometer monitoring the x-acceleration (lateral acceleration), should in addition observe a divergence, as only one side of the vehicle is affected by the pothole. Note how this phenomenon is different compared to speed bumps, where the bump hits both sides of the vehicle at the same time, making no noticeable x-acceleration deflection, if approached perpendicular. It is worth noting that the observation regarding the x-acceleration in the context of potholes was also mention by J. Eriksson et al. in their Pothole Patrol paper [4].

Moreover, in addition to examine the accelerations caused in the different directions, vehicular sensors could be monitored enhancing the detection procedure. By observing the other sensors logged, other characterization features could be extracted to complement the accelerometer sensor for a more through detection. For instance, if the pothole is detected prior, but the driver cannot avoid it because of other obstacles, a speed decrease is expected to occur in preparation of passing over it. The decrease in speed to mitigate the bump caused by the pothole could be observed by multiple monitored sensors, such as the actual speed meter or through a more subtitle mean, particularly by checking the accelerator pedal position. In fact, monitoring the accelerator pedal is more beneficial than relying on the speed information alone, as can be observed from the plots (see Figure 7.4). In the presented cases, and generally, the accelerator pedal position clearly dictates the drivers demands more distinctly then the speed meter. Above all, it is beneficial to detect if the driver indeed reduces the speed. For example, by confirming the speed decrease the possible pothole could be assured to a higher level by means of that slowing down is the expected behavior during a pothole event.

Further leveraging the vehicular sensors, given that a speed reduction occurs before a pothole, an increase in speed is the most probable occurrence right after driving over the inconsistency, regaining the speed lost. However, if no speed decrease take place at all and the pothole is still driven over, the element of surprise and its level of unexpectedness could be deduced based on a function of event severity.

7.1.2.2 Approach Constraints

While a deviation from its past values, as sensed by the accelerometer in the x and z-axis, is an indication of suboptimal road surfaces, potholes needs to be identified in the set of plausible events. One of the challenges include determining optimal thresholds for detection, enabling a high detection rate with adequate accuracy and a small amount of false-positives. However, finding the threshold is further complicated by the fact that potholes are generally unique. As a result of their individual appearances, finding a decisive value for the threshold, *thresh*, is challenging. An attempt to find the most suitable value for the collected data is done by determining the rate of success of different plausible thresholds. However, the use of thresholds can be seen as a constraint, as they are expected to be different under alternative settings, such as using a different vehicle then the one leveraged in the data gathering and evaluation.

7.1.3 Traction Loss

The wheels are the only part of a vehicle in touch with the road, and as such, it puts a tremendous importance on keeping the traction high at all times. If the vehicle's wheels loose traction to the road at an unfavorable time, severe consequence could follow, causing the vehicle swaying of the road. However, in recent vehicles several active safety systems exist that tries to overcome and correct the loss of control, such as active stability control. Nonetheless, it is impossible to completely get around the problem, and thus, detecting a traction loss event can be of great value as a preventive measure in the act of a warning message for other drivers regarding slippery surface conditions ahead.

Different types of traction loss exist, and in this thesis, three types are identified as possible scenarios. The first one is caused by high speeds in conjunction with maneuvering on a slippery surface, causing the vehicle to not follow the intended trajectory because of too little traction. The second type is motivated by applying too much braking pressure on the wheels, causing them to lock and consequently, the enabling of the Anti-Lock Braking System (ABS). This event is discussed more in Section 7.1.4. The third type, and the one dealt with here, is introduced by applying too much force on the accelerator pedal, evoking free spinning wheels and ultimately a loss of traction.

7.1.3.1 Detection

Detection of traction loss, caused by too much acceleration, can be achieved by analyzing motor revolutions per minute (rpm) in correlation to the vehicle speed. If excessive torque is applied, free-spinning wheels will result, causing a sudden spike in the motor rpm produced. However, because no significant friction exists between the wheels and the road, the achieved speed will not be matched to the rpm. This miss-match in the correlation could be detected, indicating a loss of traction. The Figure 7.5, clearly highlights the latency and mismatch occurring when the wheels are spinning while speed is not gained before around two seconds later.

However, different degrees of traction loss can occur making detection cumbersome, and thus, each event is reported with an assurance level denoting its true-positive probability. The length between the observed motor rpm spike and the time of first significant speed increase is used as part of the assurance level, with the assumption of a longer interval yielding a higher probability of an actual occurred event. The rationale is that the longer the wheels spin before gaining any speed, the more severe the traction loss is, caused by the lessened friction between the road and the wheels.

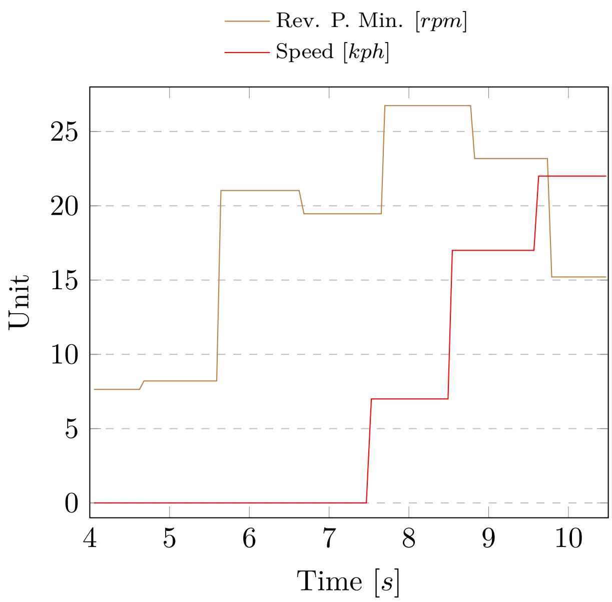


Figure 7.5: Traits of the relevant logged sensors during a traction loss event. The miss-match between gained speed and motor rpm can be observed in the chart. Observe that motor rpm (——) is divided by 100 to ease in displaying the plot.

Based on the aforementioned detection approach, it is apparent that event recognition can take effect regardless if the vehicle is losing traction from a stationary position or when traveling. In the just presented figure, Figure 7.5, loss of traction is depicted, and thus free-spinning wheels, based on a starting position where the vehicle is stationary. However, the same traction loss detection method, building on the discrepancy between the motor rpm and gained speed, still applies in other situations, such as when the vehicle is already traveling.

7.1.3.2 Approach Constraints

It is easy to assume that just revving (to increase the speed of) the motor could mislead the detection approach. However, a practical benefit of the employed detection method utilizing a combination of two vehicular sensors, is its ability to neglect false events similar to the aforementioned one, such as caused by revving the motor. If the motor rpm spike was the sole event characterization feature, the driver could in some circumstances accidentally revv the motor enough to trigger a false traction loss event. However, based on the implemented detection method building on the inconsistency of the two sensors, motor rpm and speed, just revving the motor will not deceive the detection algorithm, as no speed is gained in such cases and therefore failing to trigger the event.

7.1.4 Anti-Lock Braking System (ABS)

The Anti-Lock Braking System (ABS) is usually triggered in temperatures below freezing, when braking is initiated, and the braking force applied to each wheel is too excessive, preventing the wheels from being free-spinning. If the wheels are locked, less efficient braking is achieved and the controllability of the vehicle is lost or severely dampened. Detecting the enabling of ABS thus indicates lowered friction, which can be used to warn other nearby drivers. Furthermore, recognition of the event allows precautionary procedures, such as salting and graveling to be applied by road maintainers, improving the collective road safety.

7.1.4.1 Detection

To overcome the locking of wheels, the braking force as applied by the ABS is in a pulsating fashion, ensuring that the wheels do not lock for an extended period of time, or at all. Moreover, as these modulations motivated by the ABS causes the vehicle to shake, they could be picked up by the accelerometer sensor in the detection-system. By reason of the pulsations, a horizontal S-pattern, $\sim$, is expected along the y-axis measuring y-acceleration (acceleration towards the vehicle trajectory). These pulsating features could then effectively be detected by utilizing a moving average, which will behave similarly to the observed oscillation pattern, i.e. modulate - increase and decrease. A maximum of 15 modulations per second could theoretically be picked up, as Jack Erjavec et al. [35] states that depending on the vehicle and the road surface condition, 15 ABS engagement and disengagements can occur per second.

Furthermore, in addition to detecting the oscillations, by observing the other logged sensors, a sudden drop of the speed should be asserted with the driver prior release of the accelerator pedal. Motor revolutions per minute (rpm) should also receive an abrupt drop as the speed is decreased or the clutch engaged. In Figure 7.6, a recording of an ABS event is shown in a plotted format.

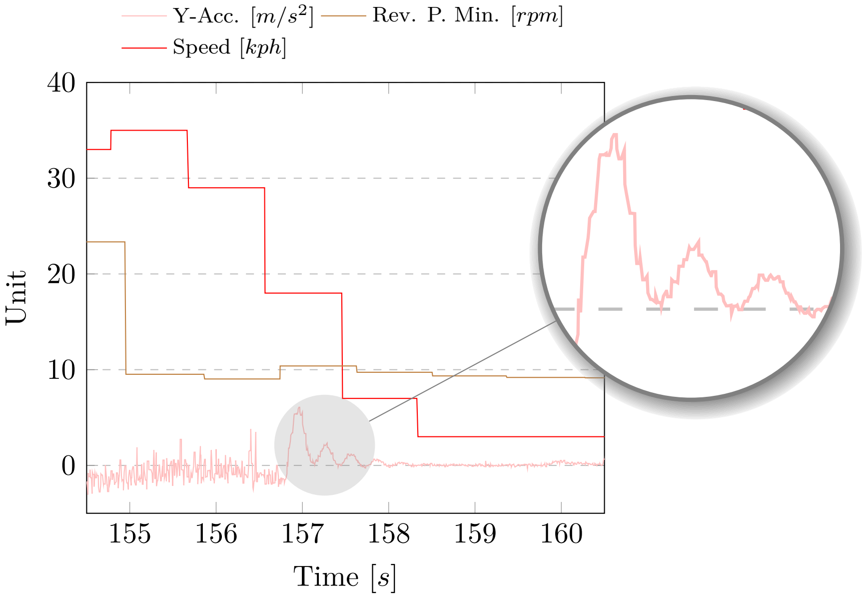


Figure 7.6: Essence of an ABS triggering event almost halting the vehicle. Note the $\sim$-pattern in the y-acceleration (——), caused by the pulsation generated by the ABS. Moreover, mind that the motor rpm (——) is scaled by 100 to fit the graph.

