HCM UNIVERSITY OF TECHNOLOGY
Faculty of Transportation Engineering
Department of Automotive Engineering

CAPSTONE PROJECT

STUDY ON TROUBLE SYMPTOMS OF D-JETRONIC TYPED ELECTRONIC FUEL INJECTION SYSTEM

Instructor: PhD Tran Dang Long
Students: Lam Huynh Phat - 2053313
Course ID: TR4347 **Semester:** 233

Contents

OVERVIEW

To meet modern automotive standards, fuel injection systems have continuously evolved, leading to the development of the Electronic Fuel Injection (EFI) system. The EFI system precisely meters fuel into the combustion chamber with respect to the amount of air charged in the intake stroke, governing engine performances in terms of fuel efficiency, emissions, and responses.

During operation, the system faces challenges due to various potential failures such as: contaminated sensors, weak actuators, damaged wires, short circuits, and mechanical issues. Technicians often use OBD function and standard SSCC diagnostic process to determine the faults, which is a complicated and time-consuming procedure, requiring skilled and experienced technicians. Therefore, our group developed an automatic diagnostic solution. By performing a specific diagnostic engine test cycle, engine live data was collected from the OBD system, and then visualized into radar-chart-type diagnostic images representing normal or abnormal engine conditions, and the obtained diagnostic image was classified by AI algorithm to identify the cause of failure. This approach required obtaining a amount of diagnostic images for AI training, as well as validating the collected images. As a result, I decided to implement the "Study on trouble symptoms of -Jetronic type electronic fuel injection systems" project.

The execution of this project provides an opportunity for group members to reinforce their foundational knowledge of automotive theory, engine structure, operation and maintenance, and control... However, due to limitations in knowledge, experience, scarce reference materials, the project may have some shortcomings. We sincerely appreciate the guidance and feedback from our instructors to identify these weaknesses, enabling the group to learn from them and strive for better improvements. Thank you.

ACKNOWLEDGEMENT

To successfully complete our project, we would like to express our deep gratitude to our families, who have provided us with unwavering support both emotionally and materially throughout our studies and research at this prestigious institution, Ho Chi Minh City University of Technology - Vietnam National University.

Next, we extend our sincere and profound appreciation to our advisors: Dr. Tran Dang Long, Dr. Pham Tran Dang Quang, and Mr. Cao Thai Duong (a fellow student from the K19 class at the University of Technology), for their dedicated guidance, provision of valuable resources, assistance with equipment and tools, and for patiently addressing our inquiries and encouraging us throughout the project.

Furthermore, we would like to sincerely thank the faculty members of the Automotive Engineering - Internal Combustion Engines Department, Faculty of Transportation Engineering, for their wholehearted teaching, imparting fundamental and advanced knowledge to students, enabling us to have a solid foundation for understanding and researching various automotive engineering topics.

Lastly, we express our sincere gratitude to Ho Chi Minh City University of Technology - Vietnam National University for providing an excellent learning environment, allowing students to acquire knowledge and develop their skills.

With deep appreciation, we send our wishes for good health and the best of everything to our esteemed instructors, staff members of the university, fellow colleagues, and all friends who have studied and worked at Ho Chi Minh City University of Technology - Vietnam National University.

PROJECT SUMMARY

The study and research of the functions of sensors and actuators, as well as the systems and technologies of the 4A91 gasoline engine in the Mitsubishi Xpander 2020, provided an overview of the research object. This enabled an understanding of common malfunctions related to these elements, as well as indirect malfunctions that could lead to faults in those components. The study was conducted based on theoretical research (reading and consulting official documents, combined with investigating symptoms and fault manifestations from various information sources) and the examination of the structure of sensors, actuators, systems, and technologies in the actual engine to gain specific and visual insights.

After establishing a comprehensive theoretical foundation, the team developed simulation procedures, particularly for mechanical faults. They then performed the diagnostic engine speed cycle to collect live data and diagnostic images. The collected live data and diagnostic images were combined with Diagnostic Trouble Codes (DTCs), the "Check Engine" light, and engine behavior to analyze the relationship between fault levels and their symptoms. Finally, the observations and evaluations of the implementation process helped refine the specialized project and establish directions for further development in the upcoming graduation project.

TABLE LIST

FIGURE LIST

TERM LIST

Term	Meaning
APS	Accelerator Pedal Position Sensor
DOHC	Double Overhead Camshaft
ECT	Engine Coolant Temperature
ECU	Electronic Control Unit
EFI	Electronic Fuel Injection
IAT	Intake air temperature
STFT	Short Term Fuel Trim
LTFT	Long Term Fuel Trim
MAP	Manifold Absolute Pressure
MIVEC	Mitsubishi Innovative Valve Timing Electronic Control System
MPI	Multi-Port Injection
O2F	Oxygen Front
O2R	Oxygen Rear
OBD-II	On-Board Diagnostics II
PCM	Powertrain Control Module
SSCC	Symtomp – System – Component – Cause
TA	Timing advanced
TPS	Throttle control Position Sensor
TWC	Three-Way Catalyst

CHAPTER 1: INTRODUCTION

1. Thesis/Capstone project title title: Study on trouble symptoms of D-Jetronic typed electronic fuel injection systems.

2. Advisor's fullname: Ph.D. Tran Dang Long

3. Student's full name: Lam Huynh Phat **- Student ID:** 2053313 ...

4. Thesis contents

4.1. Category: ☐ Product design ☐ Testing design

☐ Scientific research ☑ Other: Testing

4.2. Purpose and technical requirements

a) Objectives

Design the fault simulation methods and analyze the relationship between fault levels and symptoms in D-Jetronic typed electronic fuel injection systems.

b) Technical requirements

❖ Build the fault simulation procedure.

- Must ensuring driver safety and no harm to the model.
- Must be logical, and can vary multiple levels.
- Must be related to mechanical faults, and accurately reflect the behavior of the faults in practice.

❖ Perform the engine speed cycle and collect live data.

- The error between each measurements do not significant.
- Ensure the collected datasets remain within a stable range, minimizing unstable data during engine stage transitions for more accurate data extraction.

❖ Analyze the relationship between fault level and symptoms.

- Must represent and explain the changes of symptoms according to faults levels.
- Must be based on the operation of current systems and technologies present in the engine.

4.3. Core problems to be solved & Solving Idea/Methods :

a) Main problems to be solved:

❖ Build the fault simulation procedure.

- Choose appropriate simulation method and suitable equipments.
- Understanding about mechanical faults and its symptoms in practice.
- Understanding about engine systems.

❖ Perform the engine speed cycle and collect live data.

- Ensure the validity when executing the cycle, requires correct pushing pedal when performing cycle.
- Must take place under consistent conditions.

❖ Analyze the relationship between fault level and symptoms.

- The analysis must be consistent between faults.
- Represent the impact of each faults on each engine stage according to fault levels.
- Understanding about features and operation of engine systems and technologies.

b) Solving Idea/Methods:

❖ Build the fault simulation procedure.

- Study about common mechanical faults and its symptoms in practice.
- Study fault simulation methods: present methods, compare the advantages and disadvantages of the options. Design fault simulation options from learned fault groups, choose suitable equipments.
- Survey the structure and function of engine systems.

❖ Perform the engine speed cycle and collect live data.

- Perform the cycle and synthetic live data for at least 5 times for each datasets.
- Practice to achive the accuracy when performing cycle.
- Perform the cylce in consistent both objective and subjective conditions.

❖ Analyze the relationship between fault level and symptoms.

- Study about features and operation of current engine systems and technologies.
- Refer to diagnostic documents and related knowledge.
- Analyze the impact of each fault on the engine's operation at each stage of the engine speed cycle, comparing live data from faulty conditions to normal conditions.
- Regularly review and have an overview between analysis of each fault.
- From above analysis, draw a relationship between the error level and the symptoms.

4.4. Works to be done & Required results:

No.	Works to be done	**Required results** *(Ex: data, equations, models, diagrams, parameters, charts, findings…)*
1	Design fault simulation methods	Simulation methods for 3 faults: Cracked intake manifold, weak fuel pump and leaked evaporative purge valve
2	Analyze the relationship between fault levels and symptoms	Relationship between fault levels and symptoms

Table 1.1. *Works to be done & Required results*

4.5. Requested products:

☑ Technical report ☑ Poster ☑ Scientific paper

☐ Software ☐ Firmware ☐ Numerical model

☐ General layout drawings ☐ Detailed drawing ☐ Assembly drawings

☐ Others: ....

4.6. Scope of Thesis/Capstone project: The project is applied on the D-Jetronic typed electronic fuel injection system of the gasoline engine. And focus on the mechanical faults.

4.7. Tasks of each team member:

No.	Member's full name	Works assigned
1	Lam Huynh Phat	• Design fault simulation methods • Analyze the relationship between fault levels and symptoms

Table 1.2. *Tasks of each team member*

5. Chapters of project:

- ❖ **Chapter 1: Introduction**
- ❖ **Chapter 2: Theoretical basis**
- ❖ **Chapter 3: Study on trouble symptoms of D-jetronic typed electronic fuel injection system**
- ❖ **Chapter 4: Conclusion**

CHAPTER 2: THEORETICAL BASIS

I. OVERVIEW OF FUNCTIONAL SYSTEMS ON THE 4A91 GASOLINE ENGINE - MITSUBISHI XPANDER 2020

1.1. Overview

To study the trouble symptoms of D-Jetronic type electronic fuel injection systems, we first needed to gain a general understanding of the engine's current technologies and functional systems. This process involved surveying the system, examining the layout diagram, outlining its operational principles, and defining the roles of its components. Instead of using a sophisticated air mass flow meter which increases overall cost, the amount of charged-air can be determined by the speed-density method basing on engine speed, manifold absolute pressure, and intake air temperature. The overall diagram of a typical EFI system using the speed-density method for intake air mass measurement is illustrated in **Figure 1**.

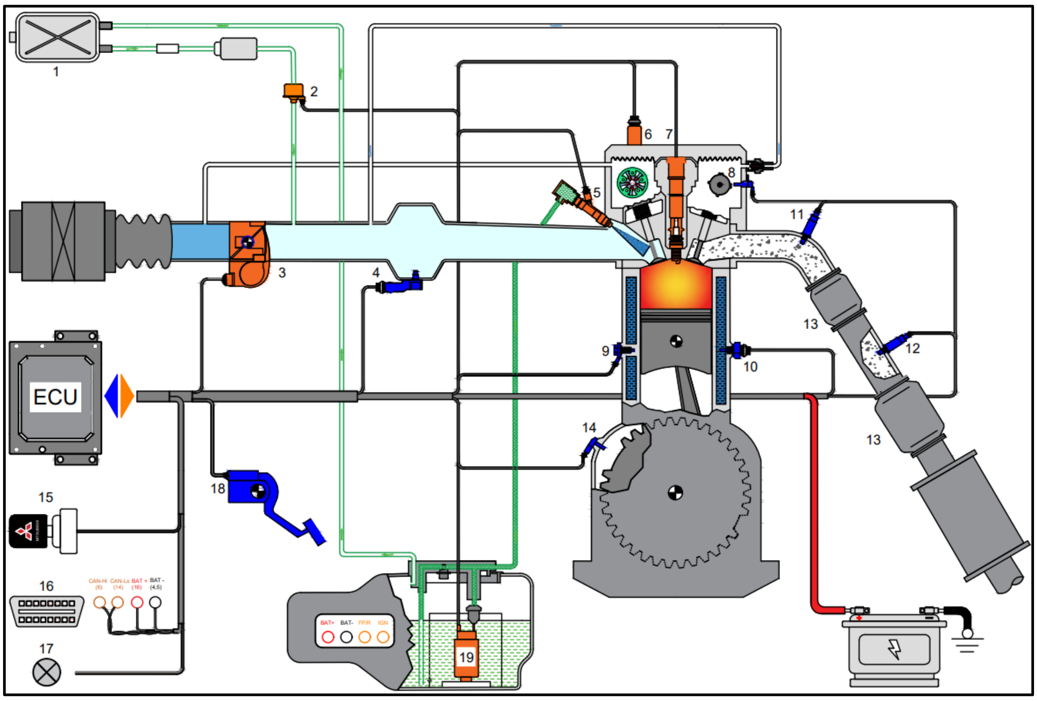


Figure 1. Overall layout diagram of the electrical - electronic control system of 4A91 engine

1- Charcoal Canister; 2- Purge control solenoid valve; 3- Electronic Throttle Control; 4-Manifold Absolute Pressure and Intake Air Temperature Sensor; 5-Injector; 6- Oil feeder control valve (MIVEC); 7- Spark plug And Coil-on plug; 8- Camshaft Position Sensor; 9- Knock Sensor; 10- Engine Coolant Temperature Sensor; 11- Pre-Oxygen Sensor; 12- Post-Oxygen Sensor; 13- Three-Way Catalyst; 14- Crankshaft Position Sensor; 15- Ignition Switch; 16- OBD-II Data Link Conector; 17- Malfunction Indicator Lamp; 18- Accelerator Pedal Position Sensor; 19- Fuel Pump

Information about the function of sensors and actuators in the electronic control system for the 4A91 engine was summarized, providing a brief overview of the installation positions and functional characteristics in **Table 2** and **Table 3.**

SENSORS	FUNCTION
MAP	Measures air pressure and temperature in the intake manifold, calculates the mass air flow by speed-density method.
IAT	
CMP	Determines the camshaft position, combines the output signal of the crankshaft position sensor to determine the TDC of the cylinders.
CKP	Determines the crankshaft angle, calculates engine speed.
K/S	Records engine vibrations caused by knocking, adjusts ignition timing accordingly.
ECT	Controls appropriate fuel injection based on engine speed and load.
Front O2	Monitors oxygen concentration in exhaust gas, assesses air-fuel ratio to adjust fuel injection accordingly.
Rear O2	Checks the operation of the catalyst.
TPS	Detects the throttle opening angle to determine the engine load mode.
APS	Controls throttle opening and appropriate fuel injection.

Table 1. Overview of Positions and Functions of Sensors on the 4A91 Engine

ACTUATORS	FUNCTION
Purge control solenoid valve	Controls and regulates the flow of fuel vapor from the fuel tank to the engine intake manifold.
Electronic throttle control	Controls the opening of the throttle control for each operating state to achieve desired performance.
Injector	Injects fuel into each cylinder.
Oil feeder control valve	Regulates the oil flow to the camshaft actuators to adjust the timing and lift of the engine's valves.
Spark plug	An individual ignition coil is placed on top, separating coils from exhaust heat.

Table 2. Overview of Positions and Functions of Actuators on the 4A91 Engine

1.2. Air mass flow calculation

Calculating air mass flow is essential for accurately determining the amount of air entering an engine's intake, which is crucial for optimizing fuel injection and combustion efficiency. In this project, the model engine calculates air mass flow using the Speed-Density method.

