CHALMERS

Testing the Effectiveness of the Misfire Detection System

Simulation of system response to potential disturbances

Master Degree Programme, Automotive Engineering

DHINESH V. VELMURUGAN

Department of Applied Mechanics
Division of Combustion
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2011

Master's Thesis 2011:36

MASTER'S THESIS 2011:36

Testing the Effectiveness of the Misfire Detection System

Simulation of system response to potential disturbances

Master's Thesis in the Master Degree Programme, Automotive Engineering

DHINESH V. VELMURUGAN

Department of Applied Mechanics
Division of Combustion
CHALMERS UNIVERSITY OF TECHNOLOGY

Göteborg, Sweden 2011

Testing the Effectiveness of the Misfire Detection System
Simulation of system response to potential disturbances
Master's Thesis in the Master Degree Programme, Automotive Engineering
DHINESH V. VELMURUGAN

Master's Thesis 2011:36
ISSN 1652-8557
Department of Applied Mechanics
Division of Combustion
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: + 46 (0)31-772 1000

Cover:
Line up of Scania vehicles, indicating several available chassis configurations

Chalmers Reproservice
Göteborg, Sweden 2011

Testing the Effectiveness of the Misfire Detection System
Simulation of system response to potential disturbances
Master's Thesis in the Master Degree Programme, Automotive Engineering
DHINESH V. VELMURUGAN
Department of Applied Mechanics
Division of Combustion
Chalmers University of Technology

ABSTRACT

A methodology to analyse and predict the behaviour of the current misfire detection system & algorithm is presented with special focus on the effects and contribution of the noise contributed mainly by the variation in driveline configuration.

The existing line up of CNG engines are used to compare the performance of the simulating model with the real time functioning of the system. Two distinct diesel vehicle models with known and reported significantly varying driveline disturbances are investigated along with the developed model of the system.

Sufficient tolerance band coupled with accurate algorithms in the existing misfire detection system have been a key advantage providing the opportunity to extend the same system across future possible vehicle variants in spite of noise contributions.

A misfire generating system designed and built with the possibilities to induce and generate misfires at controlled rate in order to assist real time evaluation of the detection system and diagnostics performance is also presented.

A comprehensive study from available literatures in the automotive research industry carried out to determine possibilities to improve the existing misfire detection system and algorithm resulted in identification of usage of a viable alternate detection system as an assisting contribution to the current algorithm.

Key words:

Misfire detection, SI Engines, Engine roughness, Misfire generator, Alternate detection systems

Contents

Acknowledgement

The entire period of the project has been a remarkable experience throughout contributing a greater extent to on the job learning and development. The Powertrain department at Scania tekniskt centrum has been my workplace for the entire duration providing me with all facilities to carry out the thesis in the most efficient manner. I would like to thank Scania AB for extending the opportunity enabling to complete my Master thesis.

I thank my Supervisor Mr. Mårten Eckerdal, NESI who has provided all the guidance required to progress with the works. A special thanks to Mr. David Holmgren and the Engine Control System Department (NE) for providing the opportunity and assistance to carry my work smoothly. My sincere thanks to Prof. Sven Andersson for his cooperation and guidance throughout the thesis work.

Göteborg June 2011

Dhinesh V. Velmurugan

1 Introduction

1.1 Background

The term misfire is applied to a total absence of combustion during a normal power stroke. Misfire can result from a number of causes, such as missing or improperly timed delivery of fuel, insufficient delivery of cylinder intake air, or a missing or improperly timed cylinder spark event (1).

Misfires are majorly caused due to unfavourable spark plug temperatures, low ignition energy, Fuel system malfunction, Improper Mixture ratio, flame propagation speed. Misfires have a great potential to destroy catalytic converters due to increased exhaust temperatures caused by unburned fuel from the misfire cylinder. Significant increase in HC and CO emissions have been observed at 2% misfire rate. (2)

Apart from emissions and catalytic converter damage, misfires lead to reduced engine torque, decreased engine efficiency, engine stall and high specific fuel consumption. Legal requirements by California Air Resources Board require reliable detection and misfiring cylinder identification over the engine operating range to comply with On Board Diagnostics-II. (OBDII) (3) The following two conditions of misfire are legislated to be detected and reported in OBDII

A. Catalytic converter damaging misfires
B. Emission related misfires

Catalytic converter damaging misfires, as the name indicates are the misfires that are required to be detected that could potentially damage the catalytic converter. Continuous operation temperatures above a certain limit of about 900 – 1000ºC cause irreversible damage to the catalyst (4).

Emission related misfires are those that lead to an increase in emissions by a factor of more than 1.5 times the legislated emission limits and the detection diagnostic is carried out every 1000 cycles. OBD II legislations require that a Malfunction Indicator Lamp (MIL) is switched on with the appropriate Diagnostic Trouble Code (DTC) and if possible cut off the misfiring cylinder to protect the catalytic converter.

This project is focussed on the misfire detection system of the Scania Engines ‘’OC9 G04 & OC9 G05’’. The CNG fuelled, Otto cycle, Euro V, lean burn engines are operated with Lambda up to 1.6. The misfire detection algorithm used is based on the crank shaft speed sensor signal processed data and determination of variation in instantaneous angular acceleration / torque through a formulated misfire index. The current system employs a crank sensor, a 58 tooth wheel and an Engine Management System (EMS). The current misfire function has been implemented and is operational in four vehicle variants including two Bus variants and two Truck variants.

1.2 Objective

The misfire detection system is evaluated for the robustness against the influence of possible influencing factors including external conditions such as rough road and vehicle conditions such as drive-train vibration. The performance of the system under different vehicle driving conditions to evaluate the system under different operating points is determined. The existing vehicle line up is evaluated and their performance is recorded.

The expected behaviour of the system for change of vehicle configuration is simulated and analysed. The choice of the vehicle configuration under study is carried out with a vehicle with a known worse behaviour and a standard available vehicle. The results of the experiments carried out with available results are used to predict the system performance on vehicle variants studied.

A misfire generator is designed to induce and generate known rate of misfires in the engine. This enables controlled production of misfires in the system thereby providing a possibility to evaluate the system response with accurately known misfire conditions. The system will assist in the evaluation of the system as to what extent the system fulfils the legislated requirements and analyses of any changes / improvements in the current system.

There are several systems available for the detection of misfires including both intrusive and non-intrusive methods, each with respective advantages and limitations. A comprehensive study of these systems is carried out to determine a possibility of improving the current functionality for future applications.

1.3 Scope and Limitations

The system under study is a simulated study and the analysis of the results thus obtained is based on theoretical estimation, limited experimental data and assumptions. Hence the vehicle behaviour may vary to a certain degree from the estimations as described under the respective sections.

The vehicle variants employed in the drive-train factor contributions study are primarily Diesel engine powered and hence the comparison of performance is done with respective diesel engine trucks to ensure non influence of the change in operating cycle. The project is primarily carried out with an interest to study drive-train and road influences on the misfire detection system. Thus other possible confounding factors are eliminated for the study.

Also an outcome of the project is to advice on future development and provides recommendations for the improvement of the system.

2 Theory behind Misfire detection by Engine Speed Fluctuation

A number of research works has been carried out to investigate the correlation of cycle to cycle variation of combustion on the resulting speed fluctuation and use of it. The following brief is an explanation of the underlying concept and logic behind the misfire detection algorithm implemented with the assistance of established and proven methodologies from the works based on the crank sensor systems for misfire detection (5) (6) (7) (8).

Absence of combustion or presence of incomplete combustion leads to instantaneous change in the torque and speed in a multi cylinder engine due to the absence of the Power stroke. This speed fluctuation when monitored is the approach that the current system uses to detect misfires.

2.1 Engine model

The balance of moments at the crankshaft is given by the equation:

$$M = W + \theta * \frac{dw}{dt} \tag{2.1}$$

Where,
M = Engine torque
W =load torque
θ = moment of inertia
w = Angular speed on the engine

The fluctuations in engine torque caused by misfires lead to fluctuations in angular acceleration $\frac{dw}{dt}$ of the crankshaft. The angular speed within the time period T_i from the ignition of one cylinder to that of the next cylinder is given by:

$$W_i = \frac{d\varphi}{dt} = \frac{4\pi}{c} * \frac{1}{T_i} \tag{2.2}$$

Where,
4π = Number of radians in 2 revolutions (for a 4 stroke engine)
c = Number of cylinders
T_i = Ignition time of firing cylinder i

Angular acceleration, $$\alpha = \frac{dw}{dt} \approx \frac{\Delta w}{\Delta t} \approx \frac{w_i - w_{i-1}}{T_i} \approx \frac{4\pi}{c * T_i} * \left(\frac{1}{T_i} - \frac{1}{T_{i-1}}\right)$$
$$\approx \frac{4\pi}{c} * \left(\frac{T_{i-1} - T_i}{{T_i}^3}\right) \tag{2.3}$$

2.2 Engine roughness index theory

The Engine roughness index is based on difference between two consecutive angular accelerations:

$$L_u = \left|\frac{\Delta(\Delta T)}{T^3}\right| = \frac{|(T_{i-1}-T_{i-2})-(T_i-T_{i-1})|}{{T_i}^3} \qquad (2.4)$$

L_u = Engine roughness index

Under steady state operating conditions, a misfire event causes a relatively high positive engine roughness Index for the misfiring cylinder's misfire index. A misfire event can be detected with a comparative evaluation of the expected engine roughness under the same operating conditions. (2)

The index obtained above also accounts for engine transient operation such as change in load or engine speed or both. Thus a correction or compensation term to eliminate this influence is to be included in the index. This term is determined by using the median mean value or the arithmetic mean of the neighbouring. The selection of the compensation term is dependent on the engine type and its operating point.

In the case of the current engine, the median mean value is used for the compensation time. The factors influencing the selection include engine operation load and speed range and expected driving factors.

Calculation of compensation time – median procedure:

The following measurement values are evaluated:

$$Dts1 = \frac{[tsk(n-1)-tsk(n-3)]}{2} \qquad (2.5)$$

$$Dts2 = [tsk(n) - tsk(n-1)] \qquad (2.6)$$

$$Dts3 = [tsk(n+1) - tsk(n)] \qquad (2.7)$$

$$Dts4 = [tsk(n+2) - tsk(n+1)] \qquad (2.8)$$

$$Dts5 = [tsk(n+3) - tsk(n+2)] \qquad (2.9)$$

$$Dgts3 = \text{median } [Dts1, Dts2, Dts3, Dts4, Dts5] \qquad (2.10)$$

Where
Dts1 to Dts5 – differential values corresponding to respective segment times
tsk(n) - Corrected segment time of crankshaft segment (n)
Dgts3 = Compensation Time

The median of the determined values is used as the compensation term. In the algorithm implementation, it corresponds to the third term after arranging $Dts1$ to $Dts5$ in the descending order.

Thus, the final expression for misfire index $luts(n)$ is:

$$luts(n) = \frac{[tsk(n+1)-tsk(n)]-Dgts3}{tsk(n)^3} \qquad (2.11)$$

2.3 Determination of the reference engine roughness value

An increase in the engine roughness index above a threshold determined from operating condition indicates the occurrence of a misfire event. The factors determining the roughness reference index include the following since non consideration will lead to large errors (9):

1. Engine Load
2. Engine Speed
3. Mechanical variations
4. Drive-train contribution
5. External environment influences

The operating range of the engine load condition is divided into 3 sub regions determined in accordance with engine expected operation and limitation in EMS computation ability. The engine speed range is similarly divided into 8 sub regions. The magnitude of variation of the misfire index is dependent upon the variation of the crank shaft sensor input.

Changes in the ignition timing over the different operating range and the variation in combustion duration have a profound influence. The observed and recorded findings of the crank speed under various load and speed operating conditions is noted from the perceptual drop in engine speed caused by misfire across the range of operation.

The reason is that the periodic duration between a normal combustion process and a misfire event differs, for instance for 6-cylinder engines, by only 0.2% although the comparable figure for low engine speed and high load factors can be as high as 8% (5).