Another observation that can be made regarding the detection of the ABS event is that the triggering of ABS heavily depends on the road condition, more specifically, on the amount of friction between the road and the vehicle wheels. Nearing freezing temperatures (around 0 $°C$), the risk of locking wheels is significantly increased because of ice or snow formation that can appear on roads, ultimately lowering the friction. When a signature similar to an actual ABS event is detected, its definite likely-hood could be determined by a function of the current temperature. Thus, by taking the current temperature into account, the false-detection rate could theoretically be lowered. It is noteworthy that obviously, however, ABS can be triggered in warm conditions also, but usually much less frequently because of the great traction betwixt the road and the vehicle.

7.1.4.2 Approach Constraints

The ABS produced distinct recognizable patterns, and hence, no known constraints of the detection method are known. The only precondition is that the smartphone accelerometer should be sensitive enough, capable of picking up the oscillations caused by the ABS engagement.

7.2 Other Classifiable Events

The previous section explored detection of events that could be of direct benefit for road operators, maintainers and automobilist. Events such as speed bumps, potholes, traction loss and Anti-lock braking system (ABS) were discussed. In this section, events referred to as other classifiable events are identified and evaluated. While these detectable events do not have a direct connection to road surface sensing, they have other valuable implications if successfully detected, such as offering improved battery savings and increased road safety.

7.2.1 Engine Stall

Detecting engine stall can be of significance in measures taken towards lowering accidents occurring on the public roads. If the engine stalls at disadvantageous location or moment, dangerous situations can arise. For example, if the engine stalls and the vehicle becomes stationary, drivers behind might notice it too late, causing a rear-end collision. Therefore, an attempt to detect driver induced stalls are made as a precautionary mean. Once the event is detected, the possibility exists to warn nearby drivers of a non-moving vehicle ahead, enabling an awareness of the other automobilist else-ways not possible to achieve.

7.2.1.1 Detection

Engine stalls are usually occurring on manual geared vehicles when the driver engage the clutch too promptly. When it occurs, the engine cannot produce enough momentum because of lacking features, such as air and fuel, causing it to halt. This phenomenon could be captured by monitoring the current engine load. Generally, the vehicle described load fluctuates widely depending on many factors, such as friction between the wheels and the vehicle, road incline and the accelerator pedal position. However, a characterization feature of engine stalls is a sudden spike of the engine load towards the maximum of 100%, before falling to 0% as the engine cease to run. The fact of motor halt, could additionally be confirmed by probing the motor revelations per minute (rpm), which should be zero as the motor is interrupted. Moreover, the vibrations as picked up by the detection-system should additionally be close to zero, signaling no motor running, ceasing the resonations caused to the vehicle by the engine itself.

The aforementioned representation of an engine stall could be observed in Figure 7.7, showing the relevant sensors. Moreover, observing the figure, another detectable aspect of the event could be found. As can be noted in the chart, the y-acceleration shows a vibrating pattern just prior to the event, before effectively flattening out as the motor stops. This vibration pattern is produced when the engine is nearing a halting state. Thus, the detection of this pattern in addition to the engine load, gives a stronger indication of an actual engine stall. Note however, that the y-acceleration feature is only noticeable if the vehicle is close to being stationary, without other significant surrounding noises. If the vehicle is moving, the pattern would not be recognizable by means of other vibrations, and thus, the engine load would have to be the sole characterization feature of the event.

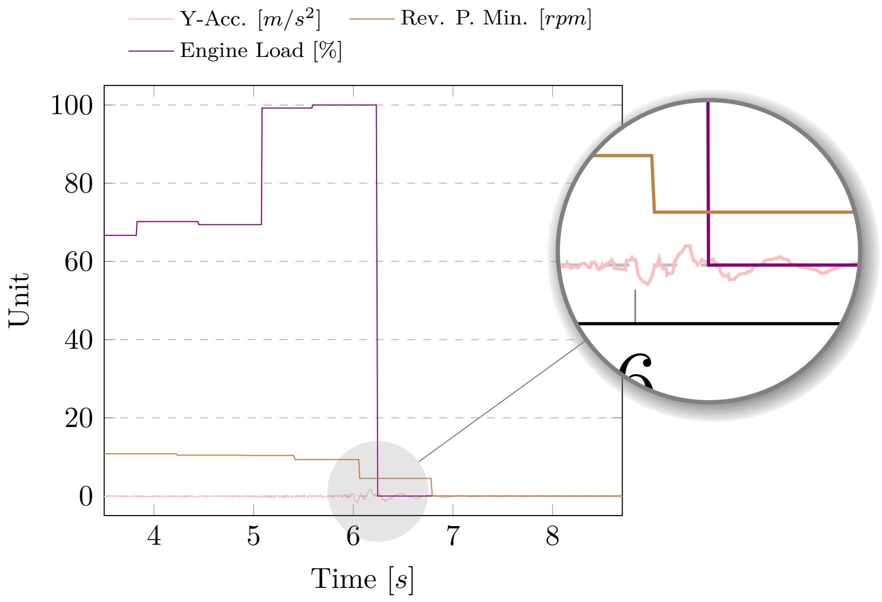


Figure 7.7: Records representing an engine stall. The motor halting due to a stall can be noticed based on the knowledge of the engine load going towards 100% and then to 0%.

The implemented detection method to frame the essence of the event, is performed by means of observing the engine load and motor rpm behavior. Therefore, it is deemed that detection of engine load is the main recognizable trait of the event, working in all conditions unlike the y-acceleration feature.

7.2.1.2 Approach Constraints

Based on the fact that the vehicle indeed behaves as observed in the collected data, i.e. an observable sudden motor load increase before falling back to 0% as the engine stalls, no limitations of the detection method is found.

7.2.2 Door Slam

A door slam is an event that is caused by the resonating vehicle when doors gets closed, i.e. slammed shut. While the event does not directly help in classify roads, it is nonetheless an event that is worth taking a closer look at. Door slams produce a high energy reading on the accelerometer, which might make the detection algorithms wrongly classify the door slam as other similar high energy events, such as potholes. This especially holds true, while not limited to, if threshold detection approaches are used. Hence, it is of great interest to reject or disambiguate door slams from other similar cases.

None of the presented related work recognize door slams as events, instead they classify them as random noise to be rejected and neglected. The rejection is usually done by rejecting all readings below a certain speed, such as 20 kilometers per hour. By using rejection of all sensory readings at low enough threshold speeds, prevention is made, inhibiting door slams to be mistaken for other high energy events actually used for road sensing. However, the drawback of this simplistic approach is that other interesting events could occur at speeds that now are rejected. To mitigate this problem, a lower cutoff speed could obviously be chosen. Nonetheless, even if low rejection speeds are used, such as five kilometers per hour (or even zero kilometers per hour), it could be worthwhile to detect door slams to know when passengers leave the vehicle to, for example, put the detection-system into a low-power mode at times when no one is in the vehicle. Hence, because of the events beneficial attributes, an attempt is made to detect door slams to be able to accept these types of events, instead of simply rejecting all sensory readings below a certain threshold.

7.2.2.1 Detection

The plot in Figure 7.8 shows the characterizing traits of a close door event. As can be seen in the figure, a temporal high energy spike occurs just as the door get closed. Other things to note is that the speed obviously should be zero in addition to that the motor revolutions per minute (rpm) and throttle position should be in an unchanged stance. However, in the chart only the speed is plotted for convenience, as it is enough of an indication that the vehicle is stationary.

Analyzing the collected data of the close door event in more detail, it can be observed that the events strength as measured by the accelerometer, depends on at least two factors. Obviously, the force used to close the door has influence, however, the placement of the smartphone in comparison to the doors is also of great importance. As can be observed in Figure 7.9, the door which is closest to the smartphone, is clearly deducible. Therefore, leveraging the strength involved in the event, the door location could be approximated.

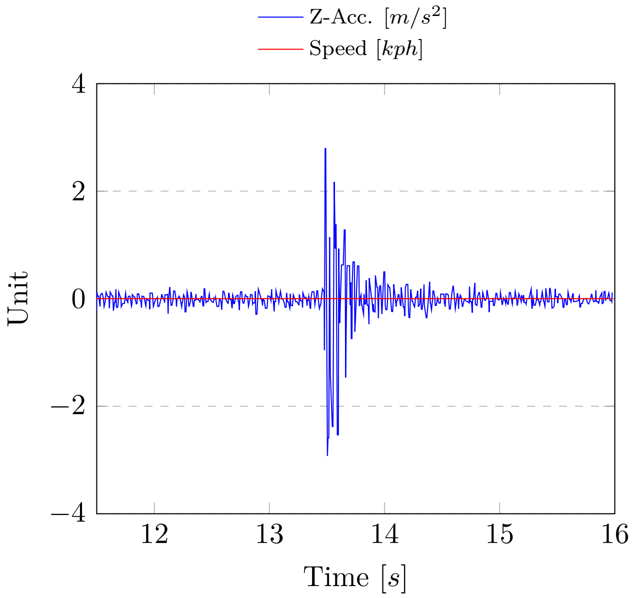


Figure 7.8: Plot showing the characterizing traits of a close door event. The high energy spike as caused by slamming the left-front door can be observed.