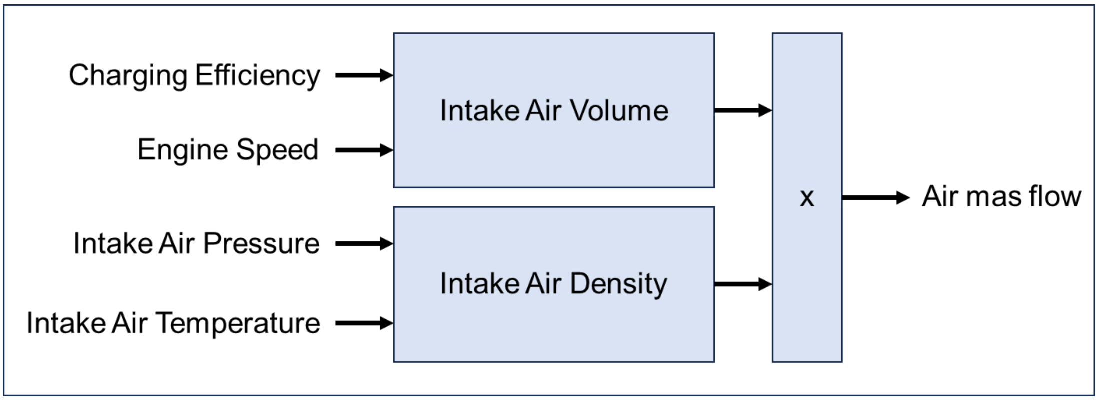


Figure 2. Air mass flow estimation based on speed density method

This method employs a speed-density equation that relates the engine's air mass flow to the intake manifold pressure, intake manifold temperature, and engine speed. By integrating these parameters, the system can effectively optimize performance and efficiency.

$$m_{Air} = \rho(T_{intake}, P) * \eta_{charge}(S, \propto, n_e) \quad (1)$$

Where:

- m_{Air}: Mass air flow
- ρ: Air density
- T_{intake}: Intake air temperature
- P: Manifold absolute pressure
- η_{charge}: Volumetric efficiency
- S: Throttle diameter
- $\propto$: Throttle opening
- n_e: engine speed

II. DIAGNOSTIC ENGINE SPEED CYCLE

The diagnostic engine speed cycle in this study was structured based on basic engine operating stages including: start-up, warm-up, idling, low and high speeds, acceleration, deceleration, coasting, and speeds beyond the optimal range with a specific performing time.

To facilitate stable data collection, the cycle was conducted with the vehicle stationary and under no-load conditions. Therefore, the coasting and exceeding optimal speed stages were not considered. Although the warm-up stage also occurred under load when turning on the air conditioning, it was included to lengthen the warm-up time. The building process of the diagnostic image was illustrated in detail in **Appendix 1**.

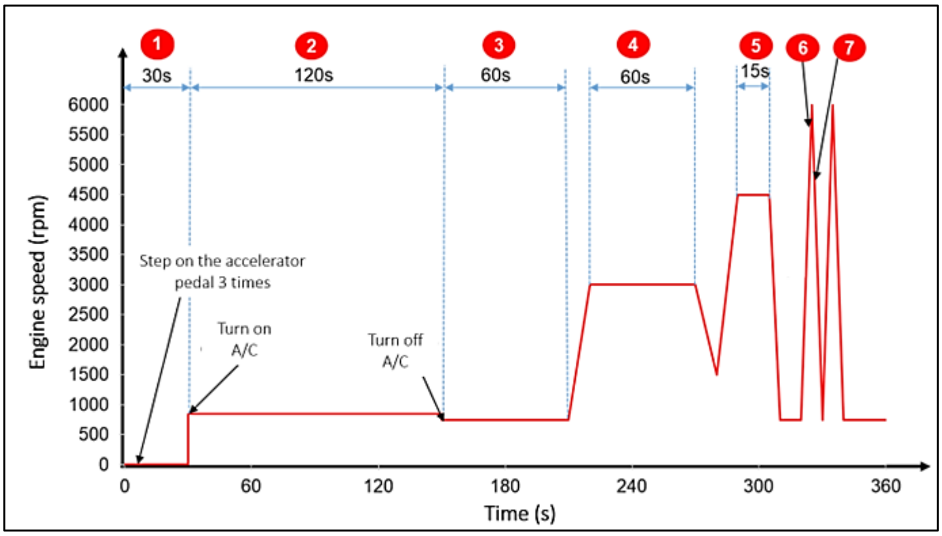


Figure 3. Engine test cycle for diagnostic purposes used in this study

In this study, live data were collected under two conditions, including normal engine operation and intentionally simulated faults. A dataset contained a total of 84 values, with 12 live data parameters obtained across 7 stages, including: Engine speed (Ne), manifold absolute pressure (MAP), engine load (Load), timing advance (TA), accelerator pedal position (APS), throttle position (TPS), front oxygen sensor voltage (O2F), and rear oxygen sensor voltage (O2R), intake air temperature (IAT), engine coolant temperature (ECT), long-term fuel trim (LTFT), and short-term fuel trim (STFT).

CHAPTER 3: STUDY ON TROUBLE SYMPTOMS OF D-JETRONIC TYPED ELECTRONIC FUEL INJECTION SYSTEM

I. CONTENTS SYNOPSIS

1.1 Basis for idea formation

The EFI system was crucial for modern gasoline engine performance, making quick and accurate fault diagnosis essential. Technicians often use OBD function and standard SSCC diagnostic process to determine the faults, which is a complicated and time-consuming procedure, requiring skilled and experienced technicians. To address this, our group developed an automatic diagnostic solution. This solution involves collecting live data by performing a diagnostic engine cycle, extracting and visualizing the live data as a diagnostic image, and finally classifying the image using an AI algorithm to identify the cause of the failure. This solution required an amount of dataset for each fauts to train the AI as well as checking the validation of collected diagnostic image. Thus, I decided to implement the "Study on trouble symptoms of D-Jetronic typed electronic fuel injection systems" project to design the fault simulation method and analyze the relationship between fault levels and it's symptoms.

1.2 Objectives

Design the fault simulation methods and analyze the relationship between fault levels and symptoms for three faults: cracked intake manifold, weak fuel pump and evaporative purge valve leak.

1.3 Requirements

❖ Build the fault simulation procedure.

- Must ensuring driver safety and no harm to the model.
- Must be logical, and can adjust multiple levels.
- Reflect the behavior of the faults in practice.

❖ Perform the engine speed cycle and collect live data.

- Data must be collected under the same consistent environmental conditions.

- Ensure the collected datasets remain within a stable range, minimizing unstable data during engine stage transitions for more accurate data extraction.

❖ Analyze the relationship between fault level and symptoms.

- Must represent and explain the changes of symptoms according to faults levels.
- Must be based on the operation of current systems and technologies present in the engine.

1.4 Contents

- Design the fault simulation method for 3 faults: Cracked intake manifold, weak fuel pump, Cracked intake manifold.
- Perform engine speed cycle and collect live data.
- Analysis the relationship between fault levels and symptoms.

II. BUILD THE STANDARD DATASET WHEN THE ENGINE NORMAL

2.1 Standard dataset and standard plot when engine is normal

Based on the engine speed cyle mentioned in **Appendix 1** and the data processing method mentioned in **Appendix 2**, we conducted measurements and collected data ten times from the engine under normal operating conditions. From these measurements, a standard dataset was compiled representing the engine's behavior when there are no faults, as shown in **Table 4**.

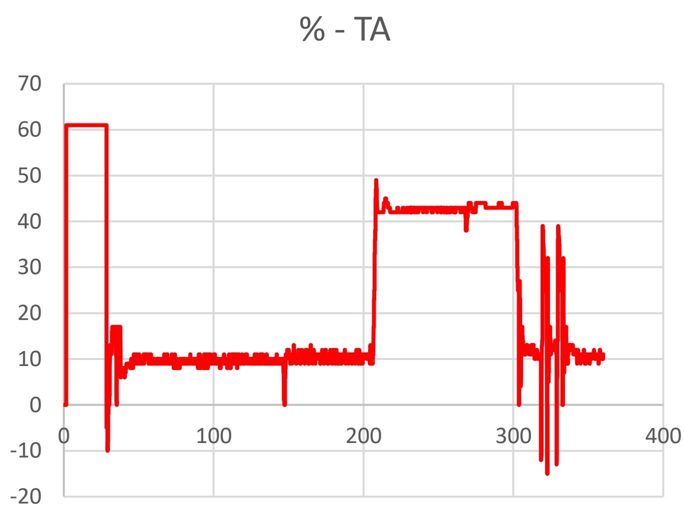
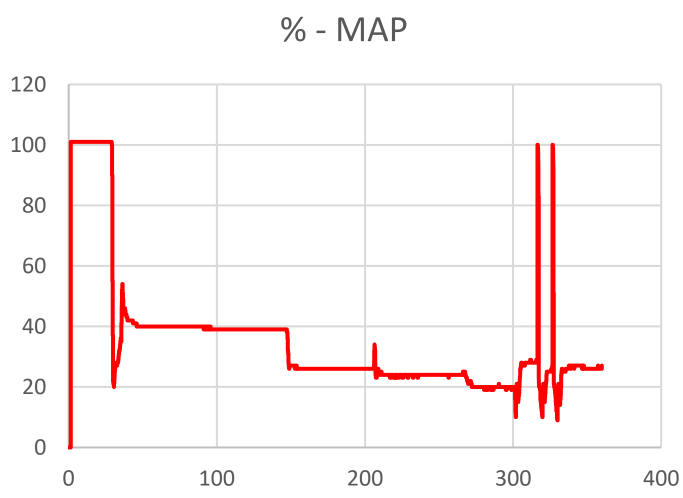
<table>
<tr><th colspan="3">STAGE / LIVE DATA</th><th>IGN "ON"</th><th>WARM UP</th><th>IDLE</th><th>3000 RPM</th><th>4500 RPM</th><th>Acceleration</th><th>Deceleration</th></tr>
<tr><td>Ne</td><td colspan="2">rpm</td><td>0</td><td>850 ± 20</td><td>740 ± 20</td><td>3000 ± 120</td><td>4500 ± 100</td><td>740 → 6000</td><td>6000 → 740</td></tr>
<tr><td>TA</td><td colspan="2">°TDC</td><td>-</td><td>10 ± 1</td><td>11 ± 2</td><td>42.5 ± 0.5</td><td>43.5 ± 0.5</td><td>10 → -10 → 40 ± 3</td><td>40 → 0 → 10 ± 3</td></tr>
<tr><td>MAP</td><td colspan="2">kPa</td><td>101</td><td>41 ± 3</td><td>26.5 ± 0.5</td><td>24.5 ± 0.5</td><td>19.5 ± 0.5</td><td>100 → 20</td><td>20 → 9 → 20</td></tr>
<tr><td>Load</td><td colspan="2">%</td><td>0</td><td>40 ± 3</td><td>26.1 ± 0.6</td><td>23.3 ± 0.2</td><td>19.4 ± 0.6</td><td>97 → 20</td><td>20 → 9.4 → 20</td></tr>
<tr><td rowspan="2">IAT</td><td colspan="2" rowspan="2">°C</td><td rowspan="2">-</td><td colspan="6">40 - 60</td></tr>
<tr><td>-</td><td>Gradually increase</td><td>Smaller than at idle</td><td>Smaller than at 3000 rpm</td><td>Gradually decrease</td><td>-</td></tr>
<tr><td>ECT</td><td colspan="2">°C</td><td>-</td><td>89</td><td colspan="5">85 - 98</td></tr>
<tr><td>APS</td><td colspan="2">%</td><td>0
0→100*</td><td>0</td><td>0</td><td>7 ± 0.25</td><td>8 ± 0.2</td><td>0 → 100</td><td>100 → 0</td></tr>
<tr><td>TPS</td><td colspan="2">%</td><td>3.92
3.92→100*</td><td>7 ± 1</td><td>3.92</td><td>10.5 ± 0.5</td><td>14 ± 0.5</td><td>3 → 100</td><td>100 → 3</td></tr>
<tr><td rowspan="3">O2F</td><td rowspan="3">V</td><td>Average</td><td rowspan="3">-</td><td>0.5</td><td>0.41</td><td colspan="2">0.5</td><td>-</td><td rowspan="3">0.94 → 0.2 then increasing and keeping stable at high voltage level in a long time.</td></tr>
<tr><td>Max</td><td>0.82</td><td>0.8</td><td colspan="2">0.82</td><td>0.94</td></tr>
<tr><td>Min</td><td>0.08</td><td>0.08</td><td colspan="2">0.08</td><td>0.2</td></tr>
<tr><td>O2R</td><td colspan="2">V</td><td>-</td><td>0</td><td>0</td><td>0 → 0.82</td><td>0.8 → 0.82</td><td>0.18 → 0.98</td><td>0.98 → 0.18 then keeping stable at low voltage level in a long time.</td></tr>
<tr><td>STFT</td><td colspan="2">%</td><td>-</td><td colspan="4">-9 → 9</td><td colspan="2">0</td></tr>
<tr><td rowspan="2">LTFT</td><td colspan="2" rowspan="2">%</td><td rowspan="2">-</td><td>3.91</td><td>-0.78 → 0.78</td><td>3.91</td><td>1.56</td><td>1.56</td><td>0</td></tr>
<tr><td colspan="6">Keep the certain level when running at steady speed</td></tr>
<tr><td colspan="10">* Step on the accelerator pedal to full travel 3 times</td></tr>
</table>

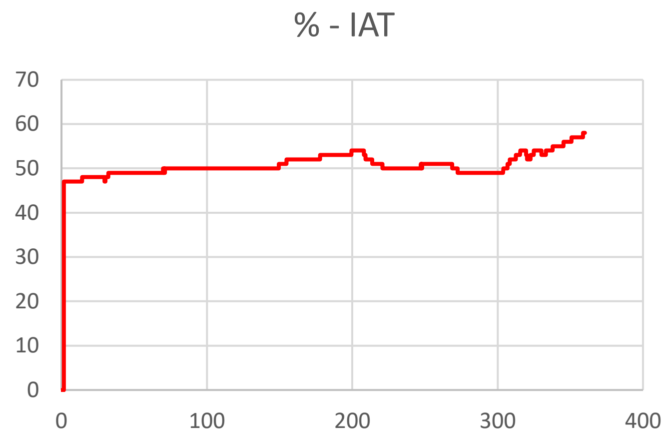
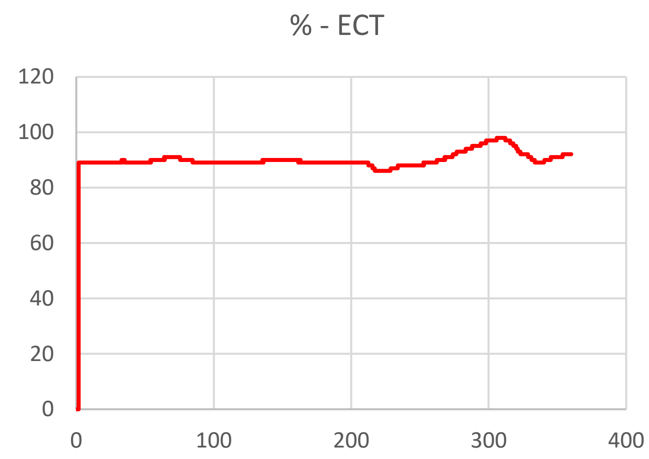
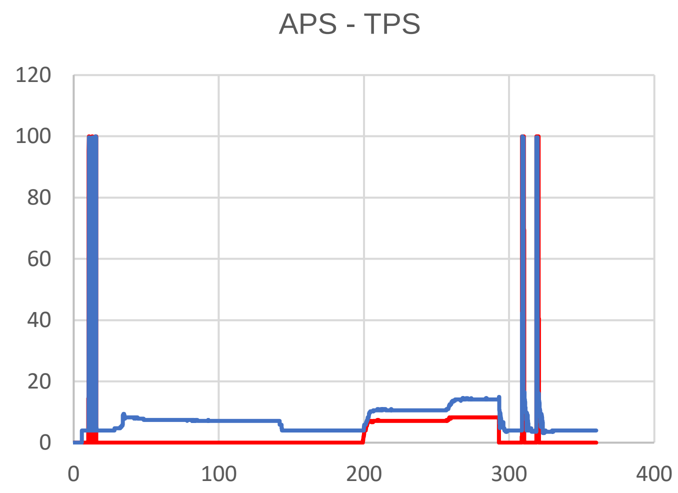
Table 3. Standard dataset when engine is normal

2.2 Analyze and evaluate the result of standard dataset

a) Analyze the changes of live data through each stages

Understanding and analyzing the relationships and interactions between live data when the engine was in a normal state were essential for gaining deeper insights during the fault analysis process. This information helped identify key operating parameters of the engine and facilitated the detection of abnormalities in the system. When a fault occurred, comparing the data from the normal state with that from the abnormal state greatly assisted in identifying the cause of the issue and providing timely repair solutions.