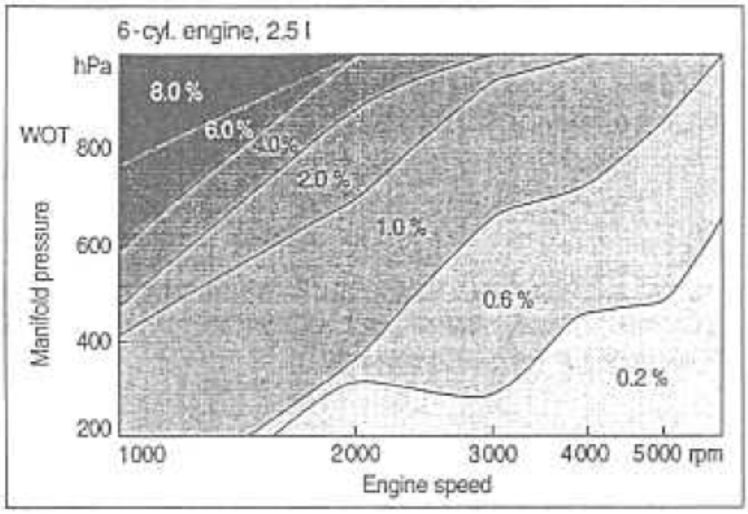


Figure 2.1 Perceptual drop in engine speed caused by misfire (5)

Mechanical variation may arise due to production tolerance of the sensor and associated measurement mechanism such as tooth machining errors, run-out, sensor – wheel gap. The correction factor for such a contribution is determined using a learning algorithm during non -misfire events. The raw evaluations are thus filtered through a factor learned from the behaviour of the speed sensor inputs at the various operating point windows defined by the engine speed and load.

A bad gear shift, transient drive-train characteristic, driveline noise or torsions contributes to an erratic change that may appear to be a misfire event even though there is no misfire occurrence. The misfire algorithm can either be turned off during the expected drive-train disturbances or the threshold can be increased. The selection is dependent upon the availability of data from drive-train. Due to the absence of the data, the threshold is set to a considerably higher limit.

External environment influences include rough road driving conditions which induce mechanical disturbances in the crank sensor measurement. The solution to this contribution is similar to the drive-train factor. The commercial implementation in most engines is using the speed sensor data of the wheels from the ABS sensors. Using the difference in their speed of rotation and suitable filtering enables evaluating the road conditions for its contribution. Alternate methodologies include gas tank pressure measurement, air mass measurement, using an accelerometer or signal & statistical processing of crank speed sensor concepts. (10)

Also observed during engine operating conditions are deviation due to cold engine operation, cranking, cylinder cut off and memory overflow conditions. In such cases, an offset may be used or the misfire detection algorithm can be disabled temporarily. The current system determines engine roughness reference value in accordance with the load, speed and learning conditions and is denoted for future references as lurs(n).

2.4 Distance detection method

From experimental verification and theoretical validation, it is found that the magnitude of difference in engine roughness is always the same between normal firing and misfiring cylinder/s. The case is valid for occurrences of all types of misfire occurrences including but not limited to single misfires, continuous misfiring of single cylinder or multiple cylinders, symmetrical misfiring cylinders, consecutive cylinder misfires etc.,

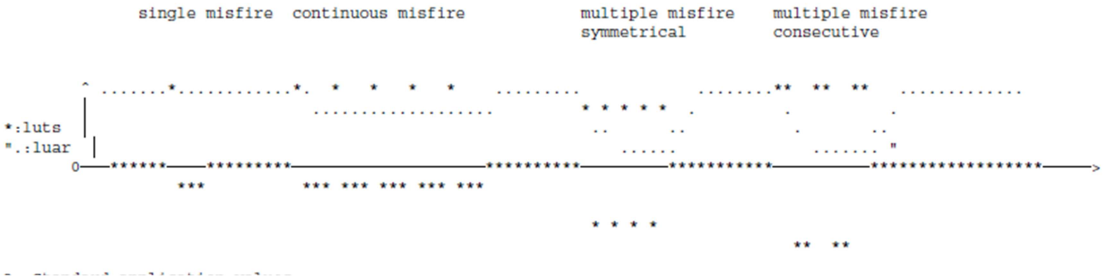


Figure 2.2 Comparison of Engine roughness indices at different conditions

This phenomenon is used for reliable detection of misfires in such conditions. The cylinder individual engine roughness luts(cyl) is filtered by a recursive low pass filter and compared with an adaption threshold luar. The threshold luar is defined to be offset by the minimum luts in the current camshaft rotation. A variation limiter is used to keep the reference value under check so that unrealistic values of engine roughness are not permitted.

The theoretical background of the misfire detection algorithm explained as above is implemented with the Bosch ME7 Engine Management System on the OC9 G04 and OC9 G05 Engines. A brief description of the hardware and the function details are elaborated in the following sections.

3 System Hardware and Engine Management System architecture

3.1 Powertrain description and Specifications

The engines under study ‘’OC9 G04 and OC9 G05’’ are Otto cycle operated, In-line 5 cylinder, Turbocharged and Euro 5 compliant engines. The engines are currently coupled to an automatic transmission gear box and are torque variant models of each other. The engines are being employed for use in two configurations each of bus and truck. A detailed specification chart of the engine is given in the Appendix 1 accompanied by the engine layout diagram in Appendix 2.

3.2 Engine Management System

The engine is controlled by the gas engine management system gEMS. The gEMS consist of the following ECUs connected via a dedicated CAN bus (CAN 3):

1. S7 ECU which acts as the interface to the truck and to the electrical architecture
2. Bosch ME7 / EGC 1.1, controlling the functions and I/O which are unique for the gas engine

The ME7 controls and monitors the airflow, fuel injection, ignition, emission control and diagnostic. The S7 control the basic functions of the engine which are identical to the Diesel engine. The diagnosis is performed in ME7 and the result is reported to S7/S8 via the CAN 3 bus. S7/S8 sets the DTC’s in DIMA. A clearer picture of the distribution of functions is given by the diagrammatic description in Appendix 3.

3.3 Misfire detection system overview

The misfire functionality system overview is provided by the function DMDUE (Diagnostic routine misfire detection overview). The function DMDUE provides an overview of the dependencies, flow of information and flags among the several sub functions constituting the misfire functionality. The functionality overview gives a broad perspective of the functions involved and highlights major data or flag interactions. The figure is a block diagram representation provided by the DMDUE function overview. A detailed description of the individual blocks that implement the theoretical definitions is followed.

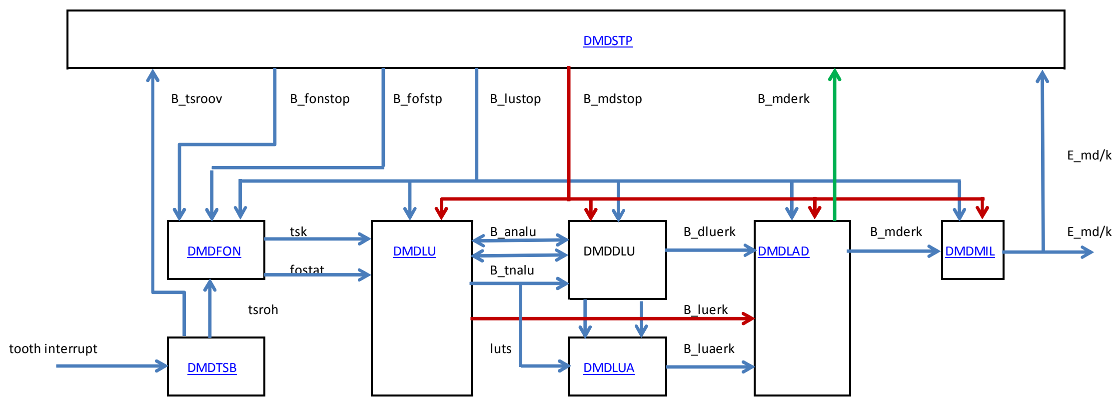


Figure 3.1 Misfire detection system functionality overview (DMDUE)

3.3.1 Segment time

The misfire detection algorithm is based upon the evaluation of the time between two ignitions during which the crankshaft covers 144° (for a 5 cylinder 4 Stroke engine = 720° /5) wide consecutive angular sectors. The segment time is evaluated from the signal of the crank sensor facing the 60 teeth wheel. The optimal position of the angular sector in the engine cycle can be selected using the calibration.

3.3.2 Segment time formation (DMDTSB)

From the tooth time table, the segment time for each ignition is determined in the measuring window, the start of which is set by a calibration value.

The ignition information is estimated from the synchronized crank sensor tooth time table using the cylinder configuration information.

Length of measuring window = 360 / (No. of cylinders/2) ºCA

= 360 / (5/2) = 144 ºCA

The analog signal from the 60 teeth wheel, mounted on the crankshaft (clutch side), is pre-processed in order to extract the time intervals needed to perform the 6°CA wide angular sectors between one tooth and the next one (called "tooth time"), evaluated by considering two consecutive zero crossings in the descending part of the analog signal. At this point, a simple sum of 24 (for the 5 cylinder engine) consecutive tooth-time intervals provides the segment time, that is the basic information for the misfire detection algorithm.

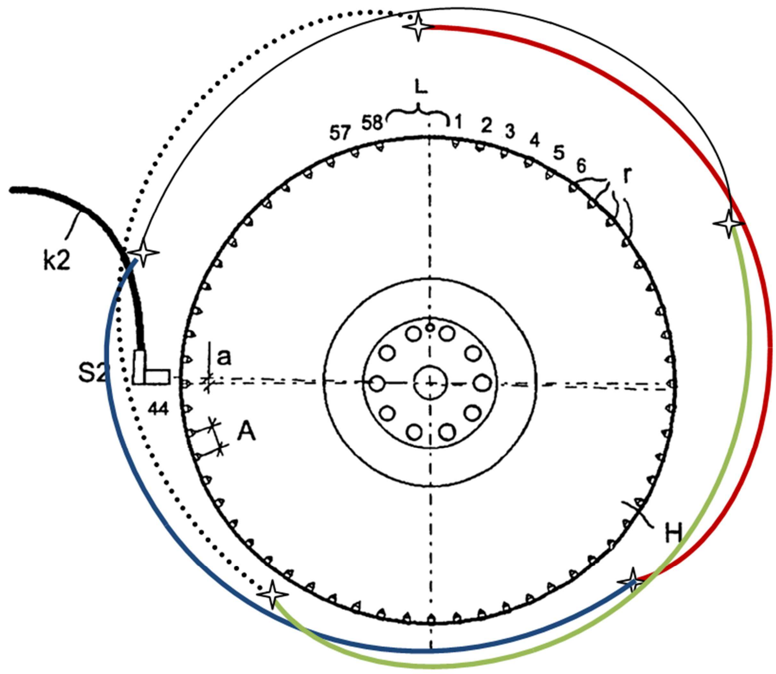


Figure 3.2 Segment time definition using the crank speed sensor and wheel

3.3.3 Segment time correction by learning and adaptation (DMDFON)

The DMDFON function outputs the corrected segment time (tsk). The adaptation learns systematic camshaft-synchronous and therewith cylinder-individual disturbances of the segment time. These disturbances include disturbances caused by mechanical inaccuracies of the sensor wheel (crankshaft-synchronous) as well as disturbances caused by torsional vibrations (camshaft-synchronous). The adaptation defines the 24 operating points with 8 base speed points and 3 load points.

$$Tsk(n) = (1 + fse(1) * ts(1)) \qquad (3.1)$$

Where,
Tsk = Corrected segment time
fse = Correction factor
ts= Segment time (Raw value)

rl relative load

rl \ nmot (engine speed)	n1	n2	n3	n4	n5	n6	n7	n8
rl3	31	23	33	43	53	63	73	83
rl2	21	22	32	42	52	62	72	82
rl1	11	21	31	41	51	61	71	81

(engine speed) nmot

Figure 3.3 Learning adaptation table

The segment time tsroh_w is assigned the individual cylinder in accordance with the firing order obtained and thus the segment times ts01, ts02, ts03, ts04, ts05 are estimated. The deviation between a computed value and a measured value is evaluated using the reference segment ts01, the measured values ts02, ts03, ts04, ts05 and the dynamic correction.

$$ds02(i) \;=\; ts01(i) - ts01(i) + \frac{[ts01(i+1) - ts01(i)]}{zylza} \qquad (3.2)$$

Where,
ds02 to ds05 = Dynamic correction factor
ts01 to ts05 = Segment times
zylza = Number of cylinders (= 5)

The deviation is normalised and converted to an angle proportional variable

$$xs02(i) = \frac{ds02(i)}{ts02(i)} \qquad (3.3)$$

Where,
xs02 to xs05 =Normalised segment time values

The normalized segment times are smoothened by a low pass filter. Further processing is done to ensure that the learning factor matrix fse(xx) is carried out under normal engine running conditions and the values learnt are reliable.