Machine detection of door slams is straightforward, considering its clear characteristics. The detection method employed is to check the current speed, before probing for an abnormally high energy event. Testing determined that vehicle vibration as caused by closing the door, lasts for a fixed amount of time. Hence, by noticing an acceleration event which deviates largely from its past values, a so called high energy event, lasting for approximately 75 ms when the vehicle is stationary, is most probably caused by closing doors.

7.2.2.2 Approach Constraints

As means of the distinct patterns, the detection method is deemed to be rigid. However, as with all detection implementations, thresholds are needed. Based on the collected traits of close door events, suitable thresholds were derived. Nonetheless, depending on the force used to close the doors, it might be possible to avoid detection. On the other hand, avoiding door slam recognition should require the actual intention of avoidance, such as closing the doors more slowly than usual, as the thresholds are set low. Therefore, based on the previous grounds, the avoidance case is assumed to be deliberate, and is thus disregarded as an approach constraint.

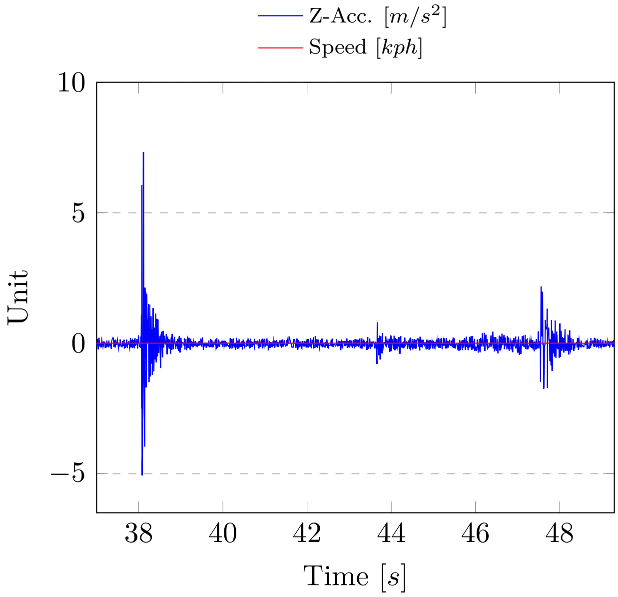


Figure 7.9: Two door slam events, one with the smartphone close to the door, while in the other event the smartphone is further away from the source of vibrations - the door. Knowing the placement of the smartphone, the location of the closed door can be deduced.

8

System Evaluation and Discussion

Till now, test data have been gathered and the proposed system developed and prototyped. In this chapter, an evaluation and discussion is made around the road detection-system. Firstly, as the smartphone placement is of influence, its positional impact is shown. Also, as having valid data to perform the evaluation is of great-most importance, the way the data acquisition was carried out is additionally argued as being sufficient in the context of the detected events. Moreover, the evaluation criteria is discussed to lay the foundation of what is considered a valid result, before the in this thesis discussed events are evaluated. Furthermore, the detection-systems battery is valued and exposed.

8.1 Chapter Orientation

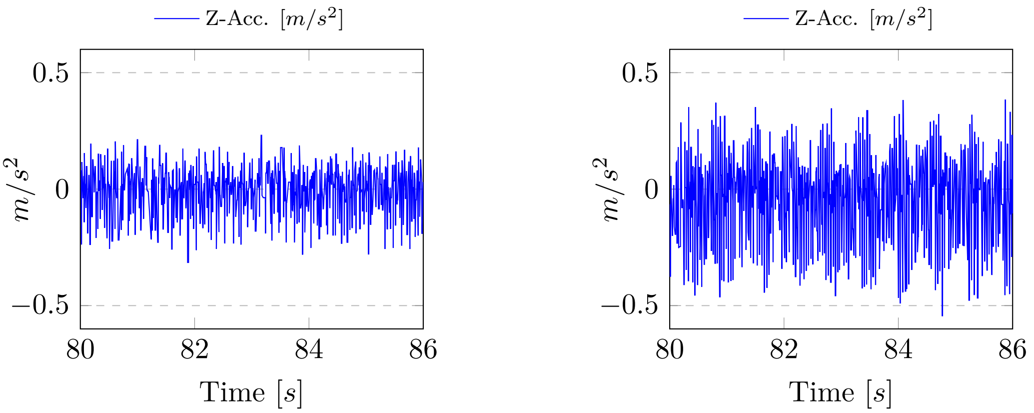
To guide the reader in this chapter, an overview orientation is given. In Section 8.2, the smartphone placement is evaluated and in Section 8.3, the data acquisition and ground truth methodology is argued for as being valid. Then, each different detectable event-type will be evaluated separately in Section 8.4, because of the difference in detection complexity. Next, in Section 8.5, the detection-system battery impact is studied. Thereafter, in Section 8.6, a broad summarizing discussion is made on the systems feasibility, noted observations are presented, and general commentary on the system is given. Finally, in Section 8.7, remarks on the utilized OBD dongle is made.

8.2 Smartphone Placement and its Effect on Signal Quality

The detection success of the different type of road conditions heavily depends on the signal quality the detection algorithms are fed with. Hence, to achieve the best possible detection rate given the presumptions, it is of paramount interest to capture true-to-world signals, with as little noise as possible. Moreover, as road anomalies are experienced differently throughout the vehicle, different sensory placements could affect the signal quality and in the end, the event detection rates. Consequently, the placement of the smartphone has to be evaluated.

Different placements can be imagined of the smartphone during road anomaly detection. However, it is reasonable to assume that most of the sensors employed would be unaffected by arbitrarily placement inside the vehicle. The GPS sensor should be able to get a signal, even if placed every which way, given the signal characteristics. Similarly, the interconnection between the vehicle and the smartphone handled through Bluetooth would be accessible by reasons of the wireless medium's range capabilities, even in an arbitrarily smartphone placement in the vehicle. The pre-included sensors inside the vehicle are also unaffected as they already are mounted in place at factory, moreover, without user control. The only sensor left for discussion with user oversight is the accelerometer that is built-in, into the smartphone. Unfortunately, it is a sensor that reasonably could be affected by the placement of the smartphone confined in the vehicle. Different material vibration characteristics and other properties can affect the signal picked-up by the accelerometer, leading to feature alterations. While soft surfaces could have a dampening effect on the vibrations caused by events and the engine itself, they could also amplify the resonations.

Out of the different tested smartphone placements, data logged from the two most different signal quality placements, are shown in Figure 8.1. The recordings were done with the vehicle stationary, with the engine on, to get baseline recording of the vibrations in different smartphone locations. As can be seen, in Figure 8.1a, with the smartphone placed on the floor, the captured vibrations are less than in Figure 8.1b, showcasing the smartphone positioned on the seat. Therefore, by means of that the placement of the smartphone on the floor caused the least disturbance out of the tested positions, it is the recommended placing.



(a) Smartphone placed on the floor.

(b) Smartphone placed on an empty seat.

Figure 8.1: Signal differences between smartphone placement. The smartphone as placed on the floor (a), produces cleaner signals than if positioned on an empty seat (b).

To summarize, in the tested vehicle, a VolksWagen Golf, the best found placement was to have the smartphone mounted on a hard surface, such as the floor. The reason could most likely be derived to the fact that hard surfaces are vibrating similarly to as the encompassing chassis itself, enabling a close true-to-world vibration capture without signal alternations.

8.3 Validity Assurance of the Data Acquisition and Ground Truth Methodology

The data that is gathered lays the foundation for not only the analysis, but also for the testing and evaluation. It is thus of a great importance that the data is both correctly gathered and that the ground truth is accurately marked. Due to time constraints, the ground truth method selected is to have a passenger in the vehicle noting the events as they are experienced. Then, when the data is to be manually analyzed, the markings made are transferred to the plotted graphs for convenience, as explained in Section 6.2.3 and exemplified in Figure 6.1.

The method chosen for collecting data is not without its critics as the human factor could contribute to a biased data-set. However, even though there is a human factor involved when taking notes as the driver passes over different conditions that generate events, it is still argued for to be correct and accurate.

The first argument for the data-set correctness is that the author of this paper is participating in the data acquisition. The expectations are clearly communicated and the author both participates and oversees the data gathering. Any data that is vague, in a sense that the event cause is unknown or not noted, is promptly discarded. While the author's participation is not an assurance of data validity, it increases the confidence and knowledge of the data collected, unlike testing scenarios where a system is fitted on vehicles driven by unknowns and then data post collected.

The second argument for the chosen ground truth method is that the roads selected are well known and have been traveled on for many years, most of the times daily. Hence, as the routes are frequently traveled, their inconsistencies are clearly acknowledged. During note-taking of the events, they do not come as a surprise, enabling an awareness often not possible in similar data gathering scenarios, such as driving on unknown routes. This prior knowledge further dictates that the event marking is done accurately.

Thirdly, the combination of knowing the route and logging each sensory reading with a location coordinate, enables post checking of the noted events. After the data is collected, each noted event location (GPS coordinates) is determined from the logged data and then checked on a satellite map. As the routes are priori known, the noted events could be verified to a higher degree by checking the detailed map, then otherwise possible. Furthermore, because of the routes familiarity, this method also accounts for the GPS inaccuracy, as the event in question easily could be deducted by checking the map in addition to the logged data. Moreover, due to tagging the logs with GPS positions, the actual event could physically be verified by manually inspecting the road irregularity, if uncertainty still exists.

The three aforementioned major arguments provide the incentive to why the chosen ground truth method is still a viable approach, despite its shortcomings of the human factor. Thus, by the former presented discussion, it is believed that the employed data-set contains creditable data and that it is marked in a legitimate way.

