Chapter 1

INTRODUCTION AND OVERVIEW

The major focus of this thesis is to develop a low cost condition monitoring system for detecting misfire and monitoring the conditions affecting fuel efficiency of a vehicle.

The scope and motivation behind this work is presented in Section 1.1 followed by the causes and effects of misfire in Section 1.2. An overview of misfire and vehicle fault detection techniques are presented in Section 1.3 and 1.4. The problem definition is in Section 1.5 followed by objectives and challenges in Section 1.6. Section 1.7 presents the conceptual frame work followed by highlights of the work in Section 1.8. Section 1.9 presents the organization of the thesis.
CHAPTER 1 INTRODUCTION AND OVERVIEW

1.1 SCOPE AND MOTIVATION

The growing global economy resulting in an increase of annual global vehicle sales by 6% year on year as projected by the Global Auto Report of Scotia bank [1] coupled with the rapid economic growth of developing countries, with India and China in the forefront, has led to a large scale increase in demand for personal transportation systems mostly using internal combustion (IC) engines. According to a recent Society of Indian Automobile Manufacturers (SIAM) statistics [2], in recent years India consumes on an average 2.5 million cars per annum and is continuously growing at 20% to 25% year-on-year.

This increasing dependence on IC engines has led to a wide range of challenges demanding immediate attention. Undesirable emissions in internal combustion engines are of major concern because of their negative impact on air quality, human health, and global warming. Therefore, there is a concerted effort by most governments around the world to control them. Undesirable emissions include unburned hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NOx), and particulate matter (PM). Continuous monitoring of an IC engine is required to ensure optimum performance and to minimise load on the environment by restricting emissions to minimum possible levels. The world over, European Union (EU) emission standard is referred to as the benchmark and all efforts are directed to comply with the same. The evolution of EU emission standards over the years from 1992, presented in Table 1.1 [3] reflects the strong concern people have on tail pipe emissions. Starting from Euro 1 the total hydrocarbon, carbon monoxide and nitrogen oxides tolerated in the tail pipe emission has been drastically reduced to a large extent pushing vehicle manufacturers to implement latest technology and advanced engine control unit (ECU) to achieve the same.
A significant contribution to pollution is due to misfire in the engine cylinder that has to be closely monitored or else the emission norms cannot be met. In developed economies, installation of misfire monitoring system is mandatory but in developing economies like India, only the high end vehicles are fitted with this system due to cost considerations. This excludes a large population of automobiles from the grips of strict misfire monitoring and correction process. In addition to misfire there are a few other parameters that affect the vehicle fuel efficiency, they are low tyre pressure, chocked air filter and driving the vehicle under improper gear. A conscious attempt is made to develop a low cost vehicle condition monitoring system capable of monitoring all the above mentioned conditions with additional thrust on misfire detection, using engine block vibration signal.

The industries are moving towards a greener business model and many developing nations are focusing on innovative methods for cost effective implementation of greener technologies. These conditions motivate the research and development of an effective and economical Vehicle Fault Detection (VFD) system which can be implemented in all the engines manufactured the world over without any exclusion based on size or economic considerations.

<table>
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<th>Tier</th>
<th>Year</th>
<th>CO</th>
<th>THC</th>
<th>NMHC</th>
<th>NOx</th>
<th>HC+ NOx</th>
<th>PM</th>
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<tbody>
<tr>
<td>Euro 1</td>
<td>1992</td>
<td>2.72</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.97</td>
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<tr>
<td>Euro 2</td>
<td>1996</td>
<td>2.2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.5</td>
<td>-</td>
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<tr>
<td>Euro 3</td>
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<td>0.20</td>
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<td>Euro 4</td>
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<td>0.08</td>
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<tr>
<td>Euro 5</td>
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<td>1.0</td>
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<td>0.06</td>
<td>-</td>
<td>0.005</td>
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<td>Euro 6</td>
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<td>1.0</td>
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<td>0.068</td>
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<td>-</td>
<td>0.005</td>
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European emission standards for petrol (Gasoline) passenger cars and light commercial vehicles (weight ≤1305 kg) in g/km

Legend

<table>
<thead>
<tr>
<th>CO</th>
<th>Carbon monoxide</th>
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<tr>
<td>THC</td>
<td>Total hydrocarbon</td>
</tr>
<tr>
<td>NMHC</td>
<td>Non-methane hydrocarbons</td>
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<tr>
<td>NOx</td>
<td>Nitrogen oxides</td>
</tr>
<tr>
<td>HC+</td>
<td>Hydrocarbon and NOx</td>
</tr>
<tr>
<td>PM</td>
<td>Particulate matter</td>
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</table>
1.2 MISFIRE: CAUSES AND EFFECTS

The major causes of misfire are presented in the California Air Resources Board (CARB) regulations [4] where misfire in an engine is defined as, “lack of combustion in the cylinder due to absence of spark, poor fuel metering, poor compression, or any other cause”.