3.3.4 Engine roughness calculation (DMDLU)

Engine roughness is calculated from corrected segment duration and compensation time. Compensation time is determined according to median procedure or arithmetic mean procedure depending on the engine speed set threshold.

$$luts(n) = \frac{(\ tsk(n+1) - tsk(n) - compensation\ time\ )}{tsk(n)^3} \qquad (3.4)$$

The reference value for engine roughness (lurs) is calculated depending upon engine conditions of load, speed, temperature, and adaptation state. The threshold reference is defined with previous learning from behaviour at different operating conditions in case of normal combustion and misfire presence.

Misfiring is detected by comparing lurs with luts. If luts>lurs, a single misfire is detected. After a misfire is detected, the misfire detection is deactivated for the next defined number of segments to avoid misdetection due to post oscillation caused by single misfire.

3.3.5 Diagnostic Misfire Detection distance method (DMDLUA)

The function is used to detect continuous misfires. As defined in theory, the engine roughness values are filtered over a low pass filter. The reference value for comparison is adapted for each cam shaft revolution based on the minimum engine roughness value in the cycle along with the offset for the engine operating conditions determined similar for luts.

$$fluts(zyl)(i) = (1 - fflutn) * fluts(zyl)(i-1) + fflutn * luts(zyl)(i) \qquad (3.5)$$

Where,
fflutn = Filter factor
zyl = Firing Cylinder number
i – Cam Shaft Revolution

$$luar = luaroff + luarmn \qquad (3.6)$$

Where,
luar – Engine roughness distance reference value
luarmn - Engine roughness distance reference value minimum
luaroff - Engine roughness distance reference value offset

If *fluts(zyl)>luar*, misfire is detected in the corresponding cylinder. Continuous, symmetrical, consecutive misfires can thus be detected.

3.3.6 Logic and delay for misfire detection (DMDLAD)

The logical block evaluates the results of the misfire detection blocks of DMDLU and DMDLUA and relays the information collectively for the logical operation of the Malfunction Indicator Lamp (MIL). The Stop conditions if present due to any other flags from external blocks are also evaluated so as to decide the final output to the MIL block.

3.3.7 Fault treatment of misfire detection, control on MIL and rectification (DMDMIL)

In accordance with legislated norms, two misfire counters are evaluated, one for every 1000 crankshaft revolutions (Emission related monitoring) and the other for every 200 crankshaft revolutions (Catalytic converter damaging misfire monitoring).

The threshold for catalytic converter damaging misfires is decided considering the temperature increase for the misfire rates and their damaging effect. The limit for emission related misfire is decided based on increase in emissions to 1.5 times. The MIL is switched on with generation of Diagnostic Trouble Codes (DTC) in the event of exceeding the threshold limit.

4 Model for simulating the Misfire detection system

4.1 Model Development

The theoretical formulations and the available information from the current system description defined in the chapters 1 and 2 are used to develop the Simulink model. The model is made up to represent the similar segments shown in the ME7 description and they are described as to how each have been created in the following sections.

4.1.1 Segment time formation

For use of the segment times with the algorithm, cylinder number assignment is carried out. The input data being supplied is the synchronous corrected segment time and cylinder number with the output being the segment times of the respective cylinders with the time stamp information. Also the synchronous engine speed is estimated from the segment time. The Simulink model for the estimation of the cylinder assigned segment times and engine speed calculation is shown.

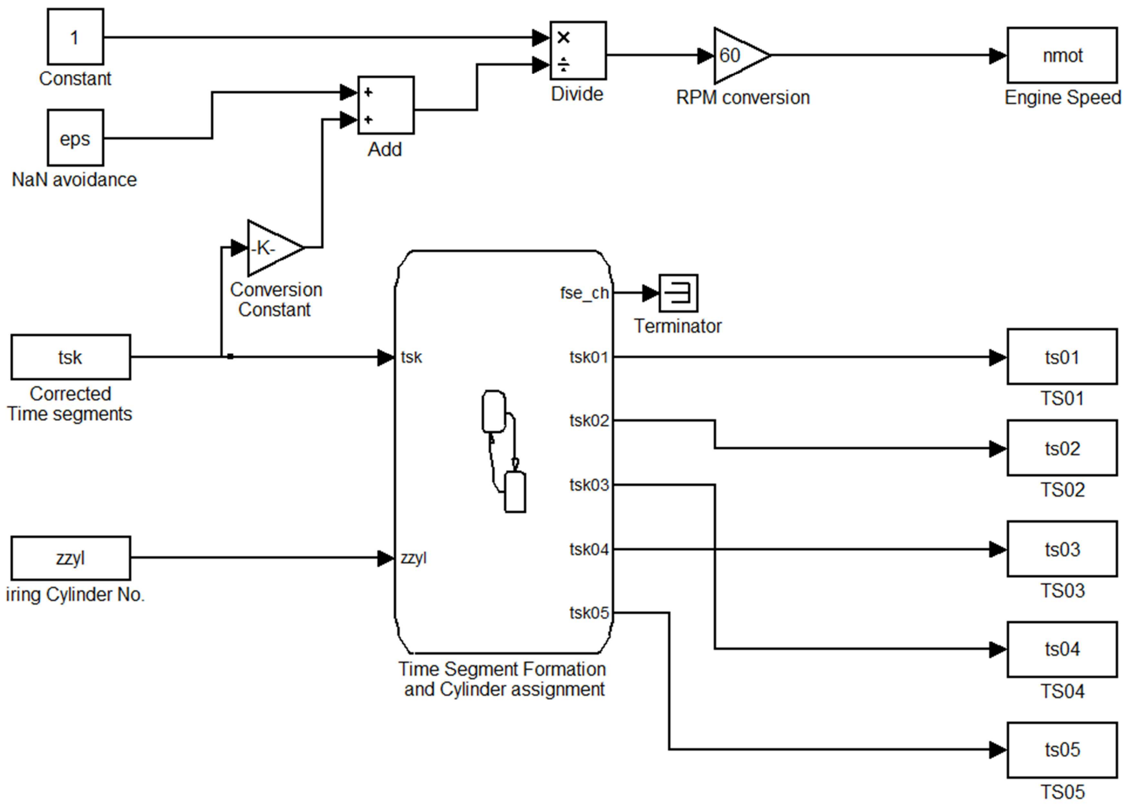


Figure 4.1 TSK calculation subsystem model

4.1.2 Engine Roughness Index Reference

All conditions to determine the reference engine roughness value is kept as standard during the recording. This includes a considerable running time of the engine to evaluate possibilities of cold start influences, higher coolant engine temperature, automatic gear transmission etc. Thus the reference value depends entirely upon the engine speed and load operating point. The vectors of the reference values are provided as input to the Simulink block for determination of the current reference values decided from the engine speed and load. The Simulink block of the same is shown.

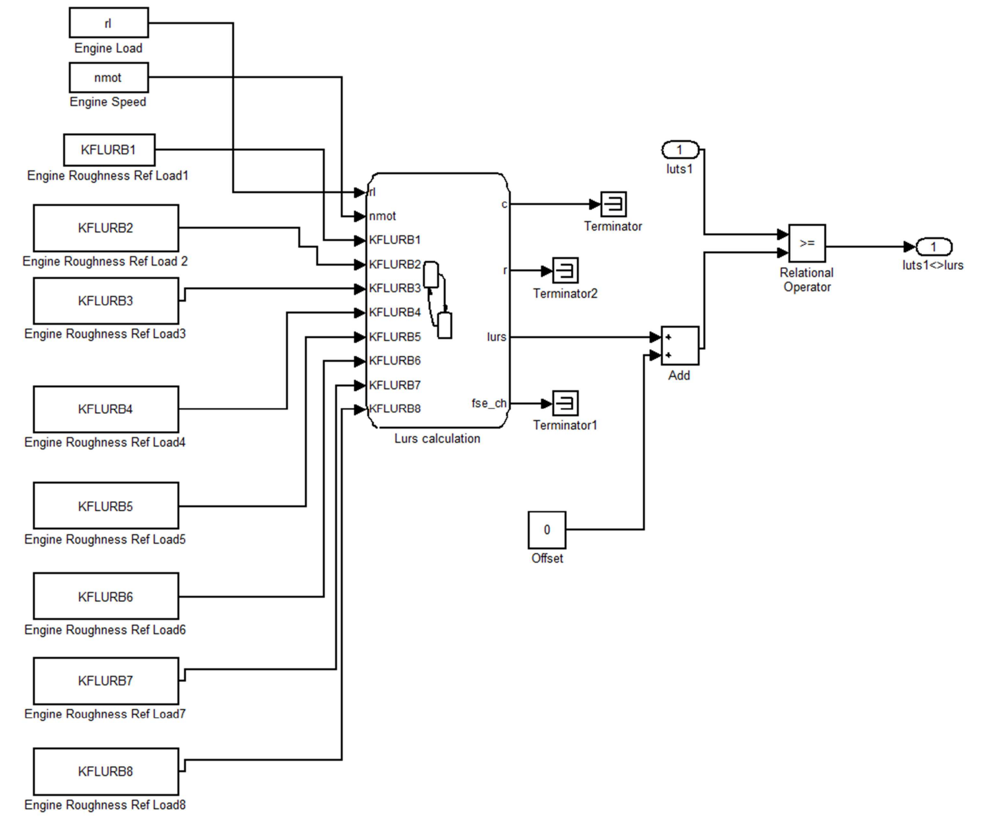


Figure 4.2 Engine roughness reference estimation model

4.1.3 Engine roughness test value estimation (luts)

The luts values (Engine roughness index) between the consecutive firing cylinders are calculated in accordance with the equation (3.4). The compensation time used in the calculation of luts values for each ignition to ignition comparison involves special care in that each value as per the equations (2.5 to 2.9) is evaluated for every set of values of segment time. The compensation time is set according to the median procedure as outlined in equation (2.10). The subsystem model for each cylinder to cylinder ignition is created accordingly. A Simulink subsystem model for the compensation time evaluation used is shown in Figure 4.3 and Figure 4.4

The overall model for calculating the luts values for one pair of consecutive firing cylinders is shown in Figure 4.5. The same is replicated for the rest of the luts calculation between other cylinders with care to change the variables internally according to the cylinder number in concern. Thus in total 5 sub models are created. The firing order with the timestamp is used to determine the synchronous luts value at any point of time. The instantaneous calculation is shown in Figure 4.6.