8.4 Event Evaluation

In this section, the developed methods to detect the different set of road anomalies and events will be evaluated. However, firstly, the assessment and evaluation criteria is presented, containing the groundwork for all future event valuations. Thereafter, each algorithm will be evaluated separately, and as will be shown, all algorithms achieve a true-positive detection of at least 80%.

8.4.1 Assessment and Evaluation Criteria

Before a discussion and evaluation of the system could be made, it has to be made clear how the testing is performed. Furthermore, a discussion on what constitutes an acceptable result have to be made.

In the testing of the prototype system, two different evaluation methodologies are used to evaluate the detection algorithms. The first is testing performed on a controlled data-set in simulation, while the second method of testing is done in real-time, on the road where the events are present. However, note that all data used to determine the algorithms detection rates also include other various events aside from the event in question. Some of them are set to be detectable, others are not, such as manhole covers and raised intersections. Refer to Section 6.2.2 for an extended list of test-track features and Section 4.1.1 for a description of events set to be detectable.

The first type of testing, hereafter referred to as the *controlled tests*, are run on the custom developed simulator. The simulator is configured to be fed with the previously collected data, as summarized in Table 6.1, before starting the simulation. Once the simulation is completed, an output is generated containing all the detected events from the routes inputted. A comparison is than carried out by comparing the algorithmically detected events as produced by the program to the manually collected ground truth. Any differences between the detected events and ground truth will be noted.

In contrast to the first type of testing, the second method involves physical driving and a near real-time detection of events. While the driving tests are performed on the same routes as from where the control data sets were derived, clearly the input data to the algorithms will not be identical to the collected drive data. This holds true even though the same vehicle and smartphone is utilized as in the data acquisition, a VolksWagen Golf with a Samsung Note 4 smartphone. The reasons are that many factors can contribute during driving yielding a similar, but non-identical data-sets, such as traffic and a subtle different driving style from previous runs. These live data tests, referred to as the *real-time tests*, are done to ensure objectiveness, in a sense that the developed detection algorithms are not unintentionally tailored to the collected data. Once the drives are performed, analysis will be carried out similarly to the controlled tests, the logged output checked post drive will be compared to the collected ground truth with any differences noted. Most favorably for the detection algorithms, the events detected in the controlled tests should also be detected in these real-time tests.

However, neither of the two evaluation methods will be weighing significantly more than the other in the conclusions drawn, if clear visually recognizable event patterns emerge. Hence, even if the said event is recognizable only by the controlled test but not in the real-time test, the fact will not signal that the event is undetectable in an uncontrolled real-time environment. The reason is that as long as there exists a unique fingerprint, which is visually clearly distinct for the different type of events, machine detection is possible with more fine-tuned algorithm parameters. If such a scenario become apparent during the evaluation, a discussion will follow.

The presented detection algorithms will be discussed in terms of true-positives, false-positives and events missed. True-positives are events that are detected within five meters from their corresponding ground truth item, while false-positives along with missed events are grouped together and collectively called as erroneous events. No detection algorithm is expected to be completely error-free, and thus, a combination of the aforementioned attributes will constitute the final evaluation. However, note that as a cloud is conceived in the system architecture, it might additionally mask some erroneous events as a result of its filtering and aggregation. Still as mentioned in Chapter 5, the cloud is considered as an external entity and will not be part of further discussions. On the point of the cloud, it is just noteworthy to know that the results achieved here could be further improved without the cost of modifying the developed local detection algorithms.

8.4.2 Speed Bump Detection

The testing methodology utilized in evaluating the detection of speed bumps, is performed in accordance with Section 8.4.1. Two different evaluation data-sets are leveraged, used to derive the implemented algorithm detection rate. The first data-set is acquired from the previously collected routes in the data acquisition phase, while the other set is from a live test-drive. From these data, 142 speed bumps were totally passed, with an identical distribution between the two batches of collections, 71 and 71 events respectively.

8.4.2.1 Data-set Features and Credibility

The acquired traits leveraged in the evaluation of speed bumps contain a diverse variety of speed reducing obstacles. Not only are the speed humps present in the collected data at different sizes, ranging from smaller to larger ones, but they also have various incline levels, altering their detectable signatures. Furthermore, as means of prevailing traffic conditions, the speed reducing obstacles were also passed at different speeds, in addition of experiencing the humps from both driving direction. Consequently, by the previously mentioned data-set highlights, it is considered that the efforts made to collect the diverse data resulted in a realistic trait collection, allowing for an accurate evaluation to be carried out.

As a final remark on the data-set; note that these results were obtained with unaltered traits, except for the removal of one speed bump event, which was so minuscule that it did not cause any recognizable vehicular vibration. Because of its insignificance and dysfunction as a speed reducing obstacle, it was implicitly removed from the results presented in the forthcoming section.

8.4.2.2 Evaluation

Studying the results from which the detection-algorithms reported a speed bump event, a detection of 114 out of the 142 events were achieved. Thus, the correctly marked events resulted in a true-positive detection accuracy of approximately 80%. Moreover, 12 erroneous events were additionally reported (8%), and 28 events were missed (20%) by the implemented algorithm. In Table 8.1, the results are summarized.

Table 8.1: Speed bump detection rate.

Total Events	True-Positive	Erroneous	Missed
142	80%	8%	20%

As expected, in the majority of the correctly marked events (80%), a clear deceleration and acceleration could be observed, in addition to the detection of the characterizing humps. Consequently, most of the time the speed bump was passed right in the valley that is produced when plotting the logged speed over time in a chart. However, if the sequence of speed change did not develop in a pronounced way, by means of heavy traffic forcing the driver to have an already low speed, the fallback method could be employed to get complementary speed information - the accelerator pedal. Almost exclusively on the collected traits, the accelerator pedal position state dropped and fell close to the minimum as the driver approached the speed hump, signaling the intention of slowing down. Thus, even if the speed did not change in a definite way, the intention could be captured by the alternative sensor. Therefore, due to the aforementioned case, the vehicular data indeed provides complementary information useful in confirming the speed reducing obstacle event.

The cause of the miss-labeled events (8%) could be deduced to multiple clues sharing similarities with speed bumps, ultimately misleading the detection implementation. For example, some road anomalies stretched across the width of road, causing recognizable accelerometer patterns with minimal x-acceleration. Moreover, as the vehicle was slowing down just prior to the obstacle and accelerated afterwards, the expected behavior was similar to a speed bump which mislead the detection algorithm. Nonetheless, the aforementioned case is considered uncommon by means of its low rate.

One of the main contributors to the fact that some events were missed (a total of 20%), was found to be caused by driving to slow over the speed hump. As the forces at play heavily depends on the speed involved, a few events did not exercise enough forces on the accelerometer to signal a possible speed hump. However, as suspected, in the majority of the events a clear declaration could be observed, followed by an acceleration after the speed bump. On less strict detection implementations, events meeting the criteria of retardation and acceleration with a small deviation in the z-acceleration, could be let trough as a possible speed bump event.

As concluding remarks on the use of vehicular sensors, by means of that the majority of events had the speed variable at play, it is established that vehicular sensors have an impact on the way the detection could be carried out. Moreover, the accelerator pedal position sensor more often than not indicated the intended speed, before the speed meter gave any indication. Thus, the supplementary sensors enabled another dimension of sensing, beneficial in the detection of events by either confirming or rejecting events. Therefore, the proposed approach is regarded as a feasible mean to detect speed bumps.

8.4.3 Pothole Detection

Evaluation of the pothole detection is accomplished with two different data-sets, as mentioned in Section 8.4.1. The first set contain 23 potholes from the previously collected data while the second set is derived from the live testing performed on the same routes, accommodating 18 potholes for a total of 41 relevant events. The attentive reader might immediately observe that there is an unbalance in the events from the two data-sets. The cause of the imbalance is that some road inconsistencies got repaired between the two runs, yielding different number of collectible pothole traits. However, the fact will not negatively affect the hereafter presented outcome by means of the general patterns deducible from the other acquired cases.

8.4.3.1 Data-set Features and Credibility

The collected traits utilized for the evaluation contain a variety of potholes. A few large potholes are passed, however, the majority of the events are in the smaller scale. The deepest pothole is around 7 *cm* deep, while the others are shallower. Besides, during acquisition, different speeds were also observed during the event, capturing the altered signal features experienced at various speeds. Therefore, on the grounds of the previously mentioned data-set features, the acquired data-sets containing the potholes are assumed to be a faithful representation of the common anomalies encountered throughout a typical drive. Likewise, the evaluation is thus expected to be valid.

8.4.3.2 Evaluation

Testing the developed implementation is carried out by adopting the previously found most favorable threshold in addition to leveraging the vehicular sensors. The detection rate for potholes marked by the detection algorithm is 88%. Moreover, eight erroneous markings (19%) and five events were missed (12%) by the implementation out of the total of 41 events. The aforementioned detection rates are compiled in Table 8.2.

Table 8.2: Pothole detection rate.

Total Events	True-Positive	Erroneous	Missed
41	88%	19%	12%

As expected, post-checking the events marked as potholes which indeed were potholes (88 %), a clear deviation in x and y-acceleration could be asserted. Moreover, similarly to the speed bump event, a deceleration and acceleration intention could be observed as passing the event. The fact of the speed change confirmed the majority of the potholes, informing that leveraging the vehicular sensors, such as the accelerator pedal position and speed meter, certainly is beneficial in capturing the anomaly.

However, no road is smooth, as can be observed from the previously presented detection rates. The main cause of the erroneous markings (19%) is by means of other road anomalies causing similar patterns, picked up and recognized as potholes by the algorithm. The most common occurrences are sunken in drain pits and manhole covers, which shares a resemblance to pothole by means of its depressed appearance. Thus, the importance of choosing an appropriate threshold yet again becomes apparent in an effort to disambiguate the different event types. Moreover, the question arises if the deep road anomalies that are not potholes should be counted towards anomalies to report for the road maintenance operators to repair or not, and if they should be counted towards the result presented. In this evaluation, it was decided that they should be disambiguated, and therefore, the results seen are presented accordingly.