Misfire detection in an internal combustion engine is very crucial to maintain optimum performance throughout its service life and to reduce emissions. The engine diagnostic system of the vehicle should be designed to monitor misfire continuously because even with a small number of misfiring cycles, engine performance degrades, hydrocarbon emissions increase, and drivability will suffer [5]. The cylinder misfire cycle also results in a large quantity of unburned fuel being sent through the catalytic converter, which causes a reduction in its service life due to high temperature exposures [6] and also contributes to significant air pollution. Misfire has to be effectively identified by the condition monitoring system for corrective action to be taken.

1.3 MISFIRE DETECTION TECHNIQUES: AN OVERVIEW

There are various misfire techniques that are practiced, each having a unique set of merits and demerits. The more reliable and time tested methods involve in-cylinder pressure measurement and crank angle encoder based techniques. The in-cylinder pressure measurement technique uses an online pressure transducers located at the head of each cylinder to record sudden loss of pressure due to misfire in the respective cylinder. However this remains largely a laboratory technique and is not actively pursued by the industry. The measurement of angular velocity of crank shaft by using a sensitive crank angle encoder to detect deviations in crank shaft speed due to misfire is a widely reported technique [7] [8] [9], with ability to locate the cylinder in which misfire has occurred by knowing the firing order and the position of the crank shaft. The use of acoustic emission systems for misfire monitoring very large engines greater than 7 MW has been reported [10].
As a result of misfire there is a sudden rise in the temperature of the catalytic converter due to ignition of un-burnt gases which can also be used as a method for misfire detection. A unique system using the ion current signal at the spark plug which essentially indicates the level of ionization of the combustion gas has been reported [11], [12] and [13]. The use of oxygen sensor to detect momentary rise in the oxygen level of the exhaust can be used as an indication of misfire [14]. This technique coupled with crank angle information can be used to locate the exact cylinder in which misfire occurred.

The use of all these sensor data has been coupled with diverse systems of data processing involving the design of filters [15], [16], analytical modeling for fault identification [7], [8] and design of expert systems based on various algorithms [17], [18], [19], [20]. All these techniques have a unique set of merits and demerits and many of these techniques excepting the use of crank angle encoder, in-cylinder pressure and engine block vibration, are not widely reported in recent years.

1.4 VEHICLE FAULT DETECTION TECHNIQUES

Monitoring vehicle parameters for VFD in small and low cost vehicles is a major thrust area for developing economies where huge populations of a variety of low cost vehicles, without adequate monitoring systems are manufactured. The survey of literature for vehicle condition monitoring yields few works published, more on the engine dynamics rather than on the entire vehicle. However there are a few interesting work published on tyre pressure monitoring.

A vehicle fault monitoring system for predicting various engine related faults using a group of 5 sensors is reported [21]. This work has evaluated the use of various classifiers in standalone and in classifier fusion modes. However the data was simulated using software and interesting results were reported. A detailed analysis is presented in the literature review Section 2.3.

The use of patented and proprietary capacitance based wireless tyre pressure sensing system capable of displaying the tyre pressure inside the vehicle cabin using the Control
Area Network is reported [22]. Another interesting work based on the resonance frequency of the tyre monitored using the existing wheel speed sensor of an anti-lock brake system (ABS) system is reported [23]. The use of vehicle acceleration based tyre pressure monitoring using the amplitude of the power spectral density is also reported [24].

A frugal VFD system has not been reported to the best of the author’s knowledge. Model for detecting misfire and multiple faults that directly impact fuel consumption in an automobile using a single sensor has also not been reported.

1.5 PROBLEM FORMULATION: MISFIRE AND VFD
Misfire detection in SI engine is formulated as a machine learning problem with inherent capabilities to detect misfire at no load, various speeds and under load conditions. The developed model should be capable of satisfactory VFD in passenger cars.