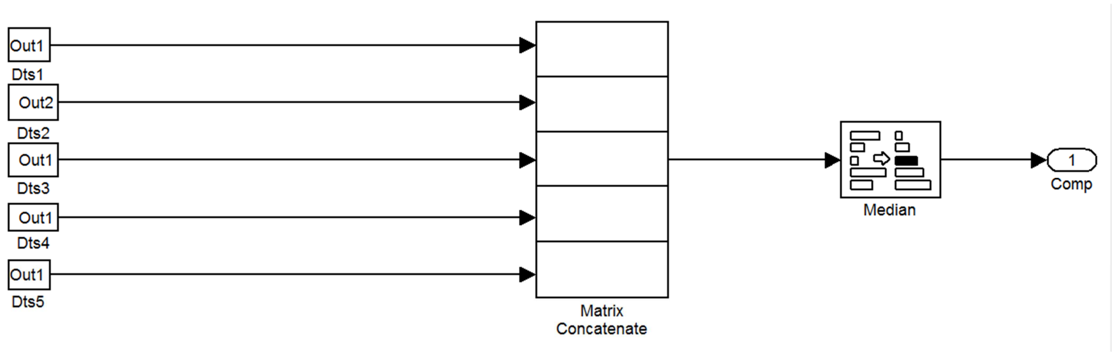


Figure 4.3 Compensation model – Median calculation subsystem model

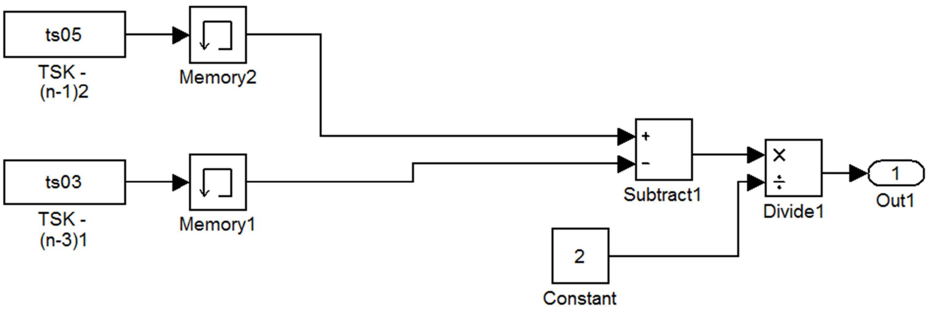


Figure 4.4 Compensation value calculation subsystem model

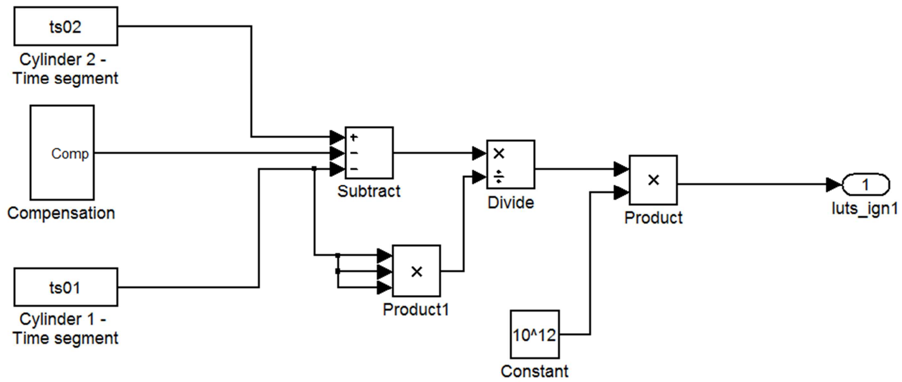


Figure 4.5 Engine roughness index calculation model

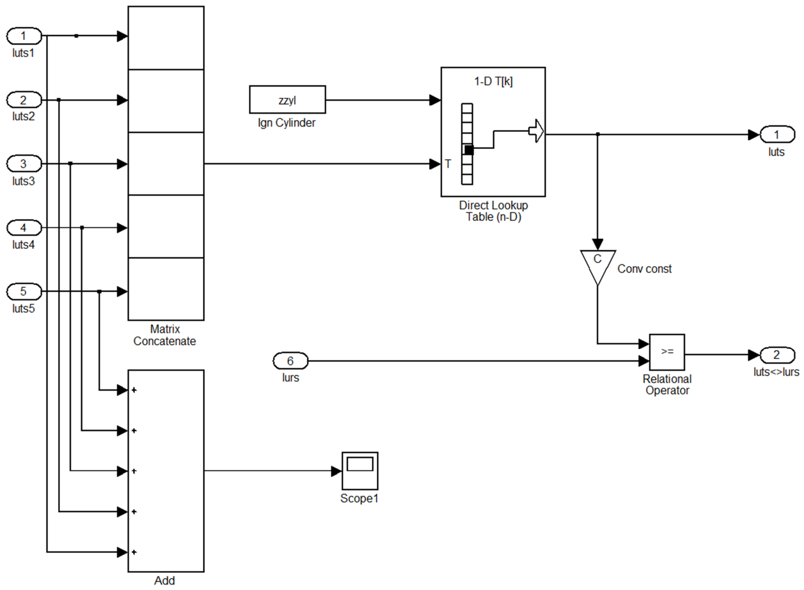


Figure 4.6 Engine roughness index comparison model subsystem

4.1.4 Engine roughness – distance detection (fluts and luar)

The calculated value of engine roughness luts is filtered by a low pass filter and fluts is thus calculated as per the equation (3.5).The determination of luaroff, luarmn and hence luar as per the equation (3.6) is done as shown in the Simulink model below. The other offsets to the luar are eliminated due to operation under standard defined conditions to avoid any other deviation / disturbance according to the driving model as described in Chapter 2.

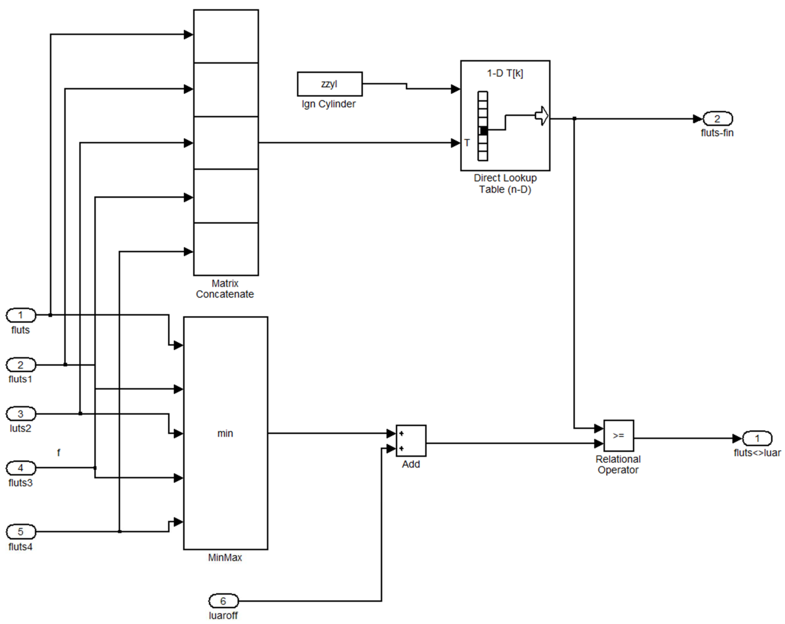


Figure 4.7 Engine roughness index comparison model subsystem – distance detection

4.1.5 Misfire detection

A misfire event is detected in case luts>lurs at any given point of time. A counter is provided to show the number of misfire events detected. Similarly a misfire event for fluts>luar is also counted. The Simulink model for the same is shown below.

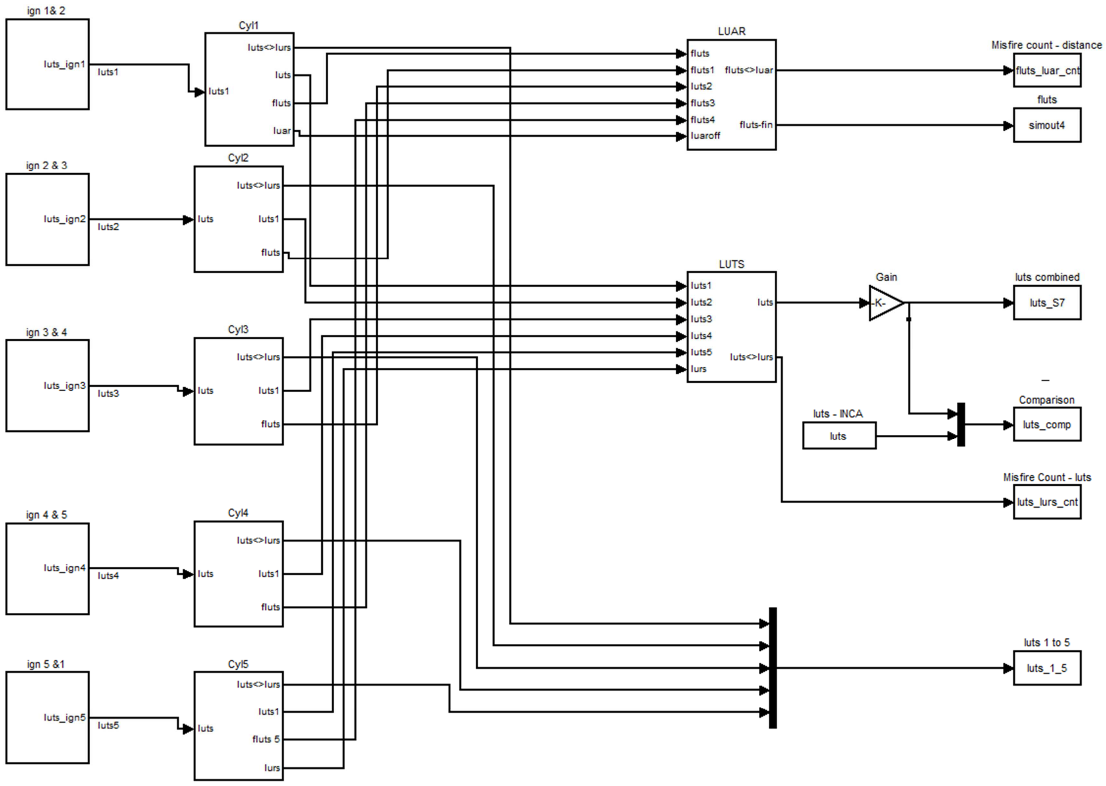


Figure 4.8 Overall model with all subsystems

4.2 Data Acquisition

The following input to the model is to be acquired from the systems to be tested

1. Time stamp
2. Segment times
3. Relative load
4. Cylinder number

Depending on the vehicle and experimental requirements, the data needs to be obtained from either the Bosch ME7 EMS or the Scania S7/8 EMS. A brief description of the methodology and approach used in obtaining the same is described in the following sections.

4.2.1 Data Acquisition from Bosch ME7 EMS

The segment time data from the CNG engine trucks is obtained by recording the synchronous corrected segment time from the Bosch Engine Management System using the INCA tool. The data thus obtained corresponds to the processed and filtered segment time with the implementation of learning from the previous segment times in the entire operating range of the engine (provided the engine has been run for a sufficiently long time under varied conditions). Hence the segment times have been adjusted for mechanical / production tolerances and measurement system variations. Each element corresponds to the current firing cylinder's segment time followed by the segment time of the subsequent firing cylinders. The time stamp of each data element is also recorded.

The algorithm has a defined and demonstrated dependence on the engine speed and load conditions. The engine speed is estimated from the crank segment times and the distance covered (144ºCA). In order to verify the validity of the same procedure, the synchronous engine speed of the engine used by the EMS was compared and found to be in congruence and sufficient agreement thus fitting the usage of the segment time to evaluate the engine speed. For defining the operating engine load, the relative load terminology defined in the EMS is used which is a percentage of the engine rated load. This is a relative term where the wide open throttle corresponds to maximum engine load demand whereas the idle is rated minimum.

4.2.2 Data Acquisition from Scania S7 ECU

The standard Scania ECU evaluates and provides a buffer with memory of the last run cam shaft revolution tooth times of the crank sensor wheel also sometimes referred to as tooth time table. Thus at any given point of time 120 tooth times are stored in this table or stack. This also includes the missing tooth information interpolated in accordance by the average between the start and end of the gap. The trigger to add new tooth times in the stack is set constant crank angle degrees (42 ºCA) before every firing cylinder. An additional set of codes is added to calculate the segment time using the trigger information. Thus the segment times of the engine are stored consecutively in their firing order. For limited memory considerations, 1000 segments are stored successively in a new data set.

The time stamp of the data is calculated using the segment time information implemented in the matlab scripts for post processing of the data file obtained. The cylinder specific segment time is calculated using cylinder numbers introduced in firing order. Engine speed is calculated using the segment time information and the segment distance covered (144ºCA). The engine load acquisition in synchronous mode is not available directly. However, the vehicle driving conditions are carried out with care to note the engine relative load in a known scale so that they are interjected manually for use. The model for the misfire algorithm is the same for both the systems thereafter since all required data required for processing has been determined either experimentally or calculated theoretically. The data acquisition is carried out using ATI Vision tool.

Synchronous relative load date is thus recorded alongside the segment time. The data thus obtained from each recording includes Time stamp, Segment times, Relative load, and Cylinder number. The additional data recorded include Engine speed, Engine roughness and associated terms predefined in the EMS and described in the algorithm and implementation sections.

5 Design of Experiments and Evaluation of System Performance

5.1 Vehicle Selection

‘Pegas’ is a CNG - 5 cylinder inline engine powered truck, which has the engine under study that will possibly be extended on other variants of trucks and buses. The truck has been tested and confirms to legal and brand performance requirements. The truck used to carry out measurements and experiments is provided with a break out box both for the S7 ECU and the ME7 ECU. Also the availability of the CNG engine in the bus chassis configuration gives the possibility for a comparison of the same engine on two variants. This also enables to achieve a congruence of the results of the misfire algorithm.