PIDs	Engine drive cycle	Description
TA		<u>From warm-up to idle</u>: TA fluctuates according to the unstable engine speed. After that, engine load decreases → Timing Advance (TA) increases. <u>3000 RPM / 4500 RPM</u>: Because engine speed increases→TA increases. <u>Acceleration phase</u>: As the sudden opening of throttle control → engine load increases → TA decreases. After that, the intake air is sucked into at high speed → engine load decreases, engine speed increases → TA increases again. <u>Deceleration phase</u>: ECU controls fuel cut-off, so TA reaches 0 and then increases.
MAP		<u>IGON</u>: Equals to the atmospheric pressure. <u>Warm-up</u>: High engine load → more air is drawn in → MAP value is higher than in other phases. <u>Idle → 3000 RPM → 4500 RPM</u>: Engine speed increases → increasing the air intake speed → more negative pressure → MAP decrease. <u>Acceleration</u>: The sudden opening of the throttle control → MAP = 100 kPa. After that, the intake air is drawn into at high speed → MAP value decreases. <u>Deceleration</u>: The sudden closure of the throttle causes the pressure to decrease and then increase.

IAT		In stable state: the IAT value gradually increases over time due to the rising engine temperature. When there is a change in operating conditions that increases the engine speed: The value decreases because the intake air is faster → the heat transfer process occurs quickly → absorbed heat is not significant → the higher engine speed is, the lower temperature is.
ECT		Warm up: ECU close the thermostat to warm up faster. Idle: Maintain high temperature to increase thermal efficiency. High speed: ECU open the thermostat to cool the coolant temperature to achieve max power/torque.
APS-TPS		The values of APS changes according to the driver's demand. The TPS increases non-linearly compared to the APS because there is a calculation of the data collected from the ECU to control the appropriate change in throttle opening.

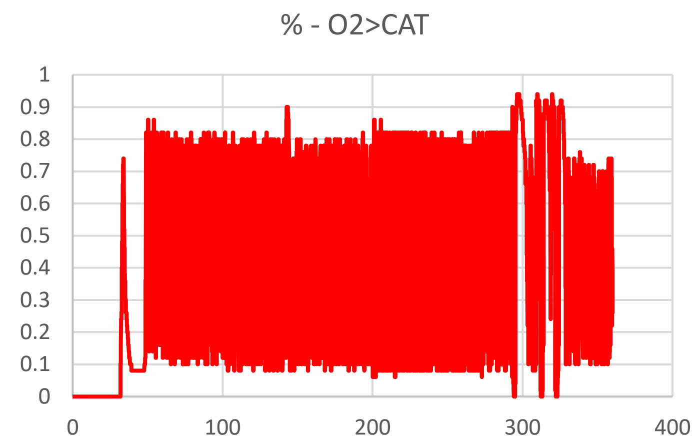
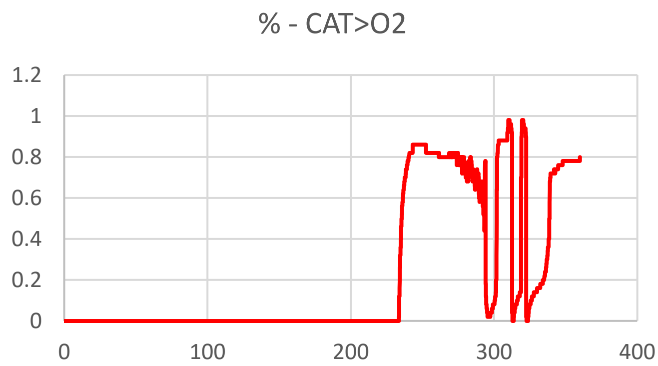
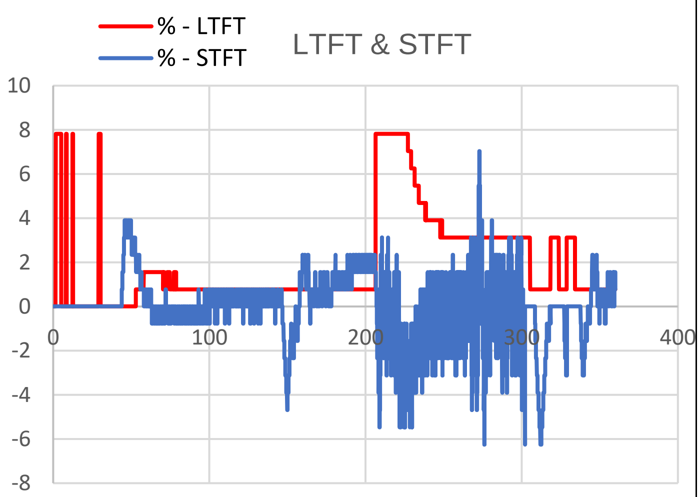
<table>
<tr>
<td>O2F</td>
<td>
</td>
<td><u>Warm-up, idle, 3000 RPM, and 4500 RPM</u>: Continuous changes in the range from 0.1 – 0.8V according to fuel injection adjustment based on the lambda closed - loop control.
<u>Acceleration</u>: When the engine speed increases suddenly → ECU increase in injection quantity, enriching the fuel mixture → O2F indicates high voltage (rich mixture).
<u>Deceleration</u>: Sudden release of the pedal, ECU adjusts fuel cut off → O2F voltage signal drops to 0.</td>
</tr>
<tr>
<td>O2R</td>
<td>
</td>
<td>Always kept within a stable range due to the absorption of exhaust gas components by the catalytic converter.</td>
</tr>
<tr>
<td>STFT & LTFT</td>
<td>
</td>
<td>Always changing within the predetermined range and continuously adjusting the injection amount according to the lambda closed – loop control.</td>
</tr>
</table>

Table 4. Changes of live data over stages

b) Evaluate the difference in the result of standard dataset of each measurements

The collected data did not show significant differences during the IGN "ON," warm-up, and idling stages. This can be explained by the fact that these are stable operating modes without any accelerator pedal input or a constant speed being maintained. Therefore, the variations in the live data were insignificant during the measurement process.

However, the live data during the 3000 RPM, 4500 RPM, acceleration, and deceleration stages showed relatively different values between measurements. The primary reason for this difference was the unstable accelerator pedal position during execution, which caused the engine speed to fluctuate and affected the other live data. This, in turn, impacted the mean value and standard deviation of the measured data sample. Additionally, other contributing factors, such as suboptimal engine operating conditions, environmental influences, random factors during the measurement process, and instrument errors, could have also played a role.

III. SIMULATE FAULTS, COLLECT LIVE DATA AND ANALYSIS

3.1. Cracked intake manifold

3.1.1 Simulate fault, perform engine speed cycle and collect dataset

For the fault simulation method, we disconnected the vacuum power booster hose from the intake manifold to simulate a crack in the manifold. An airflow meter was then connected to measure the amount of leaked air. Cause levels were categorized at 30%, 60%, 100%, 160%, 240%, and 280% by comparing the leaked air with the intake mass airflow at idle (1.277 g/s ≈ 68 l/min at 40°C, as determined by an airflow sensor). The limits of the cause levels were based on the measurement range of the airflow meter and the level to which the symptoms could be effectively simulated.

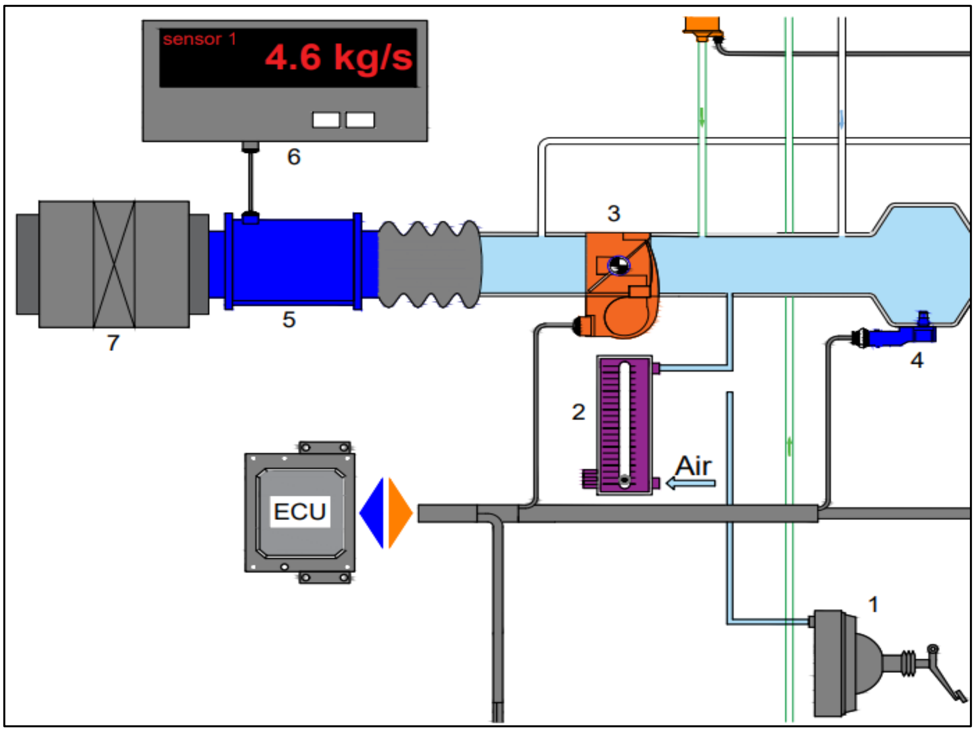


Figure 4. Cracked intake manifold simulation method

1 – Vaccum break booster; 2 – Air flow meter; 3 – Electronic Throttle Control; 4 – Manifold Absolute Pressure Sensor; 5 – Air flow sensor; 6 – Air flow sensor reader.

After premilitary check for battery voltage, oil, coolant,… of the engine, we started to simulate the fault following these step:

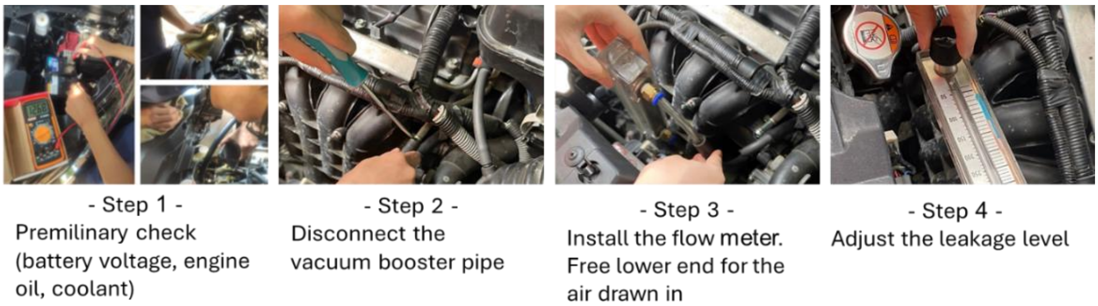


Figure 5. Cracked intake manifold simulation procedure

After installing the simulation tools, performed the engine speed cycle for each cause level to collect the live data. The live data then are visualized into diagnostic images, as illustrated in **Appendix 3**.

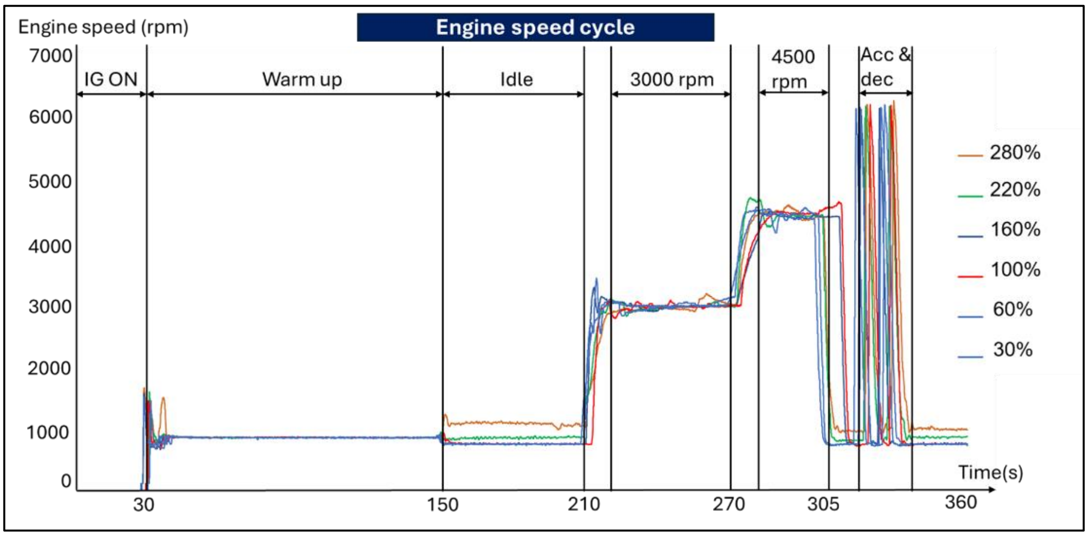


Figure 6. Perform engine speed cycle with Cracked intake manifold fault.