Conditions simulated in the engine test rig (misfire mode):
   a) No misfire in any cylinder
   b) Misfire in any one individual cylinder
   c) Simultaneous misfires in two cylinders

Conditions simulated in the in on-road passenger car (VFD mode):
   d) Choking of air filter
   e) Low tyre pressure
   f) Gear knock
   g) Excessive engine speed warning
   h) Misfire

A detailed test schedule for the test rig and passenger car is presented in chapter 5.

1.6 OBJECTIVES AND CHALLENGES
The objective is to develop a model for detecting misfire and multiple faults that directly impact fuel consumption in an automobile. The use of a single sensor for recording the
engine block vibration containing multitudes of information, followed by data processing to extract reliable information from which all fault conditions including misfire has to be identified. The primary focus will be on misfire detection with 100% classification accuracy followed by classification of all the other conditions with maximum accuracy possible.

Misfire and VFD in spark ignition (SI) engines is faced with many challenges since the fault signal is non-cyclostationary and very random which makes it difficult to establish a trend for predicting them. Identifying misfire and VFD using vibration signal is posing a challenge since the SI engine is a cluster of many rotating and reciprocating components, each operating under different speeds, generating a unique vibration pattern into the engine block. Additionally, misfire also induces torsional vibration in the crank shaft flywheel assembly. The automobile system has additional vibration sources like road induced vibrations, harmonics and subharmonics, which contribute to noise in the actual signal.

Designing a simple misfire detection system capable of identifying the exact cylinder in which the misfire has occurred, using vibration signals is difficult due to the perceived similarity in signal parameters. Moreover, identifying misfire in a particular cylinder becomes more difficult since all the misfire signals look alike and have almost the same magnitude.

Traditional spectral analyses methods rely on Fast Fourier Transform (FFT) for monitoring the specific characteristic frequency of a fault but here the frequency spectrum has a wide bandwidth contributed by all the moving parts in the engine block and also contain a good proportion of noise. The frequency analysis involves higher computational load and hence it is not pursued. All these challenges necessitate the application of extensive data processing and machine learning algorithms for mitigating these hurdles.
1.7 CONCEPTUAL FRAMEWORK FOR VFD

The use of machine learning techniques forms the core of the work. The main objective of this work is to find a computationally lean yet robust and accurate classifier with the ability to form a part of the vehicle diagnostics management unit of an automobile.

Researchers have reported the capability of some complex schemes of machine learning which demonstrates that they can be deployed for misfire detection in automobiles [17], [18], [19], [20]. There are wide possibilities for induction of various new algorithms and techniques that can be effectively tuned for VFD including misfire. The simplest system will be the one which has the least computational load and which is yet robust and accurate over the entire operating life of the SI engine.

The proposed methodology for carrying out the work is presented in Figure 1.1. The work starts with fault simulation and data acquisition on an IC engine test rig. The next step involves the extraction of statistical and histogram features from the recorded signals. This is followed by feature subset selection (FSS) process. Since all the features extracted might not contribute building the classifier due to data correlation or data redundancy. These should be identified and removed to minimise computation load and to improve the classifier performance. In this stage various FSS algorithms are evaluated and the best one is identified in association with a classifier. The identified feature subsets are further processed using feature reduction techniques to reduce the quantum of information without appreciable loss of information. This can be validated by processing the features and evaluating them with a base classifier like decision tree. Data transforms are also evaluated as part of feature reduction possibilities as mentioned above. The fine tuned model with “preferred feature - optimised feature subset selector - data preprocessor - classifier” combination is used for misfire detection, simultaneous misfire detection and is also tested under multiple speeds and in load condition. The model is then implemented on a passenger vehicle for misfire detection followed by VFD simulation and evaluation on-road. The finalized model is also tested using wavelet features, FFT, PSD and feature fusion options for the sake of completeness.
Fault simulation in engine test rig (Ambassador) and passenger car (Maruti 800)

Engine block vibration pertaining to each simulated fault is recorded using an accelerometer

Feature extraction from vibration signal *(Statistical and histogram features)*

Evaluation of the best feature subset selection algorithm

Evaluation of the best feature size reduction tool

Evaluation of the best classifier for machine learning model development using test rig data (1500 rpm at no load)

Evaluating the model performance at various speeds and under load condition using test rig (Ambassador engine)

Implementing the fine tuned model for misfire detection in a passenger car (Maruti 800)

On-Road performance evaluation of the model for detecting all vehicle fault conditions simulated on the car (Maruti 800)

Evaluating the use of wavelet features, FFT, PSD and feature fusion options on the final model

Finalising the model and comparing performance with other reported systems

Figure 1.1 Proposed methodology flowchart
1.8 HIGHLIGHTS OF THE WORK

- Low cost approach involving a single mono-axial accelerometer compared to multiple sensors and tri-axial accelerometers reported in the literature. The developed system leads to a leaner information system accomplishing the intended task effectively without compromising on classification efficiency.