In order to evaluate the influence of vehicle / chassis configuration on the misfire detection system, a choice of available vehicle variants is selected on the following basis. The worst case condition of vehicle and drivetrain vibration from Scania’s experience is the 5 cylinder, diesel run truck “lollipop”. The long vehicle wheelbase with the 2-axle chassis configuration of the vehicle makes a good case for higher drivetrain disturbances. The vehicle is thus studied owing to its drivetrain configuration and a possible future worst case vehicle configuration on the CNG engine. Appendix 4 shows the Power – torque curve of the CNG engine and the diesel engine.

Since the truck under study is diesel engine powered, a comparison to the behaviour of the gas powered engine can prove to be inconclusive due to the combustion profile deviation which could be quite unpredictable. Nevertheless, a comparison is made to study the possible visibility of contribution of the drivetrain. However in order to have a fair comparison, a known truck with lesser drivetrain disturbances “Lisen” is selected. The reasons also include that both the vehicles are driven by the same engine but with known relatively different extreme levels of drivetrain noise and vibration.

5.2 Model Validation tests

The test conditions for verification and validation are set such that the Engine operating conditions and vehicle status are monitored to be maintained to set an even platform for a fair comparison. The test / experimental conditions are classified into 3 categories with brief explanation as follows

5.2.1 Steady State Tests

The vehicle under study is set in idle with the engine operating at the set idle speed with minimal accessory load. Also the idle data acquisition is carried out after a sufficient long run at the test track so that the engine temperature conditions and associated characteristics are repeatable and reliable. Apart from this, the engine speed is raised and set to rated speeds and then the corresponding data is taken.

5.2.2 Transient conditions

These test cases are undertaken mostly to interpret the behaviour of the vehicle when it is run under expected favorable conditions. This includes a normal vehicle speed drive and a high vehicle speed drive and sometimes a mix of the two explained as below.

Low Speed normal running: This is a case of the vehicle being run at a speed of around 45 kmph. For most of the automatic transmission gear box installed vehicles, a gear shift is possibly avoided. In case of unavoidable recordings, notice is done of the shift and taken up for further consideration for a more interesting case analysis. This provides a possibility to understand system behaviour at low engine speed and low load conditions.

High Speed Normal running: The vehicle is driven at speeds of around 80-90 kmph and most of the period at high engine speeds above than 1500 rpm. The test conditions enable to study the system response at high engine speed and high load conditions.

5.2.3 Turbulent conditions

These are the worst case conditions aimed at inducing greater disturbance to the misfire detection system. The scenarios are monitored closely such that the test vehicles are given the test parameters are maintained the same.

Rough road conditions: The rough road track with intermittent speed bumps placed at regular intervals is used. The same stretch of the test track is used to have the same test conditions performed at a low vehicle speed of 30-40 kmph, it is thus carried out at low speed and low load conditions.

Tip-in Tip-out: The vehicle is run such that the throttle / accelerator is varied from zero to maximum and alternated such that there is a huge transient in engine speed and vehicle speed. These test conditions provides a system insight under appreciable transient conditions. It provides to observe the behavior at erratic acceleration demands on the vehicle.

Single cylinder and Twin Cylinder induces misfires: In the case of the gas vehicles, misfire induced running is also taken up. A test case of single cylinder misfire induction and twin cylinder misfiring condition is taken up both at idle and at transient running conditions. Also included were test cases to combine up with turbulent driving conditions.

5.3 Model Validation using Gas Engine’s data

The time segment data from “Pegas” is used in the Simulink model developed and the raw engine roughness index obtained is used to compare against the Bosch system generated roughness index. The comparison is carried out also to ensure that the time segments are assigned the ignition cylinder appropriately in the sub system model. Also to be noted is that the calibration data value is used in the model wherever applicable as provide in the ME7 documentation and available from INCA.

Having done such a comparison, engine roughness values of the data acquired from Scania S7/8 is compared against the INCA acquired results. The following compilation of test results and discussion confirms the appropriate usage. Primarily the Gas vehicle data and results are discussed and the learning is transferred to Diesel vehicles. A comparative study of the response at idle, transient and induced disturbance conditions is carried out. As verification measure misfires are induced to look for expected patterns.

5.3.1 Steady State conditions

Using data from Pegas, Kongas, and Logas, the correctness of the model to indicate a change or reflect a disturbance is studied. At idle state vehicle conditions, Engine roughness index values are compared and matched to the expected values.

Limited information is available on filtering, pre or post signal processing and simplification as discussed in the previous sections (Learning adaptation, DMXRLU, phasing by 120 combustion events). Thus the roughness index estimated from the model is sought for pattern influences rather than absolute magnitude of the signal.

A close resemblance of roughness index at idle speed condition to the INCA output is evident from the figure [5.1]. Further at idle, when the misfire is induced, it is noted that the expected characteristic from the respective cylinder contribution is observed. Thus concluding the model is fit under steady state conditions and can suitable predict misfires just as the ME7 combination system would have done.

The engine roughness comparison indicated that there is a scaling factor which is not very clear with information obtained just from idle behavior. Hence a misfire is induced to determine the limits to be set in the model. The result of a misfire induced in the 2nd cylinder under idle conditions is shown [Fig 5.2]

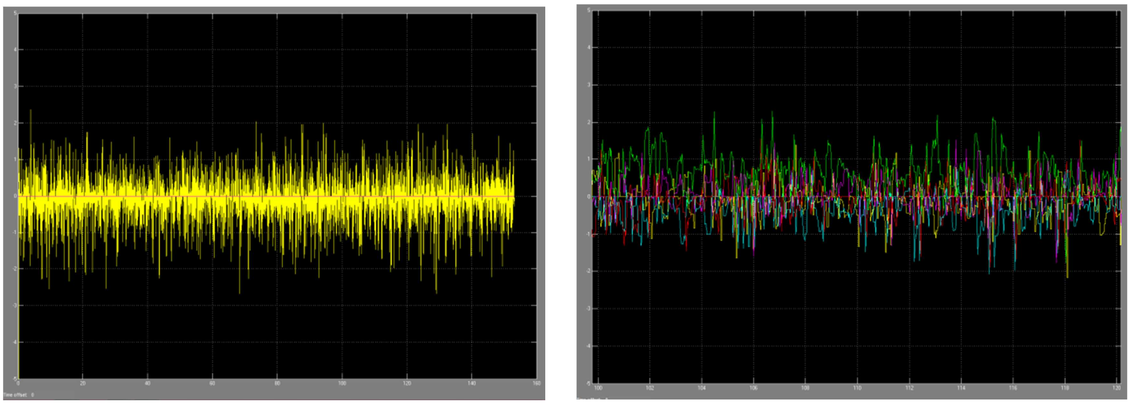


Figure 5.1 Engine roughness index comparison between model and INCA at idle (Combined and individual) - Pegas

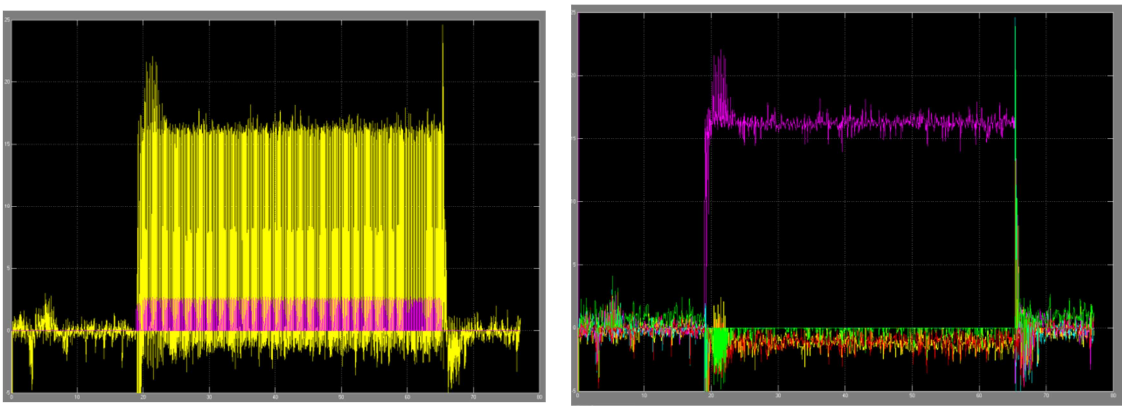


Figure 5.2 – 2nd cylinder misfiring continuously; Left - comparison of luts (INCA - magenta) and model (yellow) Right – Cylinder individual luts values (Misfire cylinder in magenta)

It is observed that the model follows closely the Bosch system behaviour quite closely and the two signals differ from each other only by a magnification factor. There is no loss of significant information required as is seen it closely congruent with the expected behaviour. As can be seen a reduction of the generated signal by a factor, arrived after comparison optimized with different factor values is close in magnitude and the behaviour is still preserved.

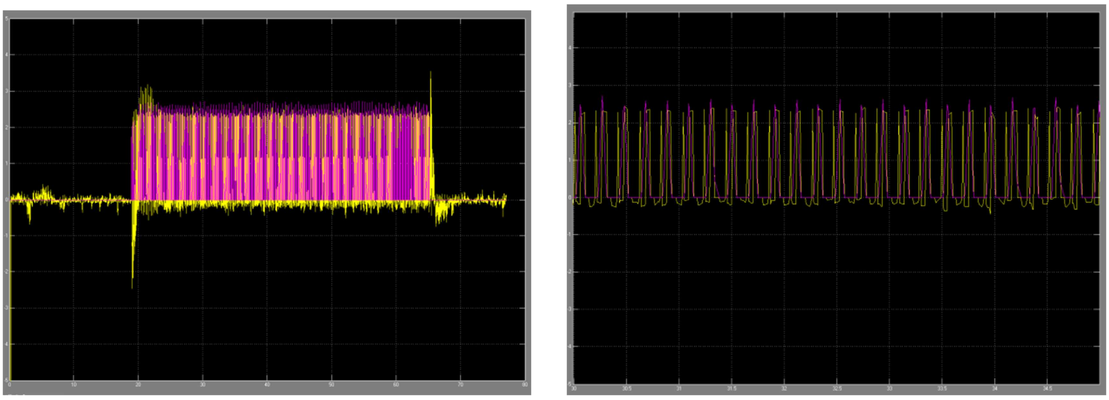


Figure 5.3 – 2nd cylinder misfiring continuously; Left - Comparison of luts (INCA - magenta) and model (including scale factor - yellow); Right – Magnified for visibility

5.3.2 Transient conditions

Depending upon the magnitude of change, variation pattern is replicated at the time of occurrence of the incident. Also to be noted is the phase difference of 128 combustion events. Transients at low speed in comparison with those at high speed show significant difference in magnitude as is expected from the system. The reduction factor to the output is provided to ease the comparison to the expected behaviour and greater visibility.

The roughness index is appreciably of a higher magnitude at high speed and load conditions in comparison to low speed and low load conditions, an expected behaviour however undesired. The distinct difference in magnitude is noted between the idle and the transient conditions due to additional noise generated by the acceleration / deceleration of the engine.

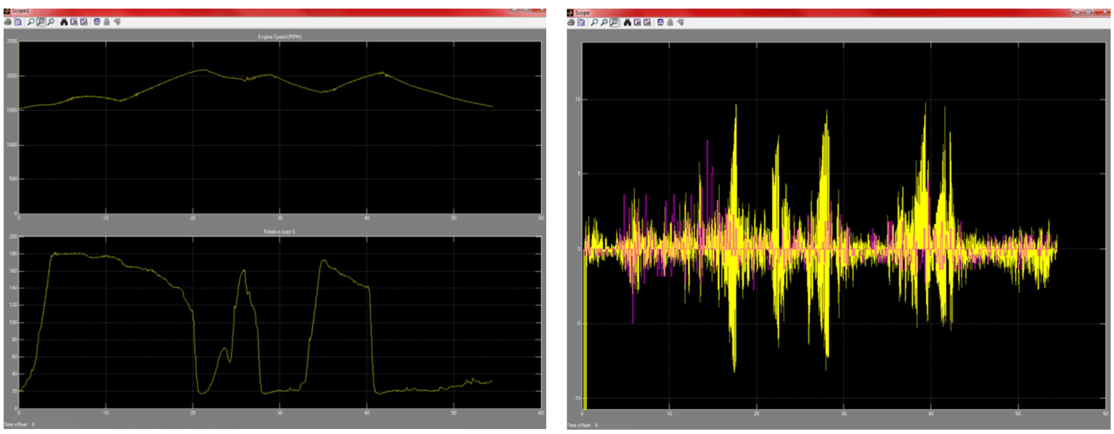


Figure 5.4 Transient operating points (Left) and Engine roughness index response comparison (INCA and model on Right)

The transient behaviour conditions thus primarily are comparable to the actual outcome from the present system in the respect of both pattern similarity and magnitude variation. The results from kongas are also confirmative of the findings from pegas. The variants show similar characteristic behaviour under transient conditions put through comparison with INCA and the model output are shown to indicate the same.