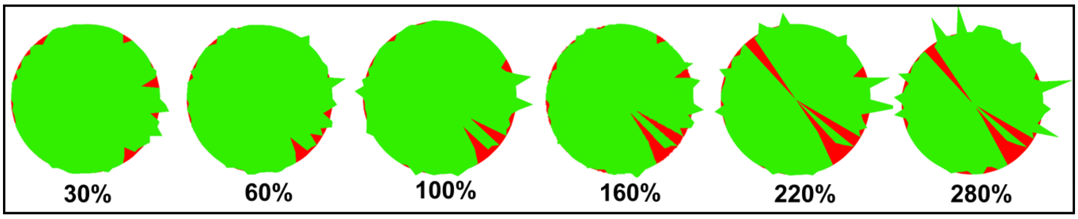


Figure 7. Diagnostic image for Cracked intake manifold

3.1.2. Analyze the impact of the fault on each operating stage

The impact of a fault varied at each operating stage based on the specific demands of that stage. Therefore, monitoring live data variations was crucial for effective fault analysis. In this section, the characteristic data from each stage, under both normal and fault conditions, are compared to assess the fault's impact at each operating stage.

a) Cracked intake manifold (30% leakage)

STAGE	CYCLE / LIVE DATA		Experimented cycle	Standard cycle
IGN "ON"	APS	%	0 → 100	0 → 100
	TPS	%	3.92 → 100	3.92 → 100
	MAP	kPa	101	101
	NORMAL			
WARM - UP	TPS	%	6.35 ± 0.3	7 ± 1
	MAP	kPa	39± 1	41 ± 3
	LOAD	%	38.4 ± 0.5	40 ± 3

	LTFT	%		-0.79 → 1.5	-0.79 → 3.91
	O2F	V	*Average*	0.45	0.5
			Max	0.82	0.8
			Min	0.08	0.08
IDLE	TPS	%		2.94± 0.3	3.92
	MAP	kPa		27	26.5 ± 0.5
	LOAD	%		26 ± 0.5	26.1 ± 0.6
	Ne	rpm		740 ± 20	740 ± 20
	TA	°TDC		10 ± 0.5	10 ± 1
	LTFT	%		-0.78	-0.78 → 0.78
	O2F	V	*Average*	0.44	0.41
			Max	0.82	0.8
			Min	0.08	0.08
When the occurs, pressure increase, which is detected by MAP sensor. Then electronic throttle control is controlled close to against the leak, resulting in other live data remaining normal.					
3000 RPM	APS	%		7.5 ± 0.05	7 ± 0.25
	TPS	%		10 ± 0.2	10.5 ± 0.5
	MAP	kPa		24	24.5 ± 0.5
	LOAD	%		23.1 ± 0.2	23.3 ± 0.2
	LTFT	%		0 → 2.34	-0.79 → 3.91
4500 RPM	APS	%		8 ± 0.2	8 ± 0.2
	TPS	%		13.8 ± 0.3	14.1 ± 0.4
	MAP	kPa		20	19.5 ± 0.5
	LOAD	%		19.2 ± 0.4	19.4 ± 0.6
	LTFT	%		0.78	0 → 1.56
At high RPMs stages, with a more open throttle, a significant amount of air enter through the intended path, making the volume of air leak becomes relatively insignificant. Combined with the adjustment of the electronic throttle control, resulting in other live data remaining normal.					

b) Cracked intake manifold (60% leakage)

STAGE	LIVE DATA \ CYCLE		Experimented cycle	Standard cycle
IGN	APS	%	0 → 100	0 → 100

"ON"	TPS	%		3.92 → 100	3.92 → 100
	MAP	kPa		101	101
NORMAL					
WARM - UP	TPS	%		5.85	7 ± 1
	MAP	kPa		39± 1	41 ± 3
	LOAD	%		38.5 ± 0.5	40 ± 3
	LTFT	%		-0.78 → 1.56	-0.79 → 3.91
	O2F	V	*Average*	0.47	0.5
			Max	0.82	0.8
			Min	0.08	0.08
IDLE	TPS	%		2.65 ± 0.2	3.92
	MAP	kPa		27	26.5 ± 0.5
	LOAD	%		26.1 ± 0.6	26.1 ± 0.6
	NE	rpm		745 ± 25	740 ± 20
	TA	°TDC		10 ± 0.2	10 ± 1
	LTFT	%		0.78	-0.78 → 0.78
	O2F	V	*Average*	0.52	0.41
			Max	0.82	0.8
			Min	0.08	0.08
When the occurs, pressure increase, which is detected by MAP sensor. Then electronic throttle control is controlled close to against the leak, resulting in other live data remaining normal.					
3000 RPM	APS	%		7.5 ± 0.3	7 ± 0.25
	TPS	%		9.4 ± 0.2	10.5 ± 0.5
	MAP	kPa		24.5 ± 0.5	24.5 ± 0.5
	LOAD	%		23.2 ± 0.5	23.3 ± 0.2
	LTFT	%		0.78 → 3.125	-0.79 → 3.91
4500 RPM	APS	%		8 ± 0.2	8 ± 0.2
	TPS	%		13 ± 0.7	14.1 ± 0.4
	MAP	kPa		20	19.5 ± 0.5
	LOAD	%		19.2 ± 0.4	19.4 ± 0.6
	LTFT	%		2.34	0 → 1.56
At high RPMs with a more open throttle, a significant amount of air enter through the intended path, making the volume of air leak becomes relatively insignificant. Combined with the adjustment of the electronic throttle control, resulting in other live data remaining normal. Howerver, decrease of throttle control make the driver push the pedal harder (APS ↑) to achieve desired speed.					

c) Cracked intake manifold (100% leakage)

STAGE	LIVE DATA \ CYCLE			Experimented cycle	Standard cycle
IGN "ON"	APS	%		0 → 100	0 → 100
	TPS	%		3.92 → 100	3.92 → 100
	MAP	kPa		101	101
	NORMAL				
WARM - UP	TPS	%		5.65 ± 0.5	7 ± 1
	MAP	kPa		39	41 ± 3
	LOAD	%		38.5 ± 0.5	40 ± 3
	LTFT	%		0 → 1.56	-0.79 → 3.91
	O2F	V	*Average*	0.47	0.5
			Max	0.82	0.8
			Min	0.08	0.08
IDLE	TPS	%		1.95± 0.2	3.92
	MAP	kPa		26.5 ± 0.5	26.5 ± 0.5
	LOAD	%		25.7 ± 0.6	26.1 ± 0.6
	Ne	rpm		747 ± 30	740 ± 20
	TA	°TDC		10 ± 0.2	10 ± 1
	LTFT	%		-0.78	-0.78 → 0.78
	O2F	V	*Average*	0.42	0.41
			Max	0.82	0.8
			Min	0.08	0.08
When the occurs, pressure increase, which is detected by MAP sensor. Then electronic throttle control is controlled close to against the leak, resulting in other live data remaining normal.					
3000 RPM	APS	%		7.6 ± 0.2	7 ± 0.25
	TPS	%		9.56 ± 0.4	10.5 ± 0.5
	MAP	kPa		23± 1	24.5 ± 0.5
	LOAD	%		22.8 ± 0.5	23.3 ± 0.2
	LTFT	%		1.56 → 3.91	-0.79 → 3.91
4500 RPM	APS	%		8 ± 0.2	8 ± 0.2
	TPS	%		13.5 ± 0.4	14.1 ± 0.4
	MAP	kPa		20 ± 1	19.5 ± 0.5
	LOAD	%		19.2 ± 0.6	19.4 ± 0.6
	LTFT	%		1.56	0 → 1.56

At high RPMs with a more open throttle, a significant amount of air enter through the intended path, making the volume of air leak becomes relatively insignificant. Combined with the adjustment of the electronic throttle control, resulting in other live data remaining normal. Howerver, decrease of throttle control make the driver push the pedal harder (APS ↑) to achieve desired speed.

d) Cracked intake manifold (160% leakage)

STAGE	LIVE DATA \ CYCLE			Experimented cycle	Standard cycle
IGN "ON"	APS	%		0 → 100	0 → 100
	TPS	%		3.92 → 100	3.92 → 100
	MAP	kPa		101	101
	NORMAL				
WARM - UP	TPS	%		4.78 ± 0.2	7 ± 1
	MAP	kPa		39± 1	41 ± 3
	LOAD	%		38.5 ± 0.6	40 ± 3
	LTFT	%		0 → 1.5	-0.79 → 3.9
	O2F	V	*Average*	0.45	0.5
			Max	0.82	0.8
			Min	0.08	0.08
IDLE	TPS	%		0.78	3.92
	MAP	kPa		26.5 ± 0.5	26.5 ± 0.5
	LOAD	%		25.7 ± 0.6	26.1 ± 0.6
	Ne	rpm		743 ± 24	740 ± 20
	TA	°TDC		10 ± 0.3	10 ± 1
	LTFT	%		0.78	-0.78 → 0.78
	O2F	V	*Average*	0.42	0.41
			Max	0.82	0.8
			Min	0.08	0.08
The model use speed density method, so MAP sensor can detect the leak when it occurs. Then electronic throttle control is controlled close to against the leak, resulting in other live data remaining normal.					
3000 RPM	APS	%		7.85 ± 0.2	7 ± 0.25
	TPS	%		9.4 ± 0.2	10.5 ± 0.5
	MAP	kPa		24.5 ± 0.5	24.5 ± 0.5
	LOAD	%		23.2 ± 0.5	23.3 ± 0.2
	LTFT	%		3.91	-0.79 → 3.91

4500 RPM	APS	%	8 ± 0.2	8 ± 0.2
	TPS	%	13 ± 0.7	14.1 ± 0.4
	MAP	kPa	20	19.5 ± 0.5
	LOAD	%	19.2 ± 0.4	19.4 ± 0.6
	LTFT	%	2.34	0 → 1.56
At high RPMs with a more open throttle, a significant amount of air enter through the intended path, making the volume of air leak becomes relatively insignificant. Combined with the adjustment of the electronic throttle control, resulting in other live data remaining normal. Howerver, decrease of throttle control make the driver push the pedal harder (APS ↑) to achieve desired speed.				

e) Cracked intake manifold (220% leakage)

STAGE	CYCLE / LIVE DATA			Experimented cycle	Standard cycle
IGN "ON"	APS	%		0 → 100	0 → 100
	TPS	%		3.92 → 100	3.92 → 100
	MAP	kPa		101	101
	NORMAL				
WARM - UP	TPS	%		3.27 ± 0.5	7 ± 1
	MAP	kPa		39 ± 1	41 ± 3
	LOAD	%		38.47 ± 0.6	40 ± 3
	LTFT	%		1.56 → 6.25	-0.79 → 3.91
	O2F	V	*Average*	0.42	0.5
			Max	0.82	0.8
			Min	0.08	0.08
	Due to high-level leak, a significant amount of leaked air is drawn into the cylinders when startup, causing the engine speed to fluctuate continuously. In response, the ECU detects a lean air-fuel mixture and increases fuel injection (LTFT ↑) to achieve a smoother warm up. To further stabilize the engine speed, the electronic throttle control is gradually closed againts the air leak.				
IDLE	TPS	%		0.26	3.92
	MAP	kPa		29 ± 1	26.5 ± 0.5
	LOAD	%		28.48 ± 0.5	26.1 ± 0.6
	LTFT	%		3.1	-0.78 → 0.78
	TA	°TDC		0	10 ± 1
	Ne	rpm		849 ± 52	740 ± 20

	O2F	V	*Average*	0.42	0.41
			Max	0.82	0.8
			Min	0.08	0.08
	When the throttle control close to 0 to against the air leak, the ECU start to incorrectly calculate the mass air flow, leads to calculated mass air flow deviate from the actual mass air flow. Consequently, the mixture is lean, ECU compensate by increase LTFT. Engine speed increase, ignition timing (TA) retard to decrease engine speed.				
3000 RPM	APS	%		7.7 ± 0.2	7 ± 0.25
	TPS	%		8.23 ± 0.3	10.5 ± 0.5
	MAP	kPa		24.5 ± 0.5	24.5 ± 0.5
	LOAD	%		23.2 ± 0.5	23.3 ± 0.2
	LTFT	%		3.4	-0.79 → 3.91
	At high RPMs with a more open throttle, a significant amount of air enter through the intended path, making the volume of air leak becomes relatively insignificant (which is also prevented by decreasing TPS). Consequently, The ECU's adjustments via LTFT decrease because the impact of the air leak is minimized. Howerver, decrease of throttle control make the driver push the pedal harder (APS ↑) to achieve desired speed.				
4500 RPM	APS	%		8.5 ± 0.2	8 ± 0.2
	TPS	%		12.5 ± 0.6	14.1 ± 0.4
	MAP	kPa		20	19.5 ± 0.5
	LOAD	%		19.2 ± 0.4	19.4 ± 0.6
	LTFT	%		1.56	0 → 1.56
	Same as 3000 rpm stage, the air leak is insignificant for higher speed. Consequently, The ECU's adjustments via LTFT decrease because the impact of the air leak is minimized. Howerver, decrease of throttle control make the driver push the pedal harder (APS ↑) to achieve desired speed.				
ACCELERATION	Ne	rpm		950 → 6187	740 → 6000
	Air leakage makes intake air increase → more fuel is injected → maximum speed can exceed 6000 rpm.				

f) Cracked intake manifold (280% leakage)

STAGE	CYCLE / LIVE DATA			Experimented cycle	Standard cycle
IGN "ON"	APS	%		0 → 100	0 → 100
	TPS	%		3.92 → 100	3.92 → 100
	MAP	kPa		101	101
	NORMAL				
WARM - UP	TPS	%		1.75 ± 0.2	7 ± 1
	MAP	kPa		40± 1	41 ± 3
	LOAD	%		39 ± 0.5	40 ± 3
	LTFT	%		-2.5 → 9.375	-0.79 → 3.91
	O2F	V	*Average*	0.52	0.5
			Max	0.82	0.8
			Min	0.08	0.08
	Due to high-level leak, a significant amount of leaked air is drawn into the cylinders when startup, causing the engine speed to fluctuate continuously. In response, the ECU detects a lean air-fuel mixture and increases fuel injection (LTFT ↑) to achieve a smoother warm up. To further stabilize the engine speed, the electronic throttle control is gradually closed againts the air leak.				
IDLE	TPS	%		0	3.92
	MAP	kPa		29	26.5 ± 0.5
	LOAD	%		28.6 ± 0.6	26.1 ± 0.6
	LTFT	%		4.7	-0.78 → 0.78
	TA	°TDC		0	10 ± 1
	Ne	rpm		1040 ± 36	740 ± 20
	O2F	V	*Average*	0.51	0.41
			Max	0.82	0.8
			Min	0.08	0.08
	When the throttle control close to 0 to against the air leak, the ECU start to incorrectly calculate the mass air flow, leads to calculated mass air flow deviate from the actual mass air flow. Consequently, the mixture is lean, ECU compensate by increase LTFT. Engine speed increase, ignition timing (TA) retard to decrease engine speed.				
3000 RPM	APS	%		8 ± 0.6	7 ± 0.25
	TPS	%		5.44 ± 0.32	10.5 ± 0.5
	MAP	kPa		24 ± 1	24.5 ± 0.5

	LOAD	%	23.4 ± 0.6	23.3 ± 0.2
	LTFT	%	-0.79	-0.79 → 3.91
	At high RPMs with a more open throttle, a significant amount of air enter through the intended path, making the volume of air leak becomes relatively insignificant (which is also prevented by decreasing TPS). Consequently, LTFT decrease because the impact of the air leak is minimized. Howerver, decrease of throttle control make the driver push the pedal harder (APS ↑) to achieve desired speed.			
4500 RPM	APS	%	8.45 ± 0.3	8 ± 0.2
	TPS	%	11.5 ± 0.6	14.1 ± 0.4
	MAP	kPa	20	19.5 ± 0.5
	LOAD	%	19.6 ± 0.4	19.4 ± 0.6
	LTFT	%	-0.79	0 → 1.56
	Same as 3000 rpm stage, the air leak is insignificant for higher speed. Consequently, LTFT decrease because the impact of the air leak is minimized. Howerver, decrease of throttle control make the driver push the pedal harder (APS ↑) to achieve desired speed.			
ACCELERATION	Ne	rpm	1031 → 6199	740 → 6000
	Air leakage makes intake air increase → more fuel is injected → maximum speed can exceed 6000 rpm.			