- Evolving an effective data pre-processing model for feature size reduction (quantum of data) and feature subset selection system which has not been addressed in recent literatures surveyed. The effects of feature transforms are also analysed.

- The portable model was built on a three tier approach. First the misfire model was developed using a stationary four cylinder engine mounted on an isolated engine test bed and the model was fine tuned for performance. The second step involved model testing at various speeds and in loaded condition, in addition to model extension for accommodating simultaneous misfire in the same engine. Finally in the third step the model was implemented for VFD on a different three cylinder automobile (Suzuki passenger car).

- The model implementation and validation in the 800cc three cylinder passenger car, triggered minor compatibility challenges due to variation in the signal and in the number of engine cylinders. These challenges have been addressed by tweaking the model.

- Model extension to incorporate a comprehensive automobile condition monitoring system with additional capability to detect gear knock, high engine speed, low tyre pressure and air filter chocking, was developed using the same information obtained from the engine block vibration and proved to be successful. The possibility of monitoring all these conditions using a frugal setup involving a single mono axial accelerometer has not been reported to the best of the author’s knowledge.

1.9 ORGANISATION OF THE THESIS

Analysis of reported literature regarding misfire and VFD are presented in chapter 2 which facilitates in arriving at a fact that the use of a single non-intrusive mono axial
accelerometer for the detection of misfire and a wide gamut of automobile fault was not reported to the best of the author’s knowledge. Chapter 3 presents the theory behind various data pre-processing techniques and data transformation techniques employed for data volume minimisation. They include simple data discretisation techniques, entropy based data discretisation, PCA, Random projection and Z transform. The effectiveness of these techniques on all classifiers with statistical and histogram features extracted from time series vibration data is to determined for choosing the best pre-processor. Chapter 4 describes all the algorithms considered for the study in detail and the various options available for fine tuning the algorithm. Chapter 5 describes the two experimental setups: a stationary engine test rig and a passenger car on which the model was implemented. The details of all experimental parameters and the choice of sensors are presented in detail.

The experimental work is divided in to two parts as part 1 and 2.

**Part 1** reports the design, development and analysis of a machine learning model built exclusively for misfire detection. This work is done using the stand alone engine test rig. **Part 2** deals with the implementation of the misfire model to a passenger car and model extension to cover VFD along with misfire detection. The evaluations of alternate features like wavelets, FFT, PSD and feature fusion are also analysed.

**1.9.1 Part 1: Misfire detection model using engine test rig (chapters 6-8)**

The performance of statistical and histogram features with various classifiers like Decision tree, Random forest, Naïve Bayes, Bayes net, Fuzzy classifiers and SVM based classifiers are evaluated in conjunction with the data pre-processing techniques. The best classifier for achieving 100% classification accuracy in detecting misfire with minimum model computation time is evaluated and the results are presented in chapter 6 for statistical features and in Chapter 7 for histogram features. The best model suitable for misfire detection using the “preferred features (statistical or histogram) – data pre-processors (choice of FSS and feature reduction) - classifier” combination is identified.

Chapter 8 reports the results of model extension including simultaneous misfire in two cylinders, testing the models at various speeds and the model performance when the engine
is loaded. This step validates the model performance under diverse engine operating conditions.

1.9.2 Part 2: Model implementation in a passenger car (chapters 9-10)

The preferred model developed and fine tuned for best performance from part 1 is implemented and analysed on the passenger car working on real road conditions in Chapter 9. Implementation challenges are encountered and the model is fine tuned to effectively accomplish the task. The evaluation of alternate features for improving the overall model accuracy is analysed and presented in Chapter 10. Wavelet based features and spectral features involving discrete Fourier transform and power spectral density are reported. Wavelet transforms using Harr and deauches (db2 to db9) based models were included for the sake of completeness and were not intended as a preferred choice from start due to computational complexity involved. In addition to these diverse features, the concept of feature fusion achieved by combining statistical features with diverse wavelet transforms is also evaluated. Chapter 10 also reports the implementation of the model extension to cover all the conditions (d to g) reported in Section 1.5 along with misfire detection.

Chapter 11 presents the conclusion of the work, the preferred model of choice is analysed along with the presentation of some of the notable contributions of the present work. Future directions of work in this field are also proposed at the end.