5.3.3 Testing under the influence of a disturbance

The potential impact of the external road influences, bad gear shifts, heavy transient operating conditions is also studied apart from the steady state and regular transient engine / vehicle conditions. The rough road track drive test and tip-in tip out tests are carried out for verification of the same. The noticed disturbances are also potentially influenced by a combination of load and speed factors. However vehicle speed expected to be driven under such rough road conditions are relatively lower. The test is thus carried out in both bands of engine operating conditions including some transients. As noticed and expected, both the model and the actual output correlate and are sufficiently lower than the tolerance band set in the calibration providing fool proof detection. The same is verified in the three CNG vehicles and confirmed.

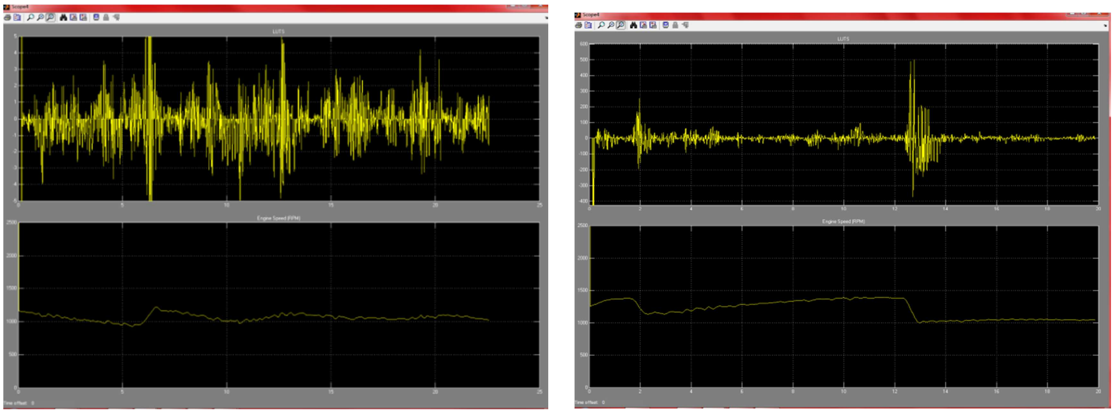


Figure 5.5 Rough road test – Engine roughness index Left – Pegas; Right - Logas

The change in gear shifts is evident when there is a sudden drop in engine speed even as engine load request continues to be linear. The roughness index increase in observed in all these cases and the magnitude of change are kept under the calibration limits. Some false trigger conditions are deviating due to the absence of filtering in the model though the severity is quite low and still not contributing to a malfunction indication. Thus the model is reliable and stable under the different operating conditions of the gas engine and matches the installed system behaviour.

The model behaviour is now validated for inputs of time segments from both the ME7 and the S7. The significant characteristic behaviour under steady state, transient and external disturbance data thus establish the developed model as fit for carrying out the simulations and experiments for the other vehicle variant conditions as laid out in the project plan.

5.4 Results and interpretation from the Diesel Engine data:

The roughness index values of the diesel vehicles obtained from the segment time data used in the validated model is discussed for evaluating primarily the expected behaviour of the misfire detection system under change of drivetrain and potential noise contributing factors. However it is to be noted that the combustion process can influence key aspects of magnitude and pattern of the roughness index since the combustion duration and torque delivery are significantly different under the perspective that each combustion event is studied in the model as input.

Thus in order to ease and provide a comparison, the choice of vehicles describes the selection of extremely performing vehicles in terms of disturbance expectancy however powered by the same diesel engine. A comparison under steady state, transient and externally induced disturbance conditions is studied to have an understanding of the possible contribution primarily by the vehicle variation in build / construction. Further the study of patterns and magnitude variations under the different conditions are compared to the Gas engine behaviour to note any possible links and predictions.

5.4.1 Steady state conditions

The model engine roughness index to idle input data is analysed. As mentioned before, care is taken to ensure that the engine has been run over a long operation sufficient enough to have a warm engine and thus analyse under standard expected engine operating conditions. The figure [5.6] shows the luts values of the vehicle variants under idle condition. It is noticed that the pattern and magnitude are similar since there are no external influences and no driveline contribution. Even though the engine idle speed settings of the vehicles are 100RPMs apart, the engine roughness index values are congruent and confirming to expected pattern.

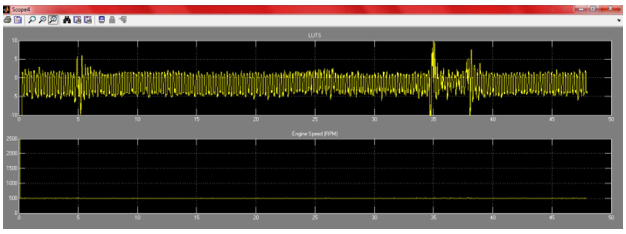


Figure 5.6 (a) Engine roughness index at idle Lisen

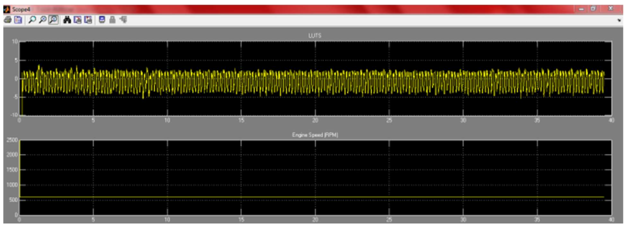


Figure 5.6 (b) Engine roughness index at idle - Lollipop

A comparison of the steady state conditions of the diesel vehicles to the gas vehicles show that the pattern of the roughness indices are the same and have a marginally higher magnitude. The attributes of the magnitude cannot be ascertained since there is a significant amount of influencing factors ranging from combustion to idle running conditions.

5.4.2 Transient operating conditions

The magnitude and pattern of engine roughness index upon operating under transient conditions by taking up a normal test drive at rated speeds, loads and including several transient conditions is analysed. The vehicle is operated with driving conditions such as low engine speed and load operations to high engine speed and load operations. Also varying vehicle speed drive conditions are studied to see the influence on the roughness index. The steady state results and the gas engine results are used for an understanding and interpretation of the phenomenon displayed.

The change in load and speed conditions has quite similar influences on the engine roughness. Also noticed is the sharp increase in roughness when a quick transient of speed or load occurs. A high speed and load condition indicates a higher roughness index than that indicated at low speed and load condition. The characteristic behaviour of a higher magnitude in case of transient and driving conditions of the CNG engines is also visible in the result. Thus in spite of a distinct engine, the influence of load and speed condition is established to be a general contributing factor to engine roughness. Also noticed is that the magnitude is quite less in the driving cases than the gas engines.

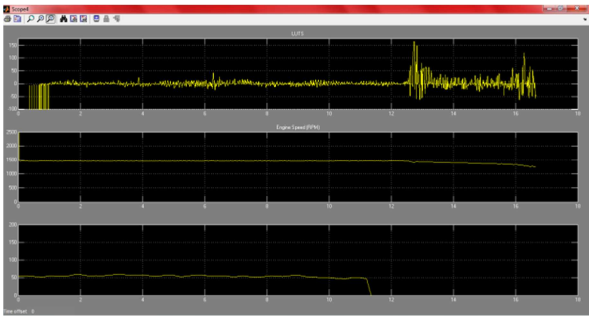


Figure 5.7 (a) Transient operating conditions Lisen

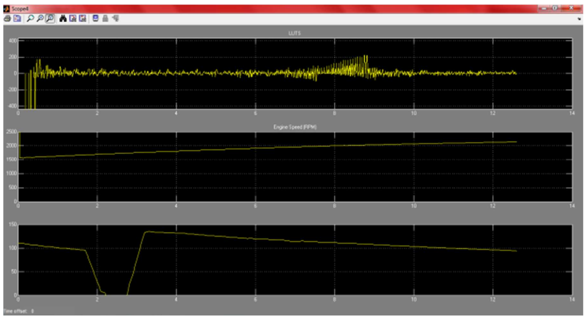


Figure 5.7 (b) Transient operating conditions Lollipop

The concluding result of the transient and steady state condition results from the diesel vehicles behaviour is that the influence of engine load and speed operating conditions on the engine roughness index are comparable and in proportion as far as the contribution of the change in driveline is concerned. The above results provide a platform for comparison of purely external disturbances provided by the rough road or high frequency transient conditions.

5.4.3 Induced disturbances

The contributing factors of the diesel combustion have been distinguished with the interpretation from the steady state and the transient engine operating conditions. The distinct contributions of the chassis variation's response to road conditions and its influence on the detection system can thus be studied.

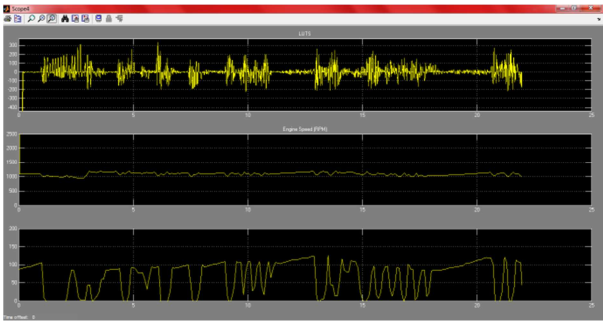


Figure 5.8 (a) Tip in Tip out test – Engine roughness index - Lisen

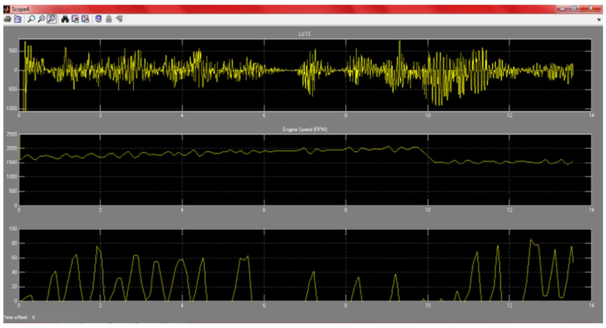


Figure 5.8 (b) Tip in Tip out test – Engine roughness index - Lollipop

The influence of change in load is profoundly noticed in case of a high frequent transient condition very much displayed by figure [5.8]. It is observed that the response pattern to the disturbance in the test cases show close relation to the operating conditions with contribution of increased engine roughness index from the turbulent conditions. The magnitude change is observed to be relatively less on the two configurations with a slightly higher level on Lollipop.

5.5 Conclusion

The model is validated and found to indicate significant characteristics of the Bosch ME7 misfire detection system confirmed with the assistance of ETAS INCA tool and the associated literature. The characteristics at the three defined operating conditions have been studied in detail. The confirmation comes after verification in three different versions of the vehicle powered by the same CNG engine.

The response to transients and turbulent conditions has assisted in interpreting the diesel engine results of the model. The learning thus transferred show that there is less deviation at almost all conditions. There is a small increase in engine roughness in lollipop when compared to Lisen under transient and turbulent conditions. However the difference in magnitude is quite small and similar to the change observed among the CNG vehicles. In summary, the extension of the CNG engine with the same misfire detection system to variants such as the Lollipop is believed to work as efficiently as it does in the current configurations.

6 Misfire Generator and Alternate detection systems

6.1 Misfire Generator concept

In order to induce a misfire artificially, the ignition or the fuel interruption is to be done. The fuel interruption in case of a non-direct injected engine and other such conditions provide a complex situation for the possibility. The ignition system in the current and future vehicles is controlled mostly by the Engine Management System. The ignition control signal in the Bosch EMS is cylinder specific. A schematic of the ignition system is shown in the following figure [6.1]. As seen in the figure, a misfire can be induced by breaking the ignition circuit. The control signal for each spark plug is provided individually from the EMS. Thus breaking this signal induces a misfire in the respective cylinder.