3.1.3. Analyze the relationship between fault levels and symptoms

The most apparent symptoms were observed during the idle stage; therefore, the live data at this stage were used to analyze the relationship between fault levels and their corresponding symptoms. The live data presented as average values at the idle stage for each fault level, as show in the figure below.

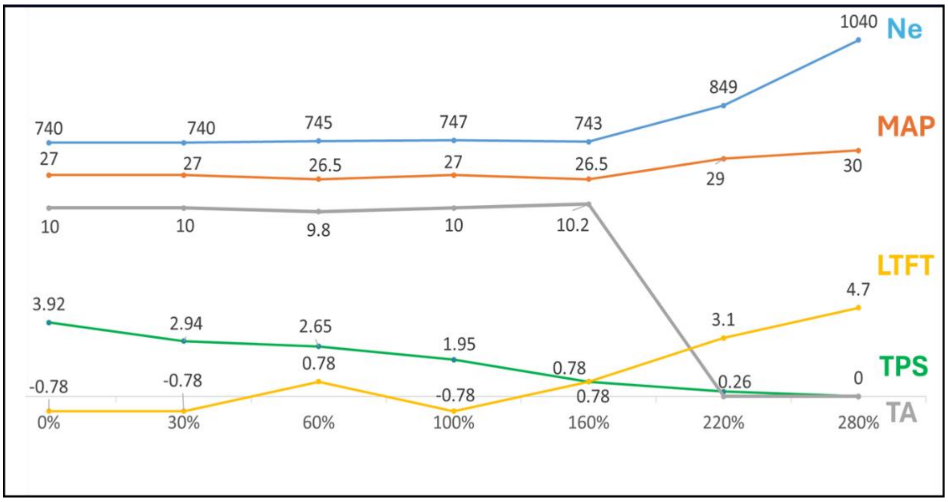


Figure 8. Diagnostic image for Cracked intake manifold

The relationship between fault levels and their corresponding symptoms was analyzed using the speed-density method :

$$m_{Air} = \rho(T_{intake}, P) * \eta_{charge}(S, \propto, n_e)$$

When a crack occurs, the pressure increases, and the ECU detects it through the MAP sensor. In response, the ECU adjusts the electronic throttle control according to the fault levels to stabilize the engine speed, ensuring that other live data remains within normal ranges.

However, at severe fault levels, when the throttle valve closes completely, the ECU begins to miscalculate the mass airflow, causing the calculated $\mathrm{m_{Air}}$ to deviate from the actual $\mathrm{m_{Air}}$. This results in a lean mixture, which the ECU detects through the oxygen sensor. To compensate, the ECU increases the LTFT. As the engine speed rises, the ignition timing (TA) is retarded to reduce the engine speed.

3.2. Weak fuel pump

3.2.1 Simulate fault, perform engine speed cycle and collect dataset

For the fault simulation method, a resistor (1.5Ω, 3.3Ω, 5.6Ω, 7.5Ω) is connected in series with each injector to reduce the voltage supplied to the injector, thereby decreasing the fuel injection amount. The fault levels will be categorized into 10%, 20%, 30%, and 40%, based on the corresponding reduction in injector power. The upper and lower limits of each fault level are set according to the minimum and maximum thresholds at which the engine can still operate while clearly exhibiting the intended symptoms.

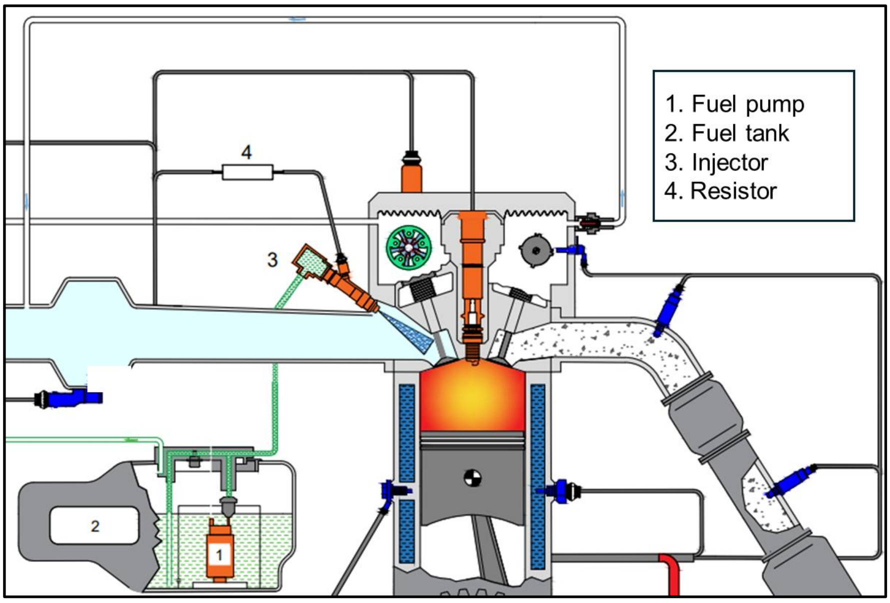


Figure 9. Weak fuel pump simulation method

1 – Fuel pump*; 2* – Fuel tank*; 3* – Injectorl*; 4* – Resistor.

After premilitary check for battery voltage, oil, coolant,… of the engine, we start to simulate the fault following these step:

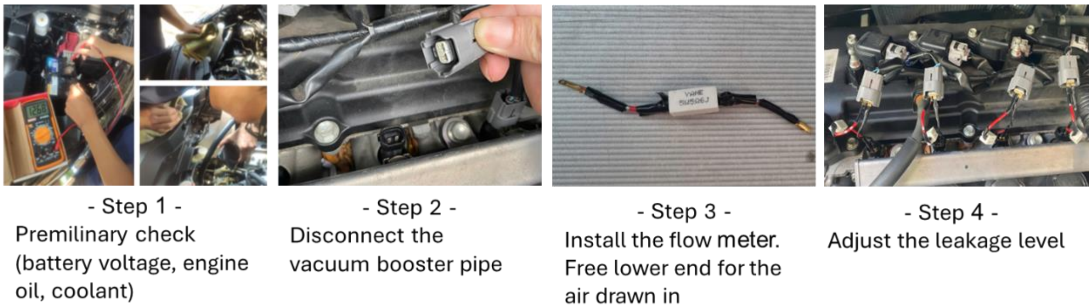


Figure 10. Weak fuel pump simulation procedure

After installing the simulation tools, perform the engine speed cycle and collect diagnostic images and live data:

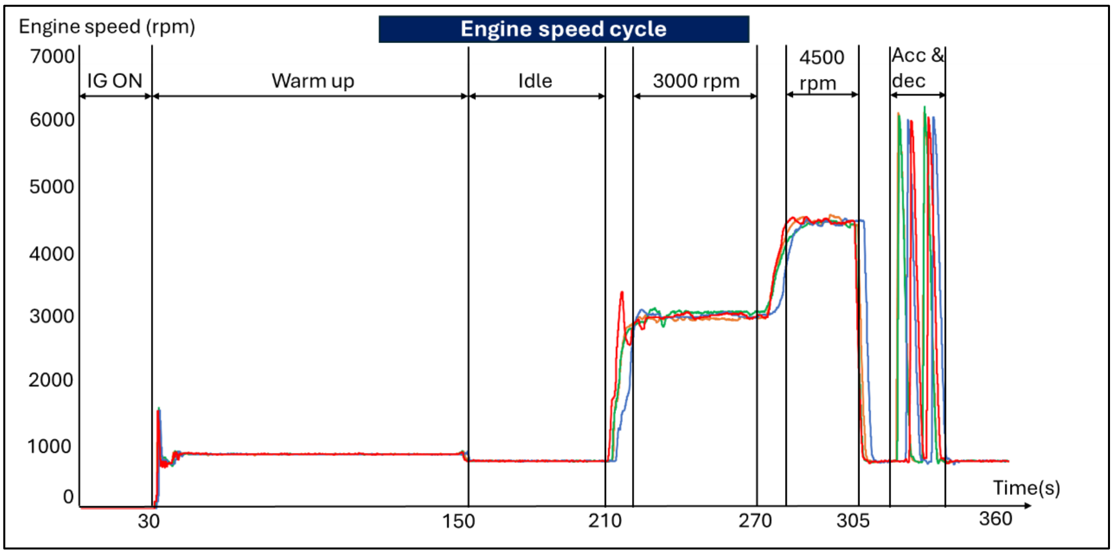


Figure 11. Perform engine speed cycle with weak fuel pump

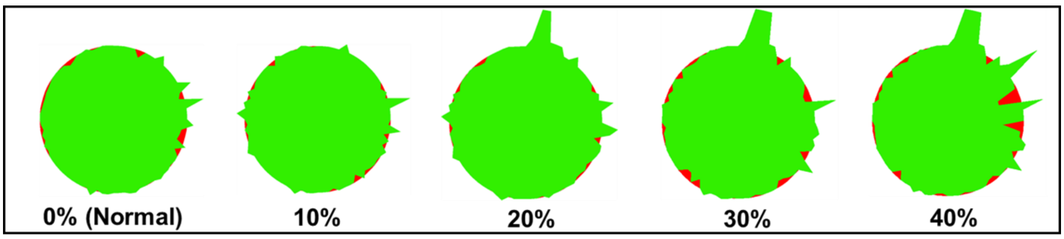


Figure 12. Diagnostic image for weak fuel pump

3.2.2 Analyze the impact of the fault on each operating stage

The impact of a fault varied at each operating stage based on the specific demands of that stage. Therefore, monitoring live data variations was crucial for effective fault analysis. In this section, the characteristic data from each stage, under both normal and fault conditions, are compared to assess the fault's impact at each operating stage.

a) Weak fuel pump (10%)

STAGE	CYCLE / LIVE DATA			Experimented cycle	Standard cycle
IGN "ON"	APS	%		0 → 100	0 → 100
	TPS	%		3.92 → 100	3.92 → 100
	MAP	kPa		101	101
	NORMAL				
WARM - UP	TPS	%		6.4 ± 0.4	7 ± 1
	MAP	kPa		39.5 ± 0.5	41 ± 3
	LOAD	%		38 ± 1	40 ± 3
	LTFT	%		3.91→0.78	3.91→-0.79
	O2F	V	*Average*	0.47	0.5
			Max	0.82	0.8
			Min	0.08	0.08
IDLE	TPS	%		3.92	3.92
	MAP	kPa		27	26.5 ± 0.5
	LOAD	%		26.3 ± 0.1	26.1 ± 0.6
	LTFT	%		0.78	-0.78 → 0.78
	O2F	V	*Average*	0.41	0.41
			Max	0.82	0.8
			Min	0.08	0.08
Idle and warm-up stage require only a small fuel amount and the weak fuel pump at this level causes a slight reduction in fuel supply. Therefore, the ECU doesn't need to compensate for this reduction.					
3000 RPM	APS	%		7± 0.15	7.25 ± 0.25
	TPS	%		10.4 ± 0.2	10.5 ± 0.5
	MAP	kPa		24.5 ± 0.5	24.5 ± 0.5
	LOAD	%		23.1 ± 0.5	23.3 ± 0.2
	LTFT	%		5.5 → 6.25	-0.78 → 3.91
4500	APS	%		8.2	8 ± 0.2

RPM	TPS	%	13.8 ± 0.4	14.1 ± 0.4
	MAP	kPa	19.5 ± 0.5	19.5 ± 0.5
	LOAD	%	18.7± 0.2	19.4 ± 0.6
	LTFT	%	6.25 → 3.91	0 → 1.56
At higher RPM stages, the engine demands more fuel to maintain performance. If the fuel pump is weak, it might not be able to deliver the required fuel amount, in this case , the ECU try to compensate by increase fuel injection.				

b) Weak fuel pump (20%)

STAGE	CYCLE / LIVE DATA			Experimented cycle	Standard cycle
IGN "ON"	APS	%		0 → 100	0 → 100
	TPS	%		3.92 → 100	3.92 → 100
	MAP	kPa		101	101
	NORMAL				
WARM - UP	TPS	%		6.75 ± 0.25	7 ± 1
	MAP	kPa		40 ± 1	41 ± 3
	LOAD	%		39 ± 1	40 ± 3
	LTFT	%		5.47	3.91→-0.79
	O2F	V	*Average*	0.47	0.5
			Max	0.82	0.8
			Min	0.08	0.08
IDLE	TPS	%		3.92	3.92
	MAP	kPa		27	26.5 ± 0.5
	LOAD	%		26.3 ± 0.1	26.1 ± 0.6
	LTFT	%		5.47	-0.78 → 0.78
	O2F	V	*Average*	0.44	0.41
			Max	0.82	0.8
			Min	0.08	0.08
Although idle and warm up stage require only a small fuel amount. The weak fuel pump at this level causes a moderate reduction in fuel supply, the ECU compensate by increase the fuel injection.					
3000 RPM	APS	%		7± 0.1	7.25 ± 0.25
	TPS	%		10.3 ± 0.2	10.5 ± 0.5
	MAP	kPa		24	24.5 ± 0.5

	LOAD	%	23.1 ± 0.5	23.3 ± 0.2
	LTFT	%	12.5	-0.78 → 3.91
4500 RPM	APS	%	8.2	8 ± 0.2
	TPS	%	13.3 ± 0.5	14.1 ± 0.4
	MAP	kPa	19	19.5 ± 0.5
	LOAD	%	18.4± 0.2	19.4 ± 0.6
	LTFT	%	12.5	0 → 1.56
At higher RPM stages, the engine demands more fuel to maintain performance. Therefore, the ECU compensate by increase a significant amount of fuel.				

c) Weak fuel pump (30%)

STAGE	CYCLE / LIVE DATA			Experimented cycle	Standard cycle
IGN "ON"	APS	%		0 → 100	0 → 100
	TPS	%		3.92 → 100	3.92 → 100
	MAP	kPa		101	101
	NORMAL				
WARM - UP	TPS	%		6.5 ± 0.2	7 ± 1
	MAP	kPa		39 ± 1	41 ± 3
	LOAD	%		38 ± 1	40 ± 3
	LTFT	%		7.03	3.91→-0.79
	O2F	V	*Average*	0.44	0.5
			Max	0.82	0.8
			Min	0.08	0.08
IDLE	TPS	%		3.92	3.92
	MAP	kPa		27	26.5 ± 0.5
	LOAD	%		26.3 ± 0.1	26.1 ± 0.6
	LTFT	%		7.03	-0.78 → 0.78
	O2F	V	*Average*	0.42	0.41
			Max	0.82	0.8
			Min	0.08	0.08
Although idle and warm up stage require only a small fuel amount. The weak fuel pump at this level causes a significant reduction in fuel supply, the ECU compensate by increase the fuel injection.					
3000 RPM	APS	%		7± 0.1	7.25 ± 0.25
	TPS	%		10.3 ± 0.2	10.5 ± 0.5