The missed events (12%) can be attributed to that each pothole is unique. The detection of an abnormal acceleration deviation is a prime characterization of a pothole. However, the depth of the pothole is one of the largest contributor to the strength of the event as logged by the accelerometer. Deeper anomalies cause a larger deflection, and is thus easier to detect. The ones which did not get detected, where too small to case any major deflection, and therefore they were not discriminated from the normal occurring accelerations. However, by means of the expected delicate play between the speed observed, deceleration and then acceleration as passing the event, the thresholds could further be lowered during the moment of lowered speed, similarly to the suggested method for speed bumps. While the aforementioned approach allows the capturing of more events, it also increases the possibility of including some erroneous events. Thus, the benefits and drawbacks carefully needs to be considered on a case by case basis.

Furthermore, before a conclusion could be presented, a note must be made regarding the objectiveness of potholes. All other discussed events are clear in what constitutes the event and what not. However, because of the fact that every pothole is unique, it is more challenging to define the set of events that resembles an *actual* pothole. Comparison is therefore also cumbersome with other implementations and results, because of the not so clear defined meaning and the possibility of subjectivity in the interpretation. Moreover, the data used as input to the detection algorithms might additionally effect the detection outcome, as especially true for potholes. Depending on the used data-sets inclusion of other similar events, such as manhole covers, different results could be achieved.

In conclusion, the achieved detection rate is not as high as some of the related work implementations, however, that is beside the two core points - to determine if leveraging vehicular sensors do aid the detection algorithms and if potholes can be detected by simple means. In the collected data, that indeed is the case. It has been shown that pothole detection is possible by simple and efficient means capable to run real-time on common smartphones. Moreover, it is evident that vehicular data support the detection, providing an additional sensing dimension. The fact is, in the collected data, a clear indication of an inconsistent road segment in addition to the sharp deviation in the x and y-acceleration, is the sudden release of the accelerator pedal. Therefore, leveraging the vehicular sensors is deemed to be beneficial for pothole detection.

8.4.4 Traction Loss Detection

The assessment of the employed detection method capable of detecting traction loss, is realized in consensus with the rest of the discussed events and Section 8.4.1. First, data as gathered by the data acquisition software is used, before the second judgement is done in a live setting, driving on the same routes as the collected data. However, as prevailing weather conditions does affect the possibility to forcefully introduce traction loss, most of the traction loss events are induced on unpaved (gravel) roads, while some on regular roadways on snowy conditions. In the data used, a total of 14 traction losses are produced with an equal split of previously collected data to live testing.

8.4.4.1 Data-set Features and Credibility

The data-set utilized for the evaluation of traction loss detection contain, as mentioned, an assorted set of traction losses produced on different surfaces, such as on graveled and snowy roads. It is argued for that by inducing traction losses on different surfaces, the essence of the event could be captured more thoroughly by means of the different prevailing condition. Thus, the act of gathering the events on a variety of road conditions implies that a respectable data-set is leveraged. Hence, the results achieved are assumed to represent a lifelike scenario, allowing for a trustworthy evaluation to take place.

8.4.4.2 Evaluation

The results achieved by the algorithm are convincing, successfully detecting 13 of the 14 different traction loss events, yielding a true-positive rate of around 93%. Thus, only one of the events was missed (7%), while no erroneous events was reported (0%). In Table 8.3, the outlines of the detection rates can be observed.

Table 8.3: Traction loss detection rate.

Total Events	**True-Positive**	**Erroneous**	**Missed**
14	93%	0%	7%

Detection of traction loss is a straight-forward process, capturing the essence of the event by analysing the discrepancy between the produced motor revolutions per minute (rpm) and the vehicular speed. Not only is the approach simplistic in its design, it also achieves a great detection accuracy (93%). Therefore, by means of the leveraged vehicular data, traction losses could be detected.

However, studying the logs produced revealed that the one undetected event (7%) was left out because of too little motor rpm deviation, not triggering the rest of the detection algorithm parts. Hence, the miss-match between the speed and motor rpm was not determined as the detection was aborted by means of not fulfilling the rpm threshold, and therefore no event was reported. While lowering the detection threshold could be seen as an alternative, it however introduces erroneous events. Thus, the originally determined threshold is deemed to be the more optimal value, allowing zero faulty events.

In conclusions, on the grounds of the presented detection rates, the method to detect the discussed traction loss type, is a viable approach. Moreover, a notable observation regarding the evaluation is that no apparent correlation between the accelerometer and traction loss could be found, denoting that this classification depends on vehicular data.

8.4.5 Anti-Lock Braking System (ABS) Engagement Detection

The assessment of the implemented ABS detection method is carried out in the same fashion as with the former detected events. Refer to Section 8.4.1 for more information. The algorithm is tested against two data-sets, one set is from the collected data containing four ABS events and the other set is from the live testing, containing six caused ABS incidents. The entire set thus include ten relevant events. The observant reader might immediately recognize the uneven distribution of the data-sets, compared to previous events evaluations. The reason for the unbalance is because of the weather condition during data acquisition simply took a quick turn for the warmer, limiting the possibility of collecting ABS traits on snowy roads. However, the additional live-testing of six other events where successfully induced during a short and temporary period of snowy weather at a later stage. Nevertheless, the low sample size should not alter the outcome of the evaluation by means of the physical workings of the ABS. Each of the four collected logs showed clearly recognizable patterns - the modulation of the ABS system. Thus, by the aforementioned fact, the results achieved here are still assumed to be correct.

8.4.5.1 Data-set Features and Credibility

The input used to evaluate the ABS detection consists of different traits where the ABS was introduced. To create a diverse data-set, different starting speeds were used before a sudden braking maneuver was initiated, causing the engagement of the system. By means of the speed differences, various length of the ABS workings could be captured. Moreover, causing the activation of the system in a variety of scenarios, permitted a range of different feature alterations to be cough. Hence, the utilized data-sets are assumed to be representing common occurrences of ABS engagement, allowing for a fair evaluation of the event recognition implementation.

8.4.5.2 Evaluation

Out of the total of ten ABS events, two events was missed (20%) by the detection algorithm and no erroneous events were reported (0%). Thus, the detection accuracy reaches the 80% mark. In Table 8.4, the results obtained are illustrated in a tabular format.

Table 8.4: Anti-Lock Braking System (ABS) detection rate.

Total Events	True-Positive	Erroneous	Missed
10	80%	0%	20%

The essence of the ABS workings could be captured by monitoring the accelerometer sensor and complementing the view with vehicular sensors, allowing for a detection of eighth out of ten events (80%). Therefore, the accelerometer plays an important role in the detection of the event by its ability to register the oscillations as caused by the ABS hardware. However, the achieved accuracy would not have been possible, if the event could not have been confirmed as a heavy braking event through the use of the other vehicular sensors. Furthermore, by executing the detection algorithm only when a sharp deceleration is occurring, valuable battery power could be saved. Thus, leveraging the vehicular data to detect ABS, or more specific, a heavy braking, proves to be beneficial.

Upon inspection, the reason that the two events went undetected (constituting 20%) was because the detection threshold was set too high, rejecting the y-signal as part of occurring oscillations. Therefore, the actual events did not trigger the recognition. However, the possibility would have existed to lower the threshold, with the prospect to introduce some erroneous events. Testing confirmed that decreasing the threshold just enough to enabled recognition of the previously unseen events, cost in terms of the introduction of two miss-labeled actions in the collected ABS traits.

However, as a result of prevailing weather conditions, the hypothesis of lowered false-positives with regards to leveraging the current ambient air temperature, could not be thorough verified. During data acquisition data on icy roads were collected. However, in the live testing a warmer climate was perceived. While the results might seem indecisive because of the aforementioned circumstance, the fact remains that ABS can be triggered by less effort in temperatures blow the freezing point. Hence, while the assumption is not confirmed by analytical means, it is still expected to hold true.

Concluding, based on the attained results and the observation that the ABS workings could be captured by simple means, the approach is believed to be applicable. In addition, the vehicular sensors aid the detection by confirming a sudden braking maneuver and enables the detection to only execute when a abrupt braking is noticed, preserving battery.

8.4.6 Engine Stall Detection

Evaluating the detection rate of the implemented method recognizing engine stalls is realized in harmony with Section 8.4.1, leveraging two different data sets. In the first set, acquired from the data acquisition phase, eight engine stalls were produced. Moreover, the live-testing similarly contains eight different engine stalls for a total of 16 between the sets.

8.4.6.1 Data-set Features and Credibility

In the employed data-sets, the nature of the produced stalls is either 1), setting the gear too high, halting the motor immediately or 2), miss-matching the harmony needed between the accelerator pedal and clutch during shifting, suspending the motor. It is notable that in the second case, the motor is ceasing to run in less abrupt way compared to the first circumstance. Moreover, it is believed that the aforementioned occurrences are the most common causes in manual geared vehicles. Thus, the data-set constitutes a realistic representation of the expected stalls, allowing for a creditable evaluation.

8.4.6.2 Evaluation

In total, 16 out of 16 events were successfully identified by the implemented detection method, reaching a true-positive detection rate of 100%. Hence, no erroneous or missed events were observed. The achieved detection rates are organized in a tabular format in Figure 8.5.

Table 8.5: Engine stall detection rate.

Total Events	True-Positive	Erroneous	Missed
16	100%	0%	0%

The results achieved are not unexpected, based on the fact that engine stalls produce a distinct pattern, which is effortless to detect. Moreover, different type of engine stalls produced the same type of sensory behavior in the system, unlike other events, enabling accurate and predictable detection.

Testing was also conducted by terminating the engine in the *normal* way, i.e. by turning off the ignition. The detection implementation did not get mislead, and therefore, no erroneous events were reported (0%).