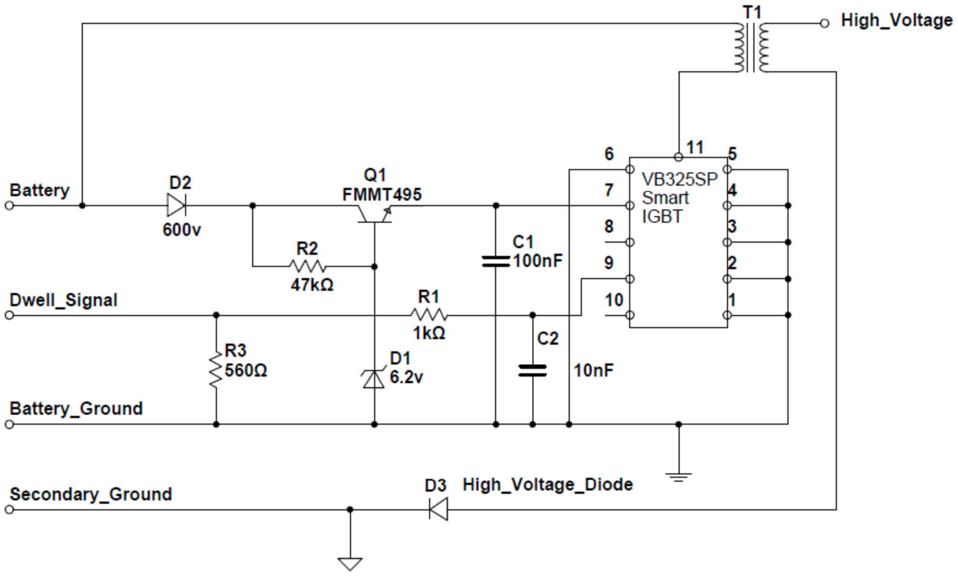


Figure 6.1 Ignition circuit – Pegas

A control signal to the ignition circuit can be controlled by a different misfire generating signal according to the requirements and desired demands. This gives the opportunity to generate misfires at an accurate known rate. Also the testing of the misfire system is done reliably to a ensuring a greater accuracy by evaluating its performance. An advantage of using such a concept is that a single control signal is sufficient to generate desired misfires in any of the cylinders at accurate misfire rates. Also it provides the capability to generate a single misfire much accurately and thus system responses to such an occurrence can monitored. Such a system thus offers to accurately generate misfires accurate to every single event and at any specific cylinder. Further several patterns of induced misfires is also possible.

6.2 Design and Construction

The ignition signal to the ignition circuit from the Bosch EMS is studied. The PWM signal present is such that at the time of ignition, the constant 5V supply is to be interrupted to 0V. In order to interrupt the ignition, an inverted signal is to be provided thus generating a misfire in the specific cylinder. The Bosch EMS provides five ignition outputs to the ignition circuit, each pertaining to a specific cylinder. In the construction of the misfire generator, the misfire generation is done for a single cylinder with a view that expansion to five cylinders can be carried out when necessary. Hence a trigger from an external control signal can be used to invert the normal signal thereby producing a discontinuity in the ignition circuit. The circuit diagram of the misfire generator is shown as below:

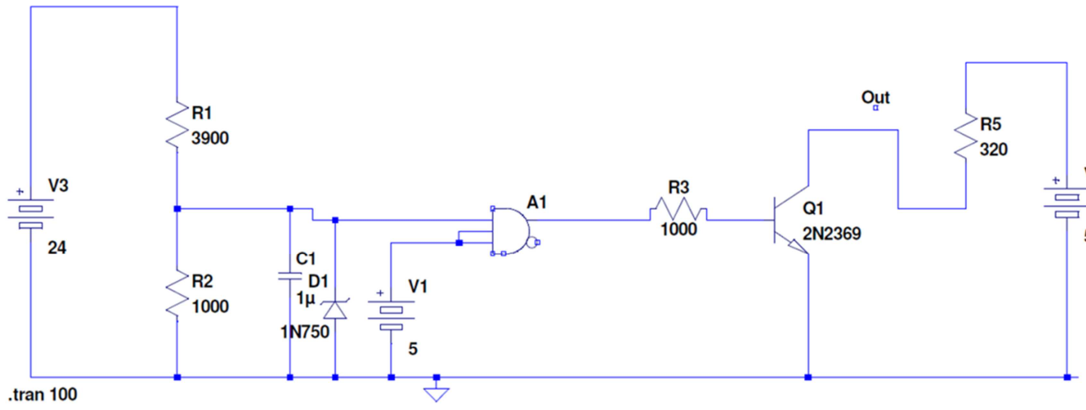


Figure 6.2 Misfire generator circuit

The circuit was tested in the Pegas truck and the misfire parameters were monitored. The control signal for the misfire generator was masked by using a 5V supply signal since it has not yet been developed. The result of using the circuit was success in generating a misfire in the specific cylinder. The circuit can be expanded to cover all five cylinders and the control signal can be generated from S7 due to availability if control system opportunities.

6.3 Alternate Detection Systems and algorithms

Alternate misfire detection systems developed using various approaches have been studied and the listed papers are discussed to highlight the principle and methodology employed. Ion current sensing is the only intrusive method and the rest are all indirect methods of detection. Misfire detection methods that have been researched upon include:

1. Crank signal processing – Several approaches / algorithms [6.3.1 to 6.3.5]

2. Ion current sensing and measurement [6.3.6]

3. Exhaust gas pressure signal processing [6.3.7]

4. Lambda – Wideband O2 sensor signal processing [6.3.8]

6.3.1 Advanced Engine Misfire Detection for SI-Engines (5)

The system concept is based on evaluation of variations in crankshaft speed. The system includes a sensor stage, signal processing & Feature extraction and classification stage. The influence of speed and load is removed from the segment time of the cylinder in a separate module and feature extraction is performed. This is the concept that has been used in the current system and defined elaborately in Chapter 2. It is to be noted that percentage drop in engine speed caused by misfiring varies on the Operating conditions of Engine load and Speed. In general Low load & high speed have minimal deviation and Full load & high speed have a bigger deviation.

6.3.2 Misfire and compression fault detection through the energy model (11)

This article proposes a simple algorithm for misfire detection in reciprocating engines. The algorithm, based on an energy model of the engine, requires the measurement of the instantaneous angular speed. By processing the engine dynamics in the angular domain, variations in the working parameters of the engine, such as external load and mean angular speed, are compensated. A dimensionless feature has been abstracted for evaluation of the combustion as well as compression process of each cylinder. The proposed technique is expected to be easy to implement and to provide useful information for on-line monitoring of the in-cylinder processes in an internal combustion engine.

The energy model estimates the energy change (kinetic and potential) in the engine components (Piston, Connecting rod, Crank shaft, Clutch). The contribution of energy change from each cylinder is assigned to the respective equal distribution according to the number of cylinders. The compression and expansion index are obtained from the division of this segment of each cylinder. The dimensionless indices are used to interpret the occurrence of misfiring.

6.3.3 Engine misfire detection (using Kalman filter) (12)

In this paper a simplified engine model is introduced in order to estimate the combustion torque from angular velocity measurement, using a Kalman filter approach. Signals from conventional angular speed sensors of available engine management systems are used. The crank speed sensor signal is processed using a Kalman filter to evaluate the combustion torque. This estimation is used for determination of misfiring. The current estimation limit of this approach is between 3000 and 4000 rpm.

6.3.4 A methodology for increasing the signal to noise ratio for the misfire detection at high speed in a high performance engine (13)

This paper is quite similar to the fuel on/off adaptation of the DMDFON function. It focuses primarily on the reduction of noise ratio in the critical operating ranges of the Engine. The paper presents a methodology for pre-processing the combustion time intervals that is the basic signal used in misfire detection strategies, with the aim of increasing the signal-to-noise ratio to enable a more efficient misfire diagnosis, especially when the engine is running at high speeds and low loads.

From the experiments, it is seen that with increasing engine speed, it becomes difficult to achieve a misfire detection performance over 80% without false alarms. The combustion time signal presents a noise level that has about the same amplitude of the misfire effect on the signal itself. A methodology to increase the signal-to-noise ratio is therefore the introduction of a pre-processing stage of the combustion time intervals, in order to decrease the noise level related to a different systematic behaviour of the combustion inside each single cylinder.

The reason for computing an 8 samples moving average is that, if the noise on the combustion time signal presents a cyclic repeatability, it should essentially disappear after the averaging process. The difference between the combustion time signal and its moving average allows isolating the noise from the signal.

6.3.5 Misfire Detection on S.I. Engines by Instantaneous Torque Analysis (14)

The instantaneous torque signal is the superposition of two major components. The first one is resulting from the combustion taking place successively in each cylinder. The second results from engine dynamics, mostly due to rotating parts dynamics. When combustion doesn't happen, or is even not complete, whatever the reason is, the combustion component of the engine instantaneous torque encounters fluctuations. The detection algorithms based on engine instantaneous torque present the same structure as the ones dealing with crankshaft angular speed. The misfire indicator used in this experimental part is a non-uniformity index, based on extremums sampling of the torque signal.

6.3.6 Ion Current Sensing for Spark Ignition Engines (15)

This paper describes an ion current measurement system with a new, modified inductive ignition system and evaluates the detection quality for misfire and knocks detection. The System uses an ignition circuit with adjustable spark duration limitation. The measurement circuit is located at the low tension side of the secondary ignition coil. The ignition and measurement system serves to sample the ion current with the spark-plug electrodes as sensing element.

The analog pre-processing delivers an ion current signal without any offset value. As the low frequency part of the signal mainly contains the combustion information, the high frequency part was suppressed by a fourth order Bessel low-pass filter. For an easy implementation of the function for misfire detection, two plain features were used, the maximum value and the integral value of the ion current signal within a specified measurement window. The ion current signal increases with increasing engine load and speed. Also affecting the signal are fuel additives, EGR dilution, Ignition retard, Stratified charge operation and Spark plug type. The advantages of Ion Current Sensing include additional capability for Knock detection and A/F ratio measurement.

6.3.7 A Time Domain Based Diagnostic System for Misfire Detection in Spark-Ignition Engines by Exhaust-Gas Pressure Analysis (16)

For the cylinder-selective monitoring of combustion cycles in spark-ignition engines, the dynamic exhaust gas pressure is analysed. It is shown that even within the operating areas of high engine speeds and low loads on engines with a high number of cylinders good classification rates can be obtained. For each combustion cycle, each exhaust valve opens once in the gas exchange phase of the engine. The pressure waves in the exhaust manifolds are excited by the sudden relaxation of the combustion gases and the piston movement when the exhaust valves open. The exhaust-gas pulsations depend on the combustion process and therefore on the cylinder pressure when the exhaust-valve opens. The formation of the resulting pressure waves is influenced by the characteristics of the exhaust system.

If a cylinder misfires, the exhaust-gas pressure drops significantly, due to the missing combustion and the resulting lower cylinder pressure. Compared to a regular combustion without misfires, additional frequency components of high intensity below the 6th EH (Engine Harmonic) arise. For the measurement of the exhaust-gas pressure, certain requirements regarding the specification of the pressure transducer and its location in the exhaust system have to be taken into account. The pressure sensor should have a cut-off frequency of at least 200 Hz (for six-cylinder) in order to measure misfire related frequency components as undamped as possible. Additionally, the measurement requires a careful design of the Tee-joint coupled pipe with regard to its damping characteristics, resonance behaviour and temperature influence.

The intensity of the spectral amplitudes depends strongly on the engine operating point and the resulting exhaust gas temperature. Since a change of exhaust-gas temperature causes a shift of the damping characteristic, the gradient of the damping characteristic around an engine operating point (engine speed and load) is crucial for the stability of the amplitudes. Since the pressure transducer is not directly positioned at the exhaust port but approximately 1.5 m away in the catalyst mixing tube, all occurring temporal delays must be taken into account in order to allocate the excited pressure waves in accordance to the cylinder. This concerns the transport delay due to the propagation speed of the pressure waves as well as the group delays of the used filters and the pressure transmitter. Taking all delays into consideration one obtains the point in time of the exhaust-valve opening of each cylinder related to the measuring point, independent on the engine operating point (engine speed and load).