	MAP	kPa	24	24.5 ± 0.5
	LOAD	%	23.1 ± 0.5	23.3 ± 0.2
	LTFT	%	12.5	-0.78 → 3.91
4500 RPM	APS	%	7.94 ± 0.4	8 ± 0.2
	TPS	%	14 ± 0.5	14.1 ± 0.4
	MAP	kPa	19	19.5 ± 0.5
	LOAD	%	18.4± 0.2	19.4 ± 0.6
	LTFT	%	12.5	0 → 1.56
At higher RPM stages, the engine demands more fuel to maintain performance. Therefore, the ECU compensate by increase a significant amount of fuel.				

d) Weak fuel pump (40%)

STAGE	CYCLE / LIVE DATA			Experimented cycle	Standard cycle
IGN "ON"	APS	%		0 → 100	0 → 100
	TPS	%		3.92 → 100	3.92 → 100
	MAP	kPa		101	101
	NORMAL				
WARM - UP	TPS	%		6.7 ± 0.5	7 ± 1
	MAP	kPa		39 ± 1	41 ± 3
	LOAD	%		38 ± 1	40 ± 3
	LTFT	%		9.37	3.91→-0.79
	O2F	V	*Average*	0.47	0.5
			Max	0.82	0.8
			Min	0.08	0.08
IDLE	TPS	%		3.92	3.92
	MAP	kPa		26	26.5 ± 0.5
	LOAD	%		25.4 ± 0.2	26.1 ± 0.6
	LTFT	%		9.37	-0.78 → 0.78
	O2F	V	*Average*	0.44	0.41
			Max	0.82	0.8
			Min	0.08	0.08
Although idle and warm up stage require only a small fuel amount. The weak fuel pump at this level causes a significant reduction in fuel supply, the ECU compensate by increase the fuel injection.					
3000	APS	%		7± 0.1	7.25 ± 0.25

RPM	TPS	%	10.5 ± 0.5	10.5 ± 0.5
	MAP	kPa	24	24.5 ± 0.5
	LOAD	%	23.1 ± 0.5	23.3 ± 0.2
	LTFT	%	12.5	-0.78 → 3.91
4500 RPM	APS	%	7.9 ± 0.2	8 ± 0.2
	TPS	%	14 ± 0.2	14 ± 0.5
	MAP	kPa	20	19.5 ± 0.5
	LOAD	%	19.2 ± 0.2	19.4 ± 0.6
	LTFT	%	12.5	0 → 1.56
At higher RPM stages, the engine demands more fuel to maintain performance. Therefore, the ECU compensate by increase a significant amount of fuel.				

3.2.3 Analyze the relationship between fault levels and it's symptoms

The most apparent symptoms were observed during the idle stage; therefore, the live data at this stage were used to analyze the relationship between fault levels and their corresponding symptoms. The live data presented as average values at the idle stage for each fault level, as show in the figure below.

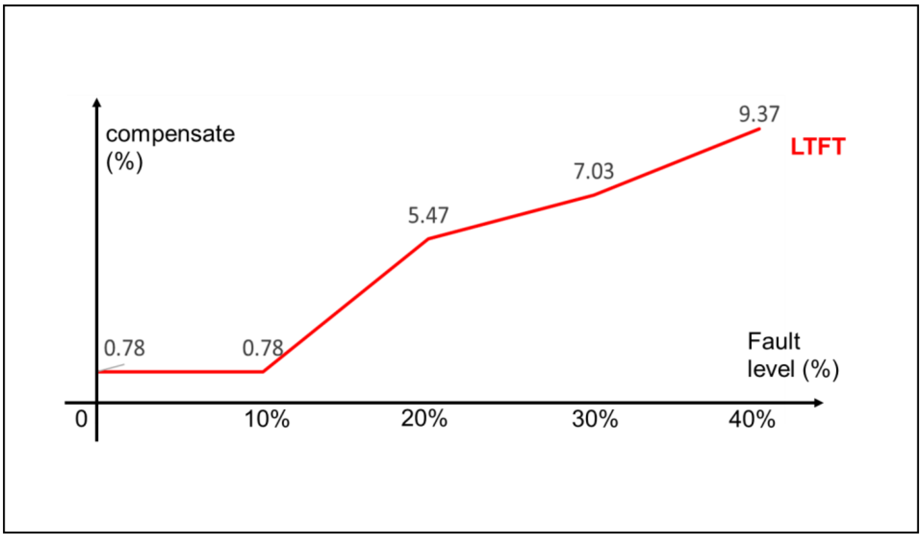


Figure 13. The chart of relationship between fault levels and symptoms

A weak fuel pump reduces the fuel injection amount according to fault levels, leading to insufficient fuel while the intake air volume remains unchanged. This results in a lean air-fuel mixture. In response, the ECU compensates by increasing the fuel injection duration to maintain the proper mixture ratio.

3.3 Leaked evaporative purge valve

3.3.1 Simulate faults, perform engine speed cycle and collect dataset

For the simulation method, the purge valve was disconnected and replaced with an airflow meter, allowing air-fuel mixture to be drawn into the intake manifold as controlled. The cause levels was categorized into 30%, 60%, 100%, 125%, and 150% by comparing the amount of leaked air-fuel mixture with the idling mass air flow. The upper and lower limits of the cause levels were defined by the purge valve's maximum flow rate (104 l/min at 40°C) and the extent to which the symptoms could occur.

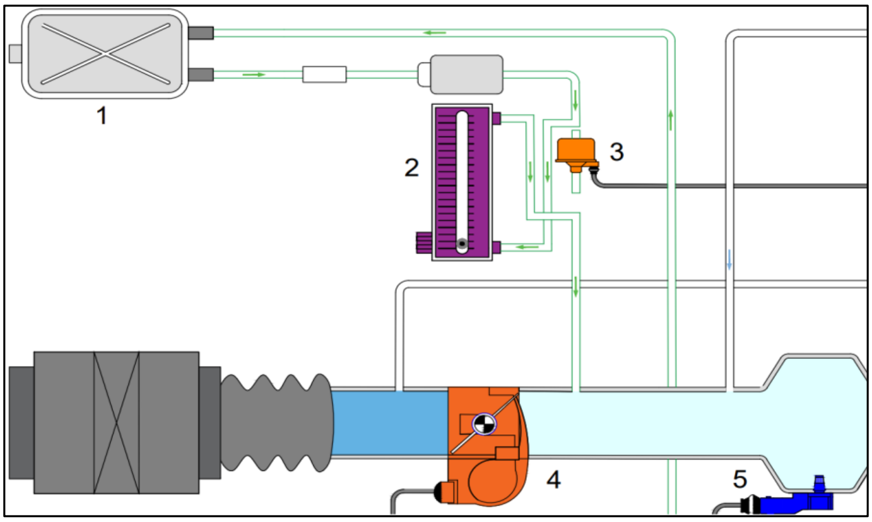


Figure 14. Leaked evaporative purge valve simulation method

1 – Canister charcoal; 2 – Air flow meter; 3 –; 4 – Purge valve; 5 – Manifold Absolute Pressure Sensor and Intake Air Temperature Sensor.

After premilitary check for battery voltage, oil, coolant,… of the engine, we started to simulate the fault following these step:

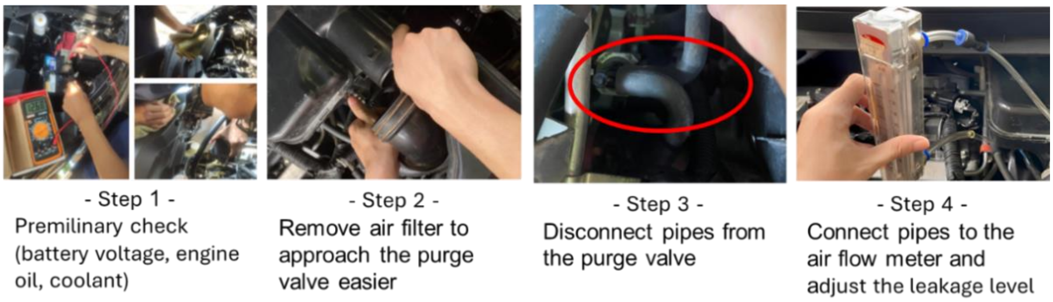


Figure 15 Leaked evaporative purge simulation procedure

After installing the simulation tools, performed the engine speed cycle for each cause level to collect the live data. The live data then are visualized into diagnostic images, as illustrated in **Appendix 3**.

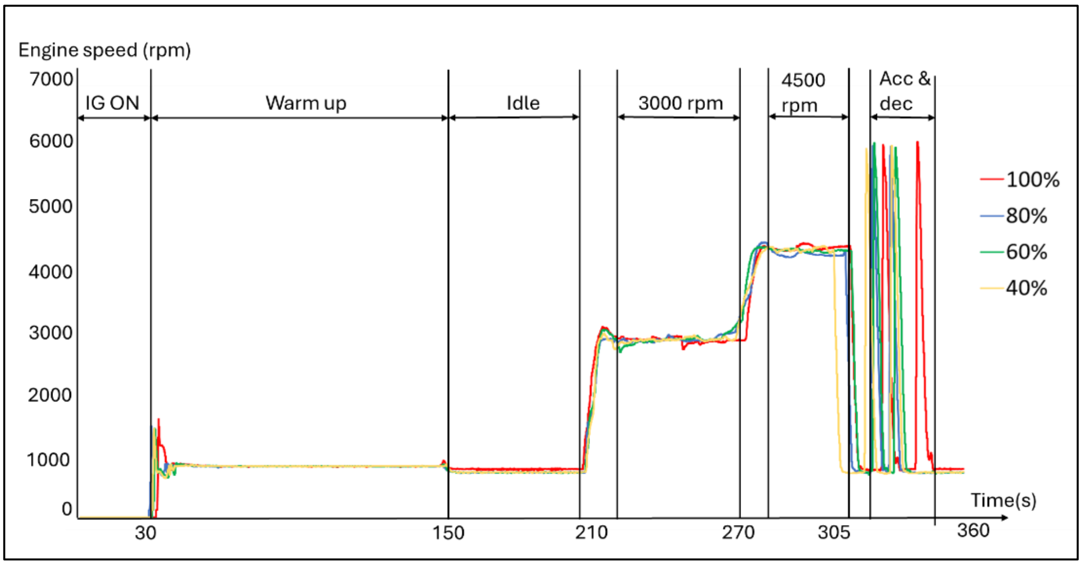


Figure 16. Perform engine speed cycle with leaked evaporative purge valve fault.

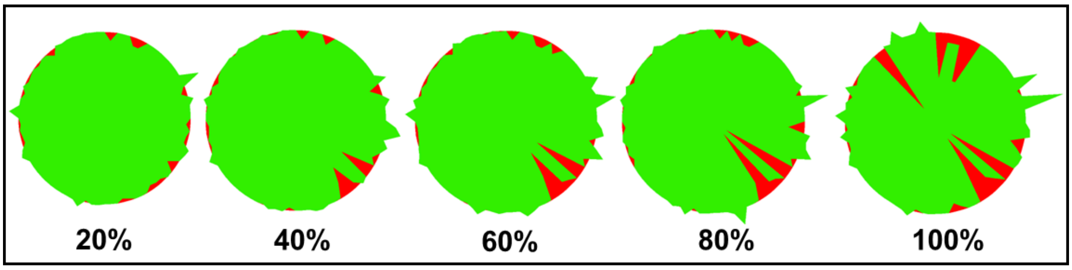


Figure 17. Diagnostic image for leaked evaporative purge valve

3.3.2. Analyze the impact of the fault on each operating stage

The impact of a fault varied at each operating stage based on the specific demands of that stage. Therefore, monitoring live data variations was crucial for effective fault analysis. In this section, the characteristic data from each stage, under both normal and fault conditions, are compared to assess the fault's impact at each operating stage.

a) Leaked evaporative purge valve (30% leakage)

STAGE	LIVE DATA / CYCLE		Experimented cycle	Standard cycle
IGN "ON"	APS	%	0 → 100	0 → 100

	TPS	%		3.92 → 100	3.92 → 100
	MAP	kPa		101	101
NORMAL					
WARM - UP	TPS	%		6.6	7 ± 1
	MAP	kPa		39	41 ± 3
	LOAD	%		38.5	40 ± 3
	LTFT	%		-4.7	3.91→-0.79
	O2F	V	*Average*	0.44	0.5
			Max	0.82	0.8
			Min	0.08	0.08
IDLE	TPS	%		3.1	3.92
	MAP	kPa		26	26.5 ± 0.5
	LOAD	%		25 ± 0.2	26.1 ± 0.6
	LTFT	%		-4.7	-0.78 → 0.78
	O2F	V	*Average*	0.42	0.41
			Max	0.82	0.8
			Min	0.08	0.08
Due to the fuel leak, the MAP value increases, causing the electronic throttle control to close to counteract the leak. This result to results to a decrease in the intake air amount, while the leak mostly fuel vapor, making the mixture rich. The ECU compensates by reducing fuel injection.					
3000 RPM	APS	%		7 ± 0.4	7 ± 0.25
	TPS	%		10.2 ± 0.2	10.5 ± 0.5
	MAP	kPa		24.5 ± 0.5	24.5 ± 0.5
	LOAD	%		23.1 ± 0.5	23.3 ± 0.2
	LTFT	%		3.91	-0.78 → 3.91
4500 RPM	APS	%		8.2	8 ± 0.2
	TPS	%		12.6	14.1 ± 0.4
	MAP	kPa		19.5 ± 0.5	19.5 ± 0.5
	LOAD	%		18.7± 0.2	19.4 ± 0.6
	LTFT	%		3.125	0 → 1.56
The engine normally opens the purge valve at high speed stage, so the leakege don't have significant impact on these stages.					