As a result of the presented detection rates, engine stall detection is viable trough the use of vehicular sensors via the OBD connection. Furthermore, the employed method is light on resources as no heavy operations are leveraged, making the detection method especially suitable in constrained devices, such as smartphones.

8.4.7 Door Slam Detection

Evaluation of the close door recognition is carried out with two different collections of data-sets, in consonance with the rest of the detectable events and Section 8.4.1. Firstly, testing is done against the collected data, containing 15 different door slams. Secondly, another 15 door slams are induced in a live setting, with the same detection algorithm run in a real-time manner. Therefore, a total of 30 event are produced.

8.4.7.1 Data-set Features and Credibility

The traits exploited for the evaluation incorporate various close door events with different strengths. Some of the doors are slammed shut with the strength expected, while others are closed with less or more force applied. Moreover, all four doors are closed, and thus, with varying distance to the smartphone containing the vibration detecting accelerometer. This variety in the data-sets is produced to create a realistic evaluation, which the data-sets are assumed to be. Moreover, by means of the leveraged events, the evaluation can be considered rational.

8.4.7.2 Evaluation

Out of the total 30 tested events, one erroneous event was reported (3%) and 27 events were successfully detected (90%) as true-positives. Therefore, three events were missed (10%). The attained results are observable in Figure 8.6.

Table 8.6: Door slam detection rate.

Total Events	True-Positive	Erroneous	Missed
30	90%	3%	10%

The majority of the door slams could be recognised (90%) via the means of asserting that the vehicle is stationary and determining that an acceleration spike occurred. However, after observing the logs generated, three undetected events (10%) got undetected by reasons of the close door action causing too little vibrations, not triggering the minimum threshold required. Particularly, they escaped the detection because the doors were closed more gently. In addition, one event of the recognized actions was erroneous (3%) by means of the engine starting, generating similar fluctuations on the accelerometer as a real event.

The importance of choosing a satisfactory threshold is apparent again. However, in this case, choosing a lowered threshold would not be possible, as other small fluctuations could then trigger an erroneous detection, such as people moving in the vehicle when it is stationary. Therefore, the chosen cutoff is deemed to be more suitable for the task, then a lowered one.

Summarizing the outcome, the total detection accuracy counting data from both the live-testing and the previously collected data is 90%. Thus, based on the results received, if a door slam event is reported, it could be assumed that indeed doors were closed with a high degree of confidence. Therefore, the approach proposed is deemed to be both a viable and a low overhead mean to detect door slams, made possible by asserting that the vehicle is stationary via the vehicular sensors.

8.5 Triggered Sensing Performance

In the proposed system, the algorithm calculations to detect road events are performed on commodity smartphones, enabling wide spread usage. However, by the nature of portable devices, only a limited battery capacity is available. Thus, it of great interest to determine the endurance of the detection-system and the viability of the proposed battery saving techniques.

Firstly, the assessment and evaluation setup is presented, before the triggered sensing techniques are evaluated. As will be presented, the implemented triggered sensing approaches certainly help prolonging the road condition detection, by approximately 15%.

8.5.1 Assessment and Evaluation Criteria

Determining the impact of running the road condition detection-system on-top of smartphones is involving, and not a straight-forward task. Battery consumption heavily depends on the amount of applications running and their interoperability, number of task spurious waking up and the operating systems ability to suspend active functions, conserving battery. In an effort to isolate the detection-systems impact, the smartphone is configured with no background tasks running during battery evaluation, excluding their possibly variable influences. The same smartphone, a Samsung Note 4, is used as for the rest of the detection-system evaluation. Moreover, to make testing feasible and prevent testing against an actual vehicle, the evaluation is conducted by converting a computer to an OBD Bluetooth transmitter. An example of a program that emulates the OBD command-set is the configurable *obdsim* [36]. The aforementioned software is configured to send the same data over a period of time, enabling deterministic behavior. Similarly, the accelerometer in the smartphone is likewise fed with mocked data. All evaluations are performed three times, and the results presented are implicitly averaged and rounded to the nearest minute mark.

8.5.2 Evaluation of the Proposed Battery Saving Techniques

The different cases evaluated, are the ones deemed to be the main battery saving contributors, building on the triggered sensing technique. At first, GPS triggered sensing is evaluated before secondly, triggered sensing is applied to the other sensors, lowering their sampling speed and excluding a few sensors, in an effort to save battery.

The *GPS (positional) triggered sensing* is evaluated by performing a test that captures the essence of the triggering. The detection algorithms are run at full speed with all sensors operating at their maximum refresh rate, except for the altered behaviour of the GPS. The positioning sensor is only periodically turned on, simulating the expected behavior of only enabling the positioning sensors when needed, i.e. by triggering on detected events. More specific, the GPS is configured to be enabled approximately 10% of the testing duration.

Next, *sensor triggered sensing* is evaluated. To determine if triggered sensing when applied to the accelerometer and vehicular sensor have any bearing, a similar test as with the GPS case is performed. Employing the triggered methodology, less sensors could be polled at uninteresting situations and other sensors sampling frequency could be lowered, and in theory, conserve battery. To test the hypothesis, the test case is implemented by letting the detection-algorithms run on less produced data by means of lowered sensor poll rate, in addition to polling less vehicular sensors simulating a triggered sensing of the sensors.

The best achievable case is with the both the *positional and sensor triggering sensing* enabled. This result is accomplished by enabling triggered sensing on all the sensors, specifically by combining both previous triggered tests cases, in an effort to maximize the road anomaly detection stamina.

Furthermore, obtaining the *baseline* is also of interest, enabling a comparison to be carried out. The baseline is measured by having the detection-system enabled with sensors sampled at full speeds, with the GPS constantly on, as it would if no measures were taken at all to conserve battery. This sets the control for the evaluation, and is expected to show the worst road condition analysis endurance.

The results achieved based on the priory described cases, namely the GPS and sensor triggered sensing, can be observed in Table 8.7. As can be seen, having the GPS mostly off, in this case 90% of the time, yielded not unexpectedly, the possibility of prolonged road condition detection. Similarly, enabling triggered sensing on the other sensors, lowering their sampling rate and reducing the number of polled sensors, had a small but positive impact. Combining these two techniques, the maximum achieved detection was 4 hours and 1 minute, compared to the baseline of 3 hours and 29 minutes, an increase of approximately 15%, or in this case 30 minutes. Thus, by means of the achieved results, triggered sensing is beneficial and should be employed.

Table 8.7: Triggered sensing and its improvement regarding lowered battery consumption. Endurance denotes the operation time achieved by the detection-system using the mentioned battery saving techniques. The sensors tab indicates the kind of sensors employed in the given triggered sensing category.

Type \ **Sensors**	**GPS**	**Other Sensors**	**Endurance**
Baseline	✗	✗	3h:29m
Positional	✓	✗	3h:42m
Sensor	✗	✓	3h:36m
Positional and Sensor	✓	✓	4h:1m

8.6 System Evaluation and Feasibility at a Broad Level

Up until now the evaluation criteria have been presented, the collected data-sets argued for as being correct and different smartphone placements tried. Moreover, each detected event were demonstrated and discussed separately, illustrating their effectiveness with the two different type of data-sets, both derived from the selected routes driven. Additionally, the triggered sensing techniques have likewise been evaluated. The remainder of this section is dedicated for formulating general remarks surrounding the detection-system, its feasibility and observations made throughout the development.

8.6.1 Discussion on the Detection of Road Events

The main road characterization sensor is the accelerometer, capable of detecting the different vibrations caused by the road and its anomalies. Even in systems such as the one proposed, where the accelerometer is augmented with vehicular sensors, the accelerometer is still performing an important role. However, as shown, valuable information could be derived from other sensors, which to varying extent complement the accelerometer, enabling less false-positives, better accuracy and a more comprehensive view of the event in question. Some events like traction loss would be undetectable, or at least considerably more challenging to detect without the extra available vehicular sensors. Other events, such as speed bump detection, can benefit of the added sensors to detect the bumps with higher accuracy. In pothole detection, the element of surprise can be captured by reasons of the extra sensors accessible in addition of offering a greater detection rate. Moreover, even if the additional sensors would not directly benefit the detection percentage, they can be used to enable control of the algorithms if so desired. Two prime examples are speed bumps and potholes, where the recognition algorithms could be configured to only execute at full capacity if a continuous deceleration occurs indicating a probable approaching event. Thus, by leveraging a form of additional sensing, battery usage could be lowered enabling prolonged road condition detection use. Concluding the previous discussions, all discussed events in this thesis are aided by the use of vehicular sensors to a varying degree. Table 8.8 depicts the detection accuracy of the recognized events, as a brief summary. Note that the achieved numbers could further be improved without the cost of modifying the local algorithms, if the conceived cloud would be commissioned to do event aggregation.

Table 8.8: Outlining the achieved detection rates of the developed algorithms. The detection methods are supplied with the data collected during the course of this thesis.

Event	**Detection Rate**
Speed Bumps	80%
Potholes	88%
Traction Loss	93%
Anti-Lock Braking System (ABS)	80%
Engine Stall	100%
Door Slam	90%

In this thesis, it has been shown that the suggested triggered sensing approaches allows for a sustained road condition detection of approximately four hours, making the system viable. Furthermore, as one of the battery saving approaches relies on having the GPS sensor disabled for the majority of the time, speed information is lost, as it cannot be derived from the disabled GPS sensor. Nonetheless, by means of that vehicular data is leveraged, accurate speed information could be obtained through the use of vehicular sensors. Hence, parts of the triggered sensing require the use of another mean of obtaining the speed, in this case from the vehicle. Thus, the aforementioned case provides another incentive of the benefits to leverage vehicular data. By this, the idea of GPS triggered sensing has been complemented and evaluated, which was deferred as future work in the paper by Mohan et al. [5].