6.3.8 Application of a Wide Range Oxygen Sensor for the Misfire Detection (17)

A wide-range oxygen sensor, installed at the confluence point of the exhaust manifold, was adopted to measure the variation in oxygen concentration in case of a misfire. The signals of the wide-range oxygen sensor were characterized over the various engine-operating conditions in order to decide the monitoring parameters for the detection of the misfire and the corresponding faulty cylinder. A misfire could be distinguished more clearly from normal combustion through the differentiation of the sensor response signal. Amplitude of the fluctuation of the differentiated signal was used as a monitoring parameter for misfire detection. Transient response was fast enough to detect the misfire even at a high engine speed of 5000RPM. The phase delay angle of the second peak of the differentiated signal from a reference signal was found appropriate for identification of the faulty cylinder.

When an ignition induced misfire is allowed to happen in a specified cylinder, hydrocarbon concentration at the confluence point in the exhaust manifold fluctuates in a pattern that has twin peaks during two cycles. Oxygen concentration also fluctuates in the same pattern as that of hydrocarbon concentration. The fluctuation of the differentiated signal by a misfiring was more noticeable than the fluctuation of the raw signal, so that the former was used as a monitoring signal for the detection of misfiring using a wide-range oxygen sensor. The response rate of the wide-range oxygen sensor increases with engine speed and the misfire detection is enabled even under high engine speed conditions, since the exhaust gas flow rate and temperature increase with engine speed. The basic pattern of twin peaks for one misfiring was maintained as the engine load changed, but the amplitude of the first peak was increased with engine load.

6.4 Conclusion

The misfire generator thus built is a starting step in the process of developing a fully functional and capable system to fulfil the inclined requirements. The current design can be extended to multiple cylinders. The control signal input can be developed from the S7 inputs.

The alternate detection systems thus studied and further discussions held so far have indicated that the current algorithm based on the crank speed is accurate in the speed range of the engine. Further in the cases of high speed, assistance to confirmation of misfire presence can be performed using the exhaust gas pressure sensor. Simplicity, accuracy and low cost of implementation are prime reasons to arrive at such a conclusion.

7 Bibliography

1. **Heywood, John B.** *Internal Combustion Engine Fundamentals.* McGraw Hill, 1988.

2. *Misfire detection by evaluating crankshaft speed— a means to comply with OBDII.* **M.Klenk, W.Moser, W.Muller, W.Wimmer,.** 1993, SAE Paper 930399.

3. **Requirements, California's OBDII.** *(Title 13, California Code of Regulations (CCR), Section 1968) Resolution 96-34, 15.* Oct. 1996.

4. *Methods of On-Board Misfire Detection.* **Günther Plapp, Martin Klenk, and Winfried Moser.** s.l. : SAE 900232, 1990.

5. *Advanced Engine Misfire Detection for SI-Engines.* **Jürgen Förster, Andrea Lohmann, Manfred Mezger, and Klaus Ries-Müller.** s.l. : SAE 970855, 1997.

6. *Experiences with a new method for measuring the engine roughness.* **Dr. R. Latsch, E. Mausner.** s.l. : ISATA 79 Automotive Technology and Automation, 1979, Vols. 1-2.

7. *An On-Line Engine Roughness Measurement Technique.* **William P. Mihelc, Stephen J. Citron.** Detroit, Michigan : SAE 840136, 1984.

8. *Diagnosis of Individual CylinderMisfires by Signature Analysis of Crankshaft Speed Fluctuations.* **Rizzoni, G.** Detroit. Michigan : SAE 890884, 1989.

9. *Advanced misfire detection using adaptive signal processing.* **Naik, Sanjeev.** 181-198, s.l. : International Journal of Adaptive Control and Signal Processing, 2004, Vol. 18.

10. *Signal Processing for Rough Road Detection.* **Tameem Assaf, David Mathews and Sanjeev Naik.** s.l. : SAE 2010-01-0673, 2010.

11. *'Misfire and compression fault detection through the energy model.* **Francisco V. Tinaut, Andre´ s Melgar, Hannes Laget, Jose´ I. Domı´nguez.** 1521–1535, s.l. : Elsevier - Mechanical Systems and Signal Processing , (2007) , Vol. 21 .

12. *Engine misfire detection.* **Kiencke, U.** 203-208, s.l. : Elsevier - Control Engineering Practice 7, 1999.

13. *A methodology for increasing the signal to noise ratio for the misfire detection at high speed in a high performance engine.* **Cavina, Nicolo` and Giovanni Cipolla, Francesco Marcigliano, Davide Moro, Luca Poggio.** s.l. : Elsevier - Control Engineering Practice 14, 2006, Vols. 243-250.

14. *Misfire Detection on S.I. Engines by Instantaneous Torque Analysis.* **V. Mahieu, P. Duponcheele, B. Leduc, J. L. Vanhemelrijk, M. Morenville, P. Deh.** s.l. : SAE 2000-01-0367.

15. *Ion Current Sensing for Spark Ignition Engines.* **Jürgen Förster, Achim Günther, Markus Ketterer, Klaus-Jürgen Wald.** s.l. : SAE 1999-01-0204.

16. *A Time Domain Based Diagnostic System for Misfire Detection in Spark-Ignition Engines by Exhaust-Gas Pressure Analysis.* **Markus Willimowski, Rolf Isermann.** s.l. : SAE 2000-01-0366.

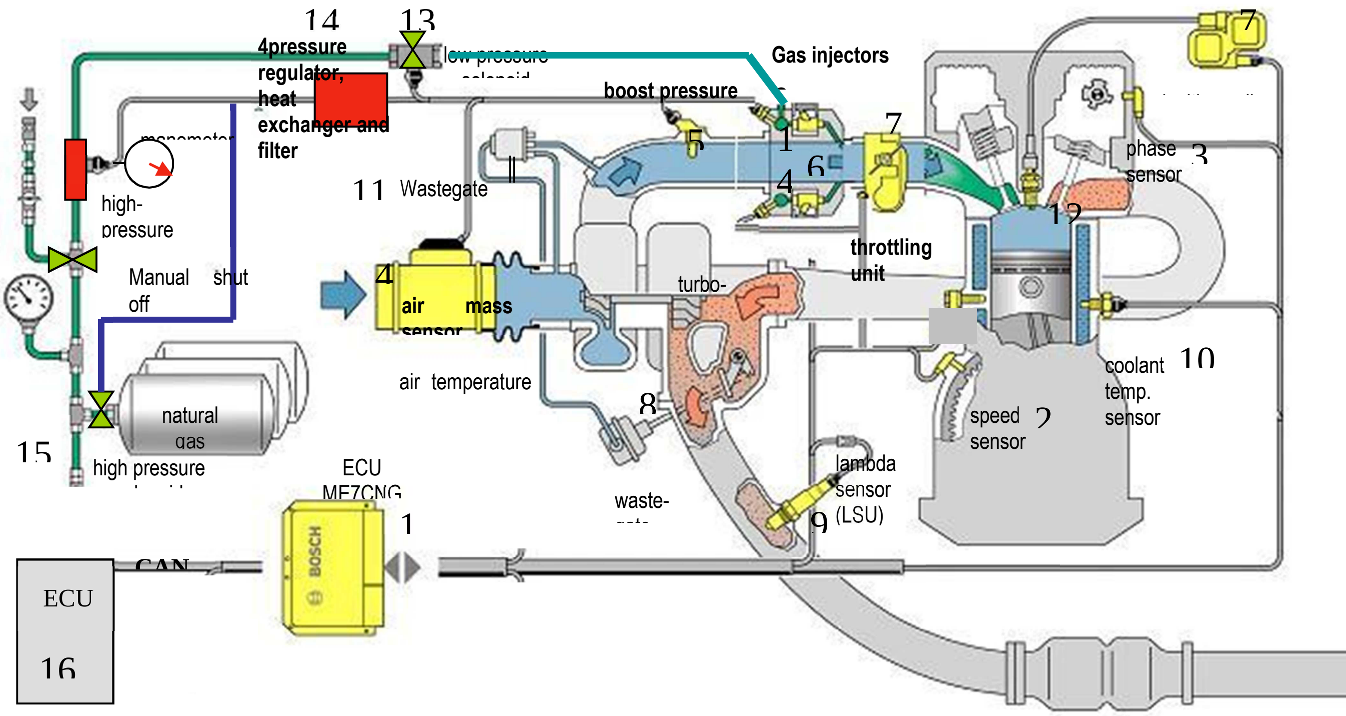
17. *Application of a Wide Range Oxygen Sensor for the Misfire Detection.* **Youngkyo Chung, Choongsik Bae, Sangmin Choi, Kumjung Yoon.** s.l. : SAE 1999-01-1485.

Appendix

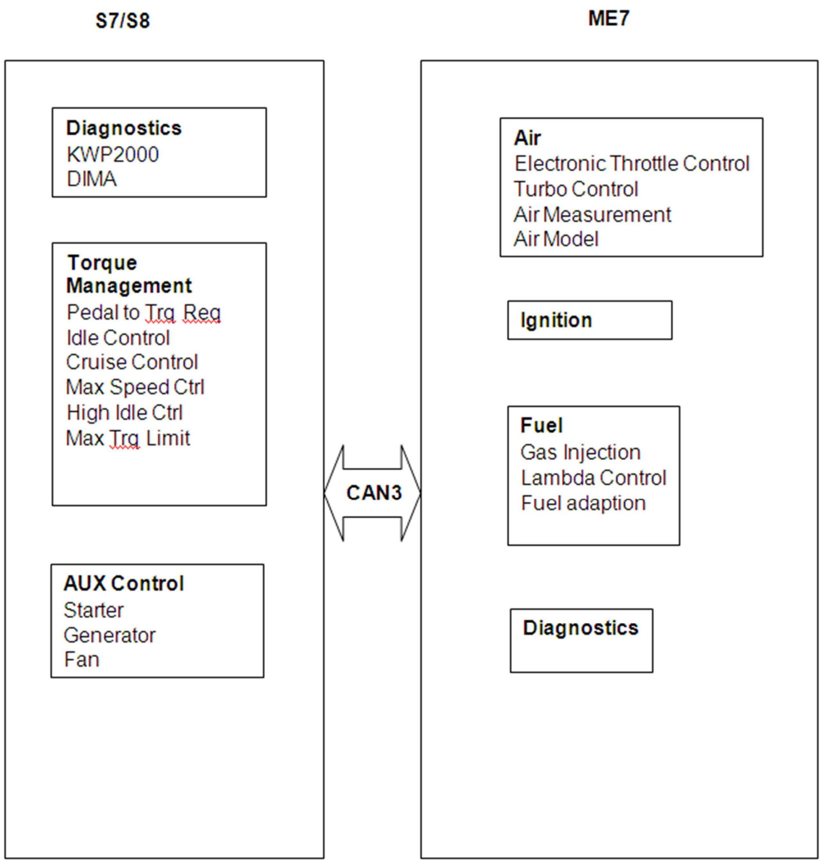
Appendix 1: Engine Specification (CNG)

	OC9 G04	**OC9 G05**
Swept volume	9.3 litres	9.3 litres
Maximum power	270 hp (199 kW) at 1900 r/min	305 hp (224 kW) at 1900 r/min
Maximum torque	1100 Nm between 1000 and 1400 r/min	1250 Nm between 1000 and 1400 r/min
Euro 5 technology	Lambda control, oxicat	Lambda control, oxicat
Gearboxes	Allison 6-speed automatic gearbox	Allison 6-speed automatic gearbox
Fuel system	Bosch	Bosch
Fuel	Compressed Natural Gas	Compressed Natural Gas
Lambda control	Broad band	Broad band
Exhaust treatment	Oxicat	Oxicat
Cylinder configuration	In-line 5 Cylinder	In-line 5 Cylinder
Aspiration & Cooling	Turbocharger with Intercooler	Turbocharger with Intercooler
Fuel delivery	Premixed CNG before throttle	Premixed CNG before throttle
Firing Order	1-2-4-5-3	1-2-4-5-3

Appendix 2: Engine Layout (CNG)



Appendix 3: Bosch ME7 and Scania S7/8 Communication and data exchange



Appendix 4: Power Torque Curves for OC9 G04 270 (CNG engine) and DC9 38 280 (Diesel engine)