b) *Leaked evaporative purge valve (60% leakage)*

STAGE	CYCLE / LIVE DATA	Experimented cycle	Standard cycle

IGN "ON"	APS	%		0 → 100	0 → 100
	TPS	%		3.92 → 100	3.92 → 100
	MAP	kPa		101	101
	NORMAL				
WARM - UP	TPS	%		6 ± 0.05	7 ± 1
	MAP	kPa		39	41 ± 3
	LOAD	%		38.3 ± 0.2	40 ± 3
	LTFT	%		-5.47	3.91→-0.79
	O2F	V	*Average*	0.45	0.5
			Max	0.82	0.8
			Min	0.08	0.08
IDLE	TPS	%		2.75	3.92
	MAP	kPa		26.5 ± 0.5	26.5 ± 0.5
	LOAD	%		25.6 ± 0.2	26.1 ± 0.6
	LTFT	%		-5.47	-0.78 → 0.78
	O2F	V	*Average*	0.45	0.41
			Max	0.82	0.8
			Min	0.08	0.08
Due to the fuel leak, the MAP value increases, causing the electronic throttle control to close to counteract the leak. This result to results to a decrease in the intake air amount, while the leak mostly fuel vapor, making the mixture rich. The ECU compensates by reducing fuel injection.					
3000 RPM	APS	%		7.45	7 ± 0.25
	TPS	%		9.8 ± 0.5	10.5 ± 0.5
	MAP	kPa		24	24.5 ± 0.5
	LOAD	%		23 ± 0.5	23.3 ± 0.2
	LTFT	%		0.78	-0.78 → 3.91
4500 RPM	APS	%		8.2± 0.2	8 ± 0.2
	TPS	%		13.8 ± 0.2	14.1 ± 0.4
	MAP	kPa		20	19.5 ± 0.5
	LOAD	%		19.2± 0.4	19.4 ± 0.6
	LTFT	%		-0.78	0 → 1.56
The engine normally opens the purge valve at high speed, so the leakage don't have significant impact on these stage.					
Acceleration	LTFT	%		-10.1 → -2.34	-0.78 → 0
	The engine need more fuel to accelerate → LTFT increase.				

c) Leaked evaporative purge valve (100% leakage)

STAGE	LIVE DATA \ CYCLE			Experimented cycle	Standard cycle
IGN "ON"	APS	%		0 → 100	0 → 100
	TPS	%		3.92 → 100	3.92 → 100
	MAP	kPa		101	101
	NORMAL				
WARM - UP	TPS	%		5.5 ± 0.2	7 ± 1
	MAP	kPa		39	41 ± 3
	LOAD	%		38.4 ± 0.5	40 ± 3
	LTFT	%		-6.25	3.91→-0.79
	O2F	V	*Average*	0.44	0.5
			Max	0.82	0.8
			Min	0.08	0.08
IDLE	TPS	%		1.95	3.92
	MAP	kPa		27	26.5 ± 0.5
	LOAD	%		26.3 ± 0.3	26.1 ± 0.6
	LTFT	%		-6.25	-0.78 → 0.78
	O2F	V	*Average*	0.45	0.41
			Max	0.82	0.8
			Min	0.08	0.08
Due to the fuel leak, the MAP value increases, causing the electronic throttle control to close to counteract the leak. This result to results to a decrease in the intake air amount, while the leak mostly fuel vapor, making the mixture rich. The ECU compensates by reducing fuel injection.					
3000 RPM	APS	%		7.4	7 ± 0.25
	TPS	%		9.8 ± 0.2	10.5 ± 0.5
	MAP	kPa		24.5 ± 0.5	24.5 ± 0.5
	LOAD	%		23.1 ± 0.5	23.3 ± 0.2
	LTFT	%		3.91	-0.78 → 3.91
4500 RPM	APS	%		8.2	8 ± 0.2
	TPS	%		13.4 ± 0.5	14.1 ± 0.4
	MAP	kPa		20	19.5 ± 0.5
	LOAD	%		19.2± 0.4	19.4 ± 0.6
	LTFT	%		1.56	0 → 1.56

The engine normally opens the purge valve at high speed, so the leakage don't have significant impact on these stage.				
Acceleration	LTFT	%	-10.1 → -2.34	-0.78 → 0
	The engine need more fuel to accelerate → LTFT increase.			

d) *Leaked evaporative purge valve (125% leakage)*

STAGE	LIVE DATA \ CYCLE			Experimented cycle	Standard cycle
IGN "ON"	APS	%		0 → 100	0 → 100
	TPS	%		3.92 → 100	3.92 → 100
	MAP	kPa		101	101
	NORMAL				
WARM - UP	TPS	%		4.7 ± 0.2	7 ± 1
	MAP	kPa		39.5 ± 0.5	41 ± 3
	LOAD	%		38.4 ± 0.5	40 ± 3
	LTFT	%		-7.81	3.91→-0.79
	O2F	V	*Average*	0.44	0.5
			Max	0.82	0.8
			Min	0.08	0.08
IDLE	TPS	%		0.78	3.92
	MAP	kPa		27	26.5 ± 0.5
	LOAD	%		26 ± 0.3	26.1 ± 0.6
	LTFT	%		-7.81	-0.78 → 0.78
	O2F	V	*Average*	0.42	0.41
			Max	0.82	0.8
			Min	0.08	0.08
Due to the fuel leak, the MAP value increases, causing the electronic throttle control to close to counteract the leak. This result to results to a decrease in the intake air amount, while the leak mostly fuel vapor, making the mixture rich. The ECU compensates by reducing fuel injection.					
3000 RPM	APS	%		7.8	7 ± 0.25
	TPS	%		8.3 ± 0.2	10.5 ± 0.5
	MAP	kPa		24.5 ± 0.5	24.5 ± 0.5
	LOAD	%		23.1 ± 0.5	23.3 ± 0.2
	LTFT	%		3.91	-0.78 → 3.91
4500 RPM	APS	%		8.2	8 ± 0.2

<table>
<tr><td rowspan="4"></td><td>TPS</td><td>%</td><td>12.6</td><td>14.1 ± 0.4</td></tr>
<tr><td>MAP</td><td>kPa</td><td>20</td><td>19.5 ± 0.5</td></tr>
<tr><td>LOAD</td><td>%</td><td>19.2± 0.4</td><td>19.4 ± 0.6</td></tr>
<tr><td>LTFT</td><td>%</td><td>-2.34</td><td>0 → 1.56</td></tr>
<tr><td colspan="5">The engine normally opens the purge valve at high speed, so the leakege don’t have significant impact on these stage.</td></tr>
<tr><td rowspan="2">Acceeleration</td><td>LTFT</td><td>%</td><td>-10.1 → -2.34</td><td>-0.78 → 0</td></tr>
<tr><td colspan="4">The engine need more fuel to accelerate → LTFT increase.</td></tr>
</table>

e) *Leaked evaporative purge valve (150% leakage)*

<table>
<tr><th>STAGE</th><th colspan="3">CYCLE / LIVE DATA</th><th>Experimented cycle</th><th>Standard cycle</th></tr>
<tr><td rowspan="4">IGN “ON”</td><td>APS</td><td colspan="2">%</td><td>0 → 100</td><td>0 → 100</td></tr>
<tr><td>TPS</td><td colspan="2">%</td><td>3.92 → 100</td><td>3.92 → 100</td></tr>
<tr><td>MAP</td><td colspan="2">kPa</td><td>101</td><td>101</td></tr>
<tr><td colspan="5">NORMAL</td></tr>
<tr><td rowspan="8">WARM - UP</td><td>TPS</td><td colspan="2">%</td><td>3.8 ± 0.2</td><td>7 ± 1</td></tr>
<tr><td>MAP</td><td colspan="2">kPa</td><td>39.5 ± 0.5</td><td>41 ± 3</td></tr>
<tr><td>LOAD</td><td colspan="2">%</td><td>38.3 ± 0.5</td><td>40 ± 3</td></tr>
<tr><td>LTFT</td><td colspan="2">%</td><td>-10.2</td><td>3.91→-0.79</td></tr>
<tr><td rowspan="3">O2F</td><td rowspan="3">V</td><td>Average</td><td>0.39</td><td>0.5</td></tr>
<tr><td>Max</td><td>0.82</td><td>0.8</td></tr>
<tr><td>Min</td><td>0.08</td><td>0.08</td></tr>
<tr><td colspan="5">Due to the fuel leak, the MAP value increases, causing the electronic throttle control to close to counteract the leak. This result to results to a decrease in the intake air amount, while the leak mostly fuel vapor, making the mixture extremely rich. The ECU compensates by significantly reducing fuel injection initially, and then gradually increasing it as the engine warm-up speed stabilizes.</td></tr>
<tr><td rowspan="6">IDLE</td><td>TPS</td><td colspan="2">%</td><td>0.39</td><td>3.92</td></tr>
<tr><td>MAP</td><td colspan="2">kPa</td><td>29</td><td>26.5 ± 0.5</td></tr>
<tr><td>LOAD</td><td colspan="2">%</td><td>28.3 ± 0.3</td><td>26.1 ± 0.6</td></tr>
<tr><td>TA</td><td colspan="2">°TDC</td><td>2.52</td><td>11</td></tr>
<tr><td>LTFT</td><td colspan="2">%</td><td>-8.6</td><td>-0.78 → 0.78</td></tr>
<tr><td>Ne</td><td colspan="2">RPM</td><td>820 ± 17</td><td>740 ± 20</td></tr>
</table>

	O2F	V	*Average*	0.4	0.41
			Max	0.82	0.8
			Min	0.08	0.08
	Same as warm up, the leak mostly fuel vapor, closing throttle control makes the mixture extremely rich. Combine with an small air leak at air vent of EVAP system, engine speed increase. ECU detects this compensate by hardly decreasing fuel injection, Ignition timing (TA) also retard to decrease engine speed.				
3000 RPM	APS	%		7.45 ± 0.2	7 ± 0.25
	TPS	%		8.3 ± 0.2	10.5 ± 0.5
	MAP	kPa		23.5 ± 0.5	24.5 ± 0.5
	LOAD	%		22.8 ± 0.5	23.3 ± 0.2
	LTFT	%		-0.78	-0.78 → 3.91
4500 RPM	APS	%		8.9	8 ± 0.2
	TPS	%		12.6	14.1 ± 0.4
	MAP	kPa		20	19.5 ± 0.5
	LOAD	%		19	19.4 ± 0.6
	LTFT	%		-1.56	0 → 1.56
The engine normally opens the purge valve at high speed. Therefore, at this level, the leakage have less impact than other stage.					
Acceleration	Engine speed	RPM		824 → 6250	740 → 6000
	LTFT	%		-10.1 → -1.56	-0.78 → 0
	Due to the air-fuel mixture vapor leakage, the maximum speed can exceed the 6000rpm. The engine need more fuel to accelerate → LTFT increase				

3.3.3. Analyze the relationship between fault levels and symptoms

The most apparent symptoms were observed during the idle stage; therefore, the live data at this stage were used to analyze the relationship between fault levels and their corresponding symptoms. The live data presented as average values at the idle stage for each fault level, as show in the figure below.

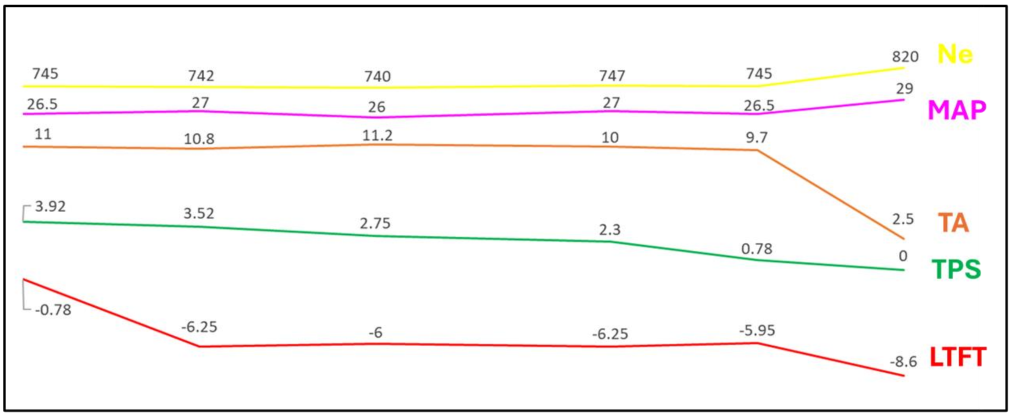


Figure 18. The chart of relationship between fault levels and symptoms

The relationship between fault levels and their corresponding symptoms was analyzed using the speed-density method:

$$m_{Air} = \rho(T_{intake}, P) * \eta_{charge}(S, \ \propto, n_e)$$

So when leak levels occur, the pressure increase, MAP sensor detect this and ECU control electronic throtle valve to close according to fault levels to stabilize the engine speed. However, this reduce the intake air amount, while the leak is mostly fuel vapor. Consequently, mixture becomes rich, ECU compensates by decreasing LTFT.

For severe fault (150%), when the electronic throttle close to 0, the intake air is minimize, the mixture becomes extremely rich. Combine with an small air leak at air vent of charcoal canister, engine speed increase. ECU compensates LTFT decrease more significantly, ignition timing (TA) also retard to decrease ignition timing.

CHAPTER 4: CONCLUSION

I. ACHIEVEMENTS

- Simulation methods related to 3 mechanical causes: Cracked intake manifold, weak fuel pump and Leaked evaporative purge valve leak.
- Analysis of the relationship between fault levels and it's symptoms:

+ Cracked intake manifold: The most noticeable symptoms included: reduced throttle opening, increased LTFT, increased engine speed, decreased ignition timing. Symptoms significantly increased with fault levels above 220%, while fault levels below 60% with less symptoms were hard to detect.
+ Leaked evaporative purge valve: the most noticeable symptoms included: reduced throttle opening, decreased LTFT. The symptoms increased with fault levels, significant at 150%, while fault levels below 30% with less symptoms were hard to detect.
+ Weak fuel pump: The noticeable symptom was the decreased of LTFT. The symptoms increased with fault levels. Fault levels below 10% with less symptoms were hard to detect.

II. LIMITATION AND DEVELOPMENT DIRECTION

2.1. Limitation

Despite achieving significant expected results, the project still encountered some unresolved issues, specifically as follows:

+ Couldn't simulate all faults cases: There were still many possible failures within the control system components while working that have not been simulated in the project.
+ The level of fault that could be detected is not comprehensive: For the same detail, when an fault appeared, for low level of faults, the data representation could be no different.
+ The diagnostic cycle had not been tested in the case of multiple faults occurring at the same time: In this project, faults were simulated in the event of each fault occurring and data was output when this fault occurs. However, in reality, the vehicle might experience damage to different parts at the same time, so the data

will appear differently from the current simulation of the topic.

+ Only applied to D-Jetronic typed fuel injection system: The implementation process currently applied to D-Jetronic typed fuel injection system, and not tested on other types.

2.2. Development direction

Based on the remaining limitations mentioned above, the group proposes the following measures to address them and provide future directions for the project:

+ Expand the scope of simulation of fault cases: Learn more about faults that can occur on details of the control system and develop a corresponding fault simulation methods.

+ Extend the data collection and cycle stages: Explore additional live data that can be collected and develop theories on how different fault levels affect the live data. Additionally, redesign the cycle to include with engine load cases.

+ Simulate multiple faults simultaneously and conduct experiments: For the faults created in this project, expand the fault simulation by simulating multiple faults occurring simultaneously and conduct experiments to collect data for building a characteristic dataset.

+ Extend the application to other types fuel injection system: Simulate faults, and collect dataset for types of fuel injection system.

APPENDIX

APPENDIX 1: ENGINE SPEED CYCLE OF 4A91 GASOLINE ENGINE - MITSUBISHI XPANDER 2020

I. ENGINE STAGES

Engine status significantly impacts a vehicle's performance, fuel efficiency, and longevity. By thoroughly understanding these statuses, drivers can make informed decisions regarding maintenance, driving habits, and fuel consumption. When the engine operation is manufunctioning, the symptoms show differently corresponding to the operating demand of each status, therefore, it is necessary to monitor live data of all the engine stages.