As shown and discussed, vehicular sensors benefit the system in numerous ways. Though, in some cases, the detection methods augmented by the extra sensors, are more prone to the human factor. Before events such as potholes and speed bumps, deceleration is expected. However, the retardation fact could be altered with a with different driving style, such as an acceleration instead, misleading the detection algorithms, yielding wrong assurance levels on the detected events. Nonetheless, the accelerometer is still the main road condition sensor, enabling event recognition, even if the usage of vehicular sensors are un-tuned to the current driving style.

Throughout the development of detection methods, constant decisions regarding the different parameters affecting the detection rate, had to be made. Some parameters enables detection of some obscure, otherwise not detectable events, with the cost of additional false-positives. Tuning the parameters in the opposite direction instead, yields less total detected events, however, with a higher accuracy. A prime example describing the challenges, is the detection of potholes, because of their varying characteristics, such as depth and form. The question of where to draw the cut-off line, rejecting events as non-potholes, arises in the effort trying to maximize true-positives. However, because of the events unpredictability, it is impossible to provide one threshold functioning equally well in all possible scenarios.

The ideal solution to the different road surfaces, driving styles and conditions, would be self-adjusting algorithms. Algorithms that calibrate themselves to the current situation, would eliminate the need for manual calibration, otherwise advised for each road type, vehicle and driving style.

Nonetheless, the results show the fact that augmenting the detection algorithms with vehicular data is beneficial. In the paper by J. Eriksson et al. [4], the authors mention the existence of unchecked conditions, "[...] error sources under uncontrolled conditions". Some of these acknowledged conditions include closing doors, passengers accidentally hitting the inside of the vehicle while accommodate their legs, and users taping a beat on the dashboard. These aforementioned ungoverned events are problematic, as they could cause accelerometer readings similar to other events, yielding erroneous classifications. One advantage of the proposed system in this thesis thus become apparent, that a broader view of the current state could be captured by means of the extra vehicular sensors, in addition to its capability to detect a wider range of events. Door slams could easily be rejected (and detected) as show, and the other mentioned uncontrolled conditions could be blacklisted by the means of the additional sensors. As an example, detecting potholes at higher speeds with the accelerator pedal pressed deeply, and thus with the intention to accelerate, is unlikely, and the event could therefore instantly be rejected. Furthermore, accelerating through a speed bump, as sensed by the pedal position, is also improbable, enabling immediate event purging. By these means, false events could already be stopped at their source, instead of being filtered out in the aggregation and clustering done at the cloud. Thus, less false events are needed to be transmitted over cellular connectivity and less data is handled at the cloud, yielding a more efficient system.

8.6.2 An Observation around the Collected Data

One of the challenges in vehicular sensing experiments, as highlighted multiple times, is the gathering of the ground truth. In this thesis, data collection was performed only on known routes with the author present, ensuring creditable data. Please refer to Section 8.4.1 for a discussion on why the employed method is accurate. However, one slightly unexpected aspect during the manual analysis of the data, have been the ease of identifying the actual events once plotted with all the logged sensors.

Without looking at the GPS positions of the logged data, the majority of event causes and locations could be derived by only considering the plot. Moreover, despite randomizing the acquired trait names which contain main feature tags of the logged routes, in addition with the GPS coordinates hidden, each drive could nonetheless successfully be identified with many of its features. Plotting the vehicular speed in addition to the acceleration pedal position and the accelerometer data, made the events visually detectable, compared to just charting the accelerometer data.

Having knowledge of the routes and participating in the data acquisition clearly have its benefits. Thus, by the previous reasoning, the author encourages the employed ground truth marking in future vehicular sensing experiments. Furthermore, the proposed method is expected to be quicker compared to manual walking as suggested by Strazdins et al. [8] for a reasonable road size sample.

8.6.3 Remarks on other Plausible Events

Few other events and observations were made during the manual data analysis. In this short section, the observations are briefly mentioned and explained for the interested reader. Note that to no automated detection methods where developed for these events, although possible.

Firstly, shifting is detectable in the set of collected data by means of relying on the vehicular sensors, without access to current gear information. Changing gears involves three phases from the driver's point of view, engaging clutch when a high enough motor rpm is reached, changing gears and then accelerating. Relying on the OBD connection, the motor rpm and the speed sensors could be accessed, in addition to the acceleration intention (accelerator pedal position). These three sensors together effectively capture the essence of the shift event, as the driver releases the accelerator pedal to clutch, shift and then press the accelerator pedal again, gaining speed. Anyone with driving experience should be able to clearly identify when the driver is changing gears studying Figure 8.2. However, as seen in the figure, this only provides indication of that a gear shift probably happened. Although, by observing each shift event throughout the drive, the current gear could most likely be derived.

A second observation that can be made in the set of data, is the detection of passengers leaving or entering the vehicle. While this has no found significance in the system, as door slams are already detectable, it is nonetheless interesting. As the doors open, unhooking from the peg holding the door shut, a small vibration is caused which is picked up by the detection-system. Then, as the passengers leave or enter the vehicle, modest vibrations increase the average baseline acceleration, indicating people moving in the vehicle. Moreover, it is also possible to confirm that the door indeed was opened by the detection of door slams, which as shown in Section 8.4.7, have a high true-positive rate.

Thirdly, during one of the acquisition routes, a heavy braking caused the smartphone which was collecting data to fly forward before hitting the end of the leg compartment. Not unexpectedly, the heavy movement caused significant disturbance to the accelerometer readings. However, observing the y-acceleration, a detectable pattern emerged. Upon braking, a sharp deceleration could be detected in the ac-

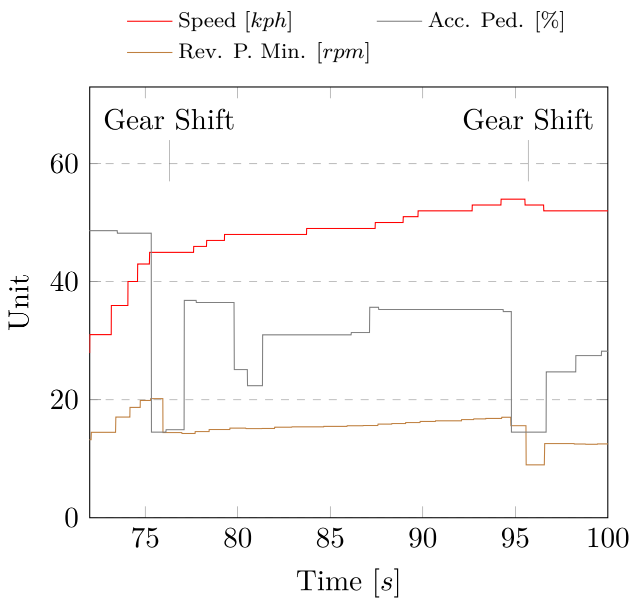


Figure 8.2: Another detectable event; shifting gears. Two different gear changes can be observed, one around the 75s mark and the other at 95s.

celerometer reading. Then, as the smartphone started to fly forwards, acceleration could be observed. When the device hit the end, a sudden deceleration occurred yet again. The pattern observed reassembled an ∽-shape. Detection should therefore be possible and straightforward. One possible use-case of the event could be as an indicator of a probable vehicular crash sending the smartphone flying, if the forces at play are detected as strong enough.

8.7 Notes Regarding the Required OBD Dongle to Acquire Vehicular Sensory Readings

In both the data acquisition and evaluation, a OBD dongle manufactured by OBD Link was used. The claim is that their proprietary OBD interpreter microchip inside the dongle is capable of achieving faster speeds than other similar devices containing the widely used ELM327 interpreter. The ELM327 equipped dongles advantage is that they can be acquired significantly cheaper. To determine if any difference exist in terms of their refresh rate, under the same circumstances, their maximum update frequency was determined per polled sensor. The results can be observed in Figure 8.3, showcasing the maximum achieved update speed per used sensor. Not unexpectedly, the OBD Link dongle performed better in all cases compared to a no-name, probably knockoff dongle. However, looking at the range of 3-6 polled sensors which is in the scope used for this system, the difference in this context, while large, is without obvious and significant advantage. Hence, this indicates that a system consisting of a cheaply acquired OBD dongle is still a viable option for road analysis.

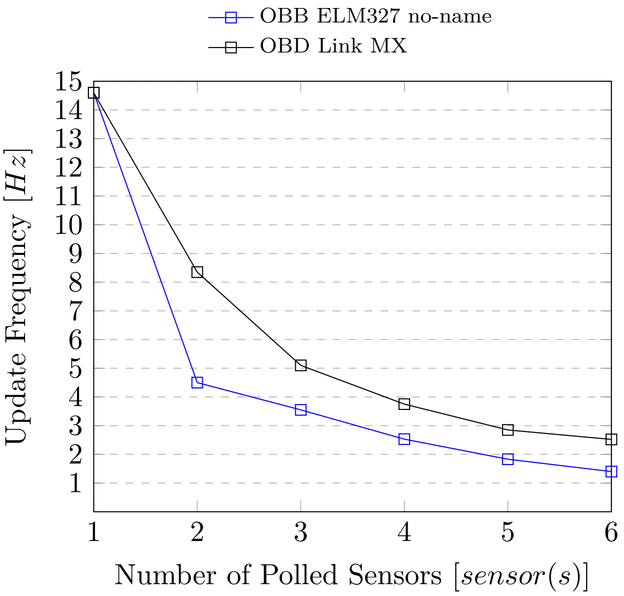


Figure 8.3: By this system achievable vehicular sensor poll rate using the tested OBD dongles.