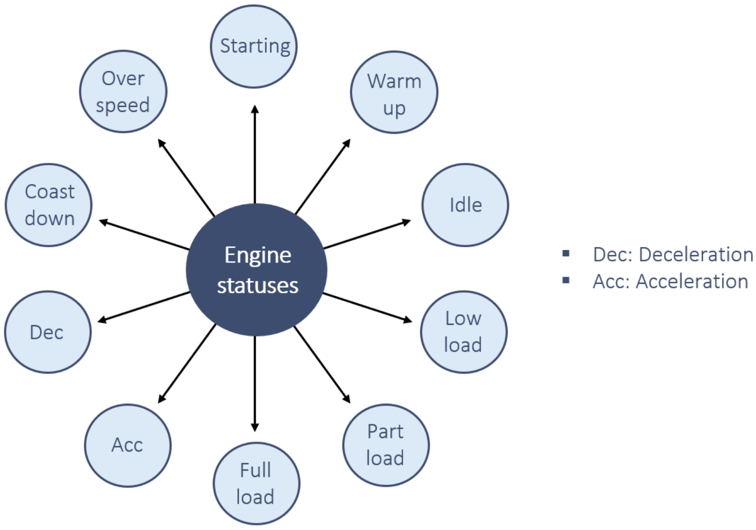


Figure 19. Basic engine operating stages

II. NON-LOAD ENGINE SPEED CYCLE USED FOR DIAGNOSING MITSUBISHI XPANDER 2020's 4A91 GASOLINE ENGINE.

Non – load engine speed cycle used for diagnosing Mitsubishi Xpander 2020's 4A91 gasoline engine serves as a basis for detecting faults when enigne has some problems because each fault has its own properties and impacts. It may not affect under one condition, but it does affect in other operating conditions.

The cycle is based on engine statuses: Starting, Warm up, Idle, Stable speed, Acceleration and Deceleration. Even though Warm up is the status in which engine is loaded, this status is required to ensure the continuity of the cycle from starting.

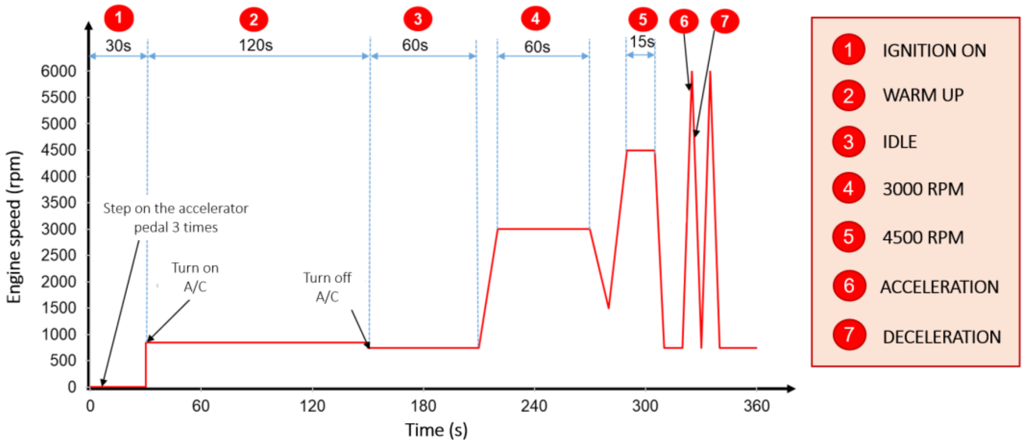


Figure 20. Non-load engine speed cycle

Engine speed cycle is implemented when engine temperature reaches 87°C - 92°C, considered as working temperature of engine. In order to reach the working temperature rapidly, it is necessary to switch on electrical devices in vehicle to increase engine load.

STAGE	IMPLEMENTATION	NOTE
0	Turn the key at IGN "ON"	To diagnose engine components at inactive status.
	Proceed to fully depress the accelerator pedal and release three times.	To survey the live data changes of components such as APS, TPS,...
1	Start the engine and turn on the A/C → Engine cranks under load to reach operating temperature quickly.	
2	Turn off A/C → Engine runs idle for 1 minute.	
3	Increase speed slowly to 3000 rpm.	
4	Maintain 3000 rpm for 60 seconds.	
5	Slowly reduce speed to 1500 rpm.	
6	Accelerate suddenly to 4500 rpm.	

7	Maintain 4500 rpm for 15 seconds.	
8	Decelerate suddenly to idle.	
9	Let the engine run idle for 15 seconds.	Allowing the engine to operate stably after a sudden throttle decrease helps increase the accuracy of the diagnostic cycle.
10	Accelerate suddenly to 6000 rpm.	
11	Decelerate suddenly to idle.	
12	Repeat steps 10-11 again.	Because suddenly accelerating and decelerating may cause the signal to not be able to send data to the reader or sent incorrectly, it is necessary to repeat the above step to read the data again.
13	Run idle for 35 seconds and end the cycle.	

Table 5. Implementation stages of non – load engine speed cycle applied to Mitsubishi Xpander 2020's 4A91 gasoline engine

APPENDIX 2: DATA PROCESSING METHOD

I. Classify the group of processing data

Based on the results of executing the cycle, the collected live data can be divided into two basic types:

+ Data that changes within a defined limit (type 1).
+ Data that changes independently in each measurement (type 2).

1.1. Data that changes within a defined limit

During the cycle execution, there exist live data whose values vary within a defined limit, and this limit is determined by performing multiple measurements combined with the manufacturer's documentation and other reference materials to conclude the range of that limit. These types of live data are presented in **Table 13** below, along with an explanation of the reasons for the changes.

Live data	Stages	Reasons
Engine speed	Acceleration/Deceleration	When the accelerator pedal is fully depressed, the speed increases from an idle state until it reaches the maximum and then decreases back to an idle state when the accelerator pedal is released.
TA		The TA is adjusted to accommodate the changes in engine operating conditions when the accelerator pedal is suddenly depressed or released.
MAP, LOAD		When the accelerator pedal is initially depressed, the MAP sensor measures the atmospheric air pressure, so it reaches the maximum MAP value. Subsequently, they are adjusted according to the engine's operating conditions.
IAT	All stages	The IAT value depends on the environmental conditions during engine operation.
ECT		Engine coolant temperature is adjust by thermostat based on each engine operating status to achieve optimal performance.

O2F, O2R		The fuel injection is adjusted according to the lambda (λ) cycle, therefore the voltage value of the oxygen sensor constantly changes within a defined range.
LTFT, STFT		Similar to the oxygen sensor, these two livedata adjust the injection quantity up or down according to the engine's operating mode.
APS	IG ON Acceleration/Deceleration	At these 3 stages, the accelerator pedal is depressed from 0 to 100% and then released back to 0%, therefore the limit of this data is always within the range of 0 - 100%.
TPS		Similar to the APS, but due to the calculations from the ECU to control the throttle control opening, there is an additional error range present.

Table 6. Data that changes within defined limit

1.2. The data changes independently across different measurements

PIDS	Stages	Reasons
Engine speed	IGN ON	Live data only depends on the current operating state of the engine, and is independent of its previous values.
TA		
MAP, LOAD		
APS, TPS		
APS	IGN ON (not push pedal yet) Warm up Idle	In the 3 stages mentioned, since the accelerator pedal is not being pressed, the APS value remains at 0.
TPS		At this stage, since the accelerator pedal is not being pressed, the TPS value remains constant at 3.92%.
Engine speed	Warm up Idle 3000 rpm 4500 rpm	Live data only depends on the current operating state of the engine, and is independent of its previous values.
TA		
MAP, LOAD		
APS, TPS		

Table 7. Data that changes independently across different measurements

II. Methods of processing each types of data

To ensure the reliability of the dataset, data is measured at least 5-6 times both when normal and when simulating faults.

2.1. Data that changes within a defined limit

For this type of data, determining the range of the standard dataset when normal and the characteristic dataset when faults is carried out through two stages:

+ Stage 1: Identifying the maximum and minimum values of each measured sample.
+ Stage 2: Identifying the maximum and minimum values among the samples from the values determined in stage 1.

2.2. The data changes independently across different measurements

For this type of data, determining the values of the standard dataset when error-free and the characteristic dataset when errors occur is carried out through 2 stages:

Stage 1: Using statistical formulas to calculate characteristic values for "each" measurement in each stage, including:

$$\text{Mean} = \bar{x} = \frac{\sum_i^n x_i}{n} \quad (2)$$

$$\text{SS} = \sum_{i=1}^{n}(x_i - \bar{x})^2 \quad (3)$$

Where:

+ $\bar{x}$ is the mean value of sample
+ n is the number of sample
+ x_i is the ith value in the sample
+ SS is the sum of squares

Stage 2: Using statistical formulas to calculate characteristic values between measurements, including:

$$\bar{x} = \frac{\sum_{i=1}^{n} \bar{x}_i . n_i}{\sum_{i=1}^{n} n_i} \quad (4)$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^{k} SS_i}{\sum_{i=1}^{k} n_i - k}} \quad (5)$$

$$x_{max} = \bar{x} + 3\sigma \quad (6)$$

$$x_{min} = \bar{x} - 3\sigma \quad (7)$$

Where:

+ $\bar{x}$ is the Grand mean
+ $\bar{x}_i$ is the mean value of ith sample
+ n_i is the size of the ith sample
+ k is the number of samples
+ σ is the grand standard deviation
+ SS_i is the sum of squares the ith sample
+ x_{max} is the upper limit
+ x_{min} is the lower limit

APPENDIX 3: DIAGNOSTIC IMAGE BUILDING METHOD

The diagnostic image was structured as a radar chart with multiple axes, each representing live data collected at 7 engine operating stages, arranged counterclockwise. However, since these data differed in units and value ranges, it was necessary to normalize these data to a common scale, ranging from 0 to 1. For each data set, appropriate processing methods were applied based on the characteristics of the data, which are divided into three groups.

Group 1: Live data collected from warm-up to 4500 rpm stages, excluding STFT and LTFT. This group denoted data continuously fluctuating around specific values. For this group, the average value of each stage was determined:

$$\mathrm{x}_{\mathrm{average}} = \frac{\Sigma_{i=n}^{n} x_i}{n} \tag{8}$$

where:

$\mathrm{x}_{\mathrm{average}}$: The average value of live data parameter at each stage

x_i: ith value in the sample

n: The number of value in the sample

Group 2: STFT and LTFT at all stages. These data had significant changes between normal and failure conditions, leading to a notable differences in the diagnostic image. To avoid distortion in the image, conventional values were assigned to the data based on conversion ranges determined through experiment.

Live data	Conversion ranges	Conversion value
STFT	$\mathrm{x}_{average} \leq$ -25%	0.5
	-25% < $\mathrm{x}_{average}$ < -9%	0.9
	-9% ≤ $\mathrm{x}_{average}$ ≤ 9%	1
	9% < $\mathrm{x}_{average}$ < 25%	1.1
	$\mathrm{x}_{average}$ ≥ 25%	1.5
LTFT	$\mathrm{x}_{average}$ ≤ -10%	0.5
	-10% < $\mathrm{x}_{average}$ < -0.78%	0.9
	-0.78% ≤ $\mathrm{x}_{average}$ ≤ 3.91%	1
	3.91% < $\mathrm{x}_{average}$ < 10%	1.1
	$\mathrm{x}_{average}$ ≥ 10%	1.5

Table 8. Conversion value for STFT and LTFT at all stages.

Group 3: Live data collected in ignition-on, acceleration and deceleration stages, excluding STFT and LTFT. For this group, the maximum values during ignition and acceleration, as well as the minimum values during deceleration, were determined to evaluate engine performance at each stage.

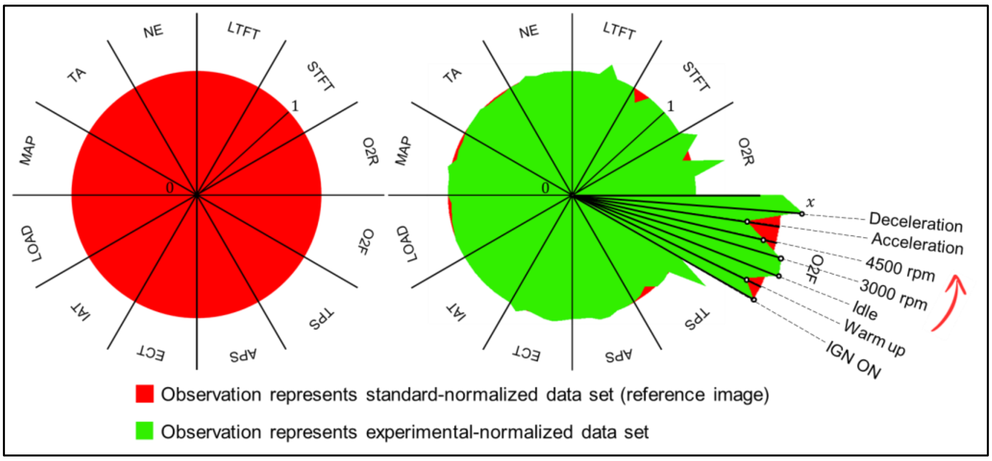


Figure 21. Structure of the diagnostic image in this study

Figure 4 depicted the first observation, which representd the standard dataset after normalization as a red circular. This first observation served as the reference image for the second observation. The second observation, representing the experimental-normalized dataset, was filled in green and constructed by connecting adjacent data points, as determined by the following formula:

$$\mathrm{x} = \frac{a_i}{A_i} \times 1 \tag{9}$$

where:

A_i: The value of live data in standard dataset

a_i: The value of live data corresponding to A_i in experimental dataset

1: The normalized value of A_i

x: The normalized value of a_i for data point

REFERENCES

[1] Nguyen Lam Vi Cuong, Duong Van Hien, Graduation thesis – *Design a practical lesson for diagnosing faults of the electrical - electronic control system on the 4A91 gasoline engine of the Mitsubishi Xpander 2020* – Ho Chi Minh City University of Technology (2022).

[2] Cao Thai Duong, Tran Thanh Khiet, Capstone project – *Develop a fast diagnostic solution of the electrical - electronic control system on the 4A91 gasoline engine of the Mitsubishi Xpander 2020* – Ho Chi Minh City University of Technology (2023).

[3] Mitsubishi, Workshop Manual – Repair documents of Mitsubishi Xpander 2020.

[4] OBD – Codes. Accessed from: https://www.obd-codes.com/ (2004-2024).

[5] Ph.D Tran Dang Long, Automotive Computer-controlled System – *On-Board Diagnostics* – Ho Chi Minh City University of Technology (2023).

[6] Bosch - Motronic ME9 OBD System Strategy (2003).

[7] Nguyen Tat Tien (2003), Nguyen ly Đong co đot trong, Nxb Giao duc, Ha Noi.

[8] Pham Van Quan, Nguyen Thai Duong, Capstone project – Design an automatic diagnostic algorithm applied to Mitsubishi Xpander 2020'S 4A91 Gasoline engine – Ho Chi Minh City University of Technology (2024).