8.8 System Implementation Status

The aim of the thesis is to implement a prototype system capable of detecting the said road anomalies in order to evaluate and draw conclusion on its feasibility. The concepts implemented are those which are required for sensing, detecting and analyzing road anomalies. This include means to detect road conditions, collect data for analysis and to finally test the data using a simulator. In addition, a prototype system capable of detecting the events in real-time on an actual device is similarly developed and gauged. All the aforementioned software is implemented and examined on a Samsung Note 4 Android device. However, because of time constraints and complexity, some concepts were left for future completion and implementation. Those concepts left partially unimplemented are the ones related to triggered sensing, especially some of the power-save features.

9

Conclusion

The most frequent used mean of transportation is transportation on roads. Hence, for every travellers' safety, it is of great interest to keep the roads in great conditions to minimize the risk of severe accidents caused by poor maintenance. A continuous monitoring of the roads thus becomes a vital part in the solution to proactively identify and fix each road anomaly before any casualties occur. However, overseeing the vast amount of roads available quickly becomes a non-trivial issue to solve. Deploying RSUs (Road Side Units) on every stretch is often not feasible and alternative solutions must be considered.

In this thesis, the idea of leveraging a smartphone in addition to the available vehicular sensors for road condition analysis was born and realized. By commodity hardware, the smartphone connects to the vehicle's diagnostics system enabling the retrieval of vehicular sensory data. The vehicular data is then sensor-fused with selected smartphone sensors, on the smartphone itself. The system consisting of commodity hardware, a smartphone, a vehicle and a way to interconnect these platforms, enables road surface sensing. Furthermore, one of the systems inherit advantage is that it is executed on commodity hardware, making the system low-cost with high availability, enabling deployment even in developing countries.

A smartphone augmented with vehicular data have been shown to be a viable solution to detect a variety of conditions. The proposed system successfully identified different road conditions, as validated both in a simulator and in a live setting. The events detected include potholes, traction loss and the engagement of the Anti-Lock Braking System (ABS). Several other sub-events, namely, speed bump, door slam and engine stall are similarly detected. It is also shown that road analysis augmented by vehicular data, has a positive impact on the detection rate, helping to reduce the number of false-positives encountered. Moreover, a few detected events would be undetectable without the addition of vehicular sensors, confirming that leveraging the supplementary sensors indeed is beneficial.

Furthermore, as a side effect of leveraging vehicular sensors, it can be observed that a prolonged detection endurance could be achieved from the smartphone's finite battery capacity. Different techniques akin to triggered sensing has been employed with good results, further dictating the viability of a system such as the one proposed.

Consequently, based on the results achieved, the system and the concept is deemed to be feasible as a low cost, low overhead and easy to implement mean to detect road events.

10

Future Work

The results achieved in this thesis are convincing in the context presented, however, a larger evaluation data-set containing more routes with other diverse features and events would be beneficial. Similarly, while the essence of the tested algorithms would most probably work on other vehicles and smartphones, more system-configurations needs to be evaluated. The author believes that if time permits, a higher detection accuracy is still achievable and maintainable on other routes and configurations, given access to more driving traits enabling algorithm fine-tuning.

As additional future work, the other openly available vehicular sensors not dealt with here, could be explored to determine their usefulness in the road analysis context. Likewise, the residual usable sensors in the smartphone could also be of interest. An example is to leverage the build-in smartphone microphone to additionally enhance the detection rate, as events in the same event categories often share similar sound characteristic features. Further leveraging the microphone, the detection algorithms might benefit from detecting honks, as a way to infer tumultuous situations to moreover increase the situation awareness.

This thesis presented battery-lengthening approaches in an effort to conserve battery life of the detection-system, prolonging the systems maximum usage time. However, further research into methods to lower the detection applications footprint in terms of battery consumption on the smartphone could be beneficial. A possibility is to utilize the fact that some routes are heavily trafficked. If the detection algorithms operate with a high true-positive probability, the detection of a road stretch could be divided among the participating drivers. Thus, each driver d, on a route with length l, could be configured to contribute only during its defined interval l/d. With a distributed solution such as the aforementioned one, each drivers' detection-systems active time could significantly be lowered, conserving battery.

Lastly, other applications than road condition detection could still be imagined by the system proposed in this thesis. Examples include collision detection and automatic emergency handling, global determinant of vehicle efficiency and emission characteristics depending on driving style, and finally, general road usage analysis which as of now is done manually.

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A

Appendix 1 - Pseudocode of the Detection Algorithms

In this appendix, all the developed detection algorithms are presented in a simplified manner using a pseudocode-like approach. For a textual description and evaluation of each algorithm, please refer to Section 7 and Section 8. The former section discusses the detection methodology in more details and the later evaluates the implementations and approaches.

This section is merely to enable quick referencing and look-up.

Detection Algorithm 1 Speed Bump

```
procedure SpeedBump($dm$)    ▷ The data model contains all sensory information
    $devZ \leftarrow isMediumZDeviation(dm)$    ▷ Determine if a significant $z$-deviation is in the signal
    if $speed \geq 5$ & $devZ$ then    ▷ If speed is acceptable and devZ is not empty
        if $isTwoConsHumps(dm)$ then    ▷ Determine if two successive humps are in the signal by means of 'area under the graph', indicating a possible speed bump
            if $devZ.eventLenght \geq 0.5s$ then    ▷ Event length should be around the observed normal speed bump value
                $assurance \leftarrow isSlowingDown(dm)$    ▷ The validity depends on if the vehicle is slowing down (throttle, speed, rpm)
                $assurance \leftarrow isMinimalXDeviation(dm)$    ▷ The validity also depends on the perceived $x$-acceleration
                return $(true, assurance)$    ▷ Speed bump detected with assurance level set
            end if
        end if
    end if
    return $false$
end procedure
```

Detection Algorithm 2 Pothole

```
procedure POTHOLE($dm$)                          ▷ The data model contains all sensory information
    $avgZ \leftarrow getZAvg(dm)$                ▷ Determine the current $z$-acceleration average
    $devZ \leftarrow getZDev(dm)$                ▷ Get the $z$-acceleration deviation from two consecutive readings
    $avgX \leftarrow getXAvg(dm)$                ▷ Resolve the average $x$-acceleration, as the event only affect one side of the vehicle
    if $(avgZ \geq thresh\ \ \&\ \ devZ \geq thresh$
      $\&\ \ avgX \geq thresh)$ then             ▷ Plausible pothole if all conditions are met
        $assurance \leftarrow isSlowingDown(dm)$ ▷ The event validity depends on if the vehicle is slowing down (throttle, speed, rpm)
        $assurance \leftarrow (avgZ, devZ, avgX)$ ▷ The event validity is also affected by the observed accelerometer readings
        return $(true, assurance)$               ▷ Pothole detected with assurance level set
    end if
    return $false$
end procedure
```

Detection Algorithm 3 Traction Loss

```
procedure TRACTIONLOSS($dm$)                     ▷ The data model contains all sensory information
    $devRpm \leftarrow isLargeRpmDeviation(dm)$  ▷ Probe for a significant rpm deviation is in the signal, if any
    if $devRpm$ then                             ▷ If devRpm is not empty
        $sgfntSpeedTs \leftarrow getSgfntSpeedTs(dm)$   ▷ Get the time of when sgfnt. speed increase occurred, if it did
        if $sgfntSpeedTs \neq -1$ then           ▷ If sgfnt. speed gain is noticed
            $lenght \leftarrow sgfntSpeedTs - devRpm.startTs$   ▷ Determine speed gain delay
            if $length > 0$ then                 ▷ If not instant speed gain, traction loss is observed
                $assurance \leftarrow length$    ▷ Event assurance depends on the observed rpm and speed mismatch length
                $assurance \leftarrow devRpm.amount$   ▷ The rpm deviation amount is also factored in to the assurance level
                return $(true, assurance)$       ▷ Traction loss detected with assurance level set
            end if
        end if
    end if
    return $false$
end procedure
```

Detection Algorithm 4 Anti-Lock Braking System (ABS)

```
procedure ABS($dm$)                                   ▷ The data model contains all sensory information
    if $speed \geq 5$ & $isConsHumps(dm)$ then        ▷ Detect if consecutive oscillations are happening utilizing a moving average technique
        if $isBraking(dm)$ then                       ▷ Check if sharp braking is occurring (throttle, speed, rpm)
            return $true$                             ▷ ABS detected
        end if
    end if
    return $false$
end procedure
```

Detection Algorithm 5 Engine Stall

```
procedure EngineStall($dm$)                                   ▷ The data model contains all sensory information
    $engineStallBehaviour \leftarrow motorLoadToMin(dm)$      ▷ Determine if the motor load is observed in a pattern going from heavy load to 0%
    if $engineStallBehaviour$ then                            ▷ If recognized engine stall behaviour
        $avgZAcc \leftarrow getZAvg(dm)$                      ▷ Probe the current $z$-acceleration average, should be minimal if engine stalled
        $speed \leftarrow dm.getSpeed()$                      ▷ Get the current vehicular speed, should be zero if engine stalled
        $rpm \leftarrow dm.getRpm()$                          ▷ Acquire the current rpm, should be zero if engine stalled
        if $avgZAcc \leq \mathcal{E}$ & $speed$ & $rpm$ then  ▷ If reported vibrations are less then a small error margin $\epsilon$, and the other conditions hold, the engine has halted
            return $true$                                     ▷ Engine stall detected
        end if
    end if
    return $false$
end procedure
```

Detection Algorithm 6 Door Slam

```
procedure DoorSlam($dm$)                          ▷ The data model contains all sensory information
    $devZ \leftarrow isLargeZDeviation(dm)$       ▷ Determine if a sharp $z$-deviation is in the signal
    if $speed \leq 5$ & $devZ$ then               ▷ If speed is small and devZ is not empty
        if $devZ.eventLenght \geq 0.75s$ then     ▷ Length should be around the observed close door value
            return $true$                         ▷ Door slam detected
        end if
    end if
    return $false$
end procedure
```