# Simulation of engine faults and their impact on emissions and vehicle performance for a liquified petroleum gas taxi

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## Abstract

Deterioration of emissions control systems in a spark ignition engine is predominantly a gradual process of wear and tear occurring as vehicles accumulate mileage. As new innovations in engine and emissions technology have been progressively introduced to meet lower emissions targets, the impact of gradual deterioration of hardware has become more challenging to quantify/identify in the repair industry. When a pioneering emissions control programme utilising remote sensing to detect high emitting gasoline and liquified petroleum gas (LPG) vehicles was to be introduced in Hong Kong, it became apparent the repair industry needed specialised training to assist with identifying the types of failures which would lead to high vehicle emissions. To identify the impact of hardware deterioration and failures, a Toyota Crown Comfort LPG taxi was used to demonstrate simulated failures of engine hardware systems to measure the impact on emissions, fuel consumption and drivability using a chassis dynamometer. This novel study simulated a broad range of deterioration and failures covering the intake, fuel supply, ignition, and exhaust systems. The results of the study showed significant THC and CO increases of up to 317% (0.604 g/km) and 782% (5.351 g/km) respectively for a simulated oxygen sensor high voltage fault and a sticky mixture control valve. The largest increase in $NO_x$ emissions was for restricted main fuel supply in the LPG vapouriser, producing an increase of 282% (1.41 g/km). Fuel consumption varied with increases of up to 15.5%. Drivability was impacted with poor idle from a number of faults and especially by a worn throttlebody which produced rough acceleration characteristics as well. This study clearly highlights the importance of having properly maintained emissions and engine hardware systems to achieve optimal fuel economy and compliant pollutant emissions levels, which could be reproduced in other regions for prescribed emissions regulation.

Keywords: Fault simulation, Emissions, High emitting vehicles, Inspection and maintenance, Training programmes

## Abbreviations

| | |
|---|---|
| **AFR** | Air Fuel Ratio |
| **AQO** | Air Quality Objectives |
| **BAR** | California Bureau of Automotive Repair |
| **CARB** | California Air Resources Board |
| **CLA** | Chemiluminescence Analyser |
| **CO** | Carbon monoxide |
| **$CO_2$** | Carbon dioxide |
| **CVS** | Constant Volume Sampler |
| **EGR** | Exhaust Gas Recirculation |
| **ECU** | Engine Control Unit |
| **FID** | Flame Ionisation Device |
| **HP** | Horsepower |
| **HKTET** | Hong Kong Transient Emissions Test |
| **I/M** | Inspection Maintenance |
| **kW** | Kilowatts |
| **NDIR** | Non-Dispersive Infra-Red |
| **NEDC** | New European Drive Cycle |
| **Nm** | Newton Metres |
| **NO** | Nitrogen Oxide |
| **$NO_2$** | Nitrogen Dioxide |
| **$NO_x$** | Total Oxides of Nitrogen |
| **RDE** | Real Driving Emissions |
| **THC** | Total Hydrocarbons |
| **TWC** | Three Way Catalytic converter |

# 1 Introduction

The performance of vehicles being driven on road has long been a focus of manufacturers, regulators and users (De Simone et al., 2019). Characteristics such as reliability, speed, handling and fuel consumption were often the focus of manufacturers and users as these impacted sales, user satisfaction and operating costs (Grigoratos et al., 2019). As vehicle fleet sizes increased and road traffic density intensified, the negative environmental emissions impact of vehicles became evident (Haagen-Smit, 1962; Requia et al., 2016; Weber et al., 2019). Identification of the pollutants and the mechanisms that created them lead to a progressive development of increasingly stringent regulations to address the problems at the source. In turn validation of emissions performance/compliance was necessary and the evolution of laboratory emissions testing of vehicles developed and became the standard for regulatory type approval. Testing technology has progressed to improve measurement capabilities in the years since regulations were established and more recently the introduction of real driving emissions (RDE) to measure on road emissions have enabled regulators and manufacturers to reduce the gap between real world and laboratory performance (Bishop et al., 2019; Huang et al., 2019c; Kumar Pathak et al., 2016). The goal of these testing mechanisms is to support the target of reducing emissions from vehicles to meet Clean Air Plan targets or Air Quality Objectives (AQOs) that have been established in various regions and cities around the globe.

On the vehicle side to achieve this continuous drive for lower emissions, numerous technological advancements have evolved to address the various aspects of pollution control and mitigation (Chandra and Camal, 2016). The majority of vehicles being manufactured and in use currently utilise engines based on the Otto cycle. For these engines, developments in emissions control, fuel injection, engine management and hardware have improved their emissions performance and fuel economy. Developments and innovations such as Exhaust Gas Recirculation (EGR), the progression from carburettor to mechanical then electronic fuel injection (EFI), pressurised fuel systems, manifold absolute pressure (MAP) sensors, manifold airflow (MAF) meters, electronic throttle control (ETC), spark plug development, three way catalysts (TWC) and oxygen sensors all of which are connected and controlled by an engine control unit (ECU). All of these systems have been studied extensively by manufacturers to investigate the effectiveness of each of the individual systems and how they improve vehicle performance and reduce emissions throughout a vehicle’s lifecycle (Zhang et al., 2018). When vehicles utilising these technologies are new or on the road with low mileage the systems will still be in good condition and performing effectively to meet regulatory requirements. As mileage increases, the maintenance of each of these systems is crucial in maintaining the overall driving and emissions performance of vehicles (Austin and Ross, 2001; Hickman, 1994). Since the usage of each vehicle on road varies, deterioration of these systems whether by tampering, lack of or infrequent maintenance or failure as mileage accumulates begins to impact the capability of vehicle to maintain their compliance to performance standards/regulations(He et al., 2019).

This brings the focus of this study to the technical training for mechanics and technicians. Training standards vary in each country around the globe and overall training for students requires them to learn and assimilate knowledge on all the various systems present in vehicles. As such the focus regarding exhaust emissions compliance is just one of the many aspects of the overall vehicle knowledge which students will need to learn during their training. What is identified from this is that mechanics and technicians working in the automotive repair industry could have a lack of detailed knowledge or experience when it comes to the overall emissions performance impact of malfunctions and failures of one or more of these technologies. It should also be noted that the primary focus for maintenance/repairs and vehicle performance had been to make sure that faults which impact driveability, safety and fuel economy are repaired promptly to ensure costs are minimised. Furthermore consideration of costs and these elements were regularly put before vehicle emissions. As deteriorating or poor air quality in major cities like Hong Kong continued to be an on-going issue, it was evident that without a process or mechanism to push vehicle owners to keep vehicles in good condition and the automotive repair industry to improve the effectiveness of maintenance to reduce emissions. This issue would likely see the continuation of deteriorating air quality.

To help facilitate improvements in air quality it was determined that a real-time monitoring tool capable of passively measuring hundreds of passing vehicles per hour should be utilised to identify high emitting vehicles. The tool selected to be most effective for this task was remote sensing (Huang et al., 2018b; Organ et al., 2019) .Before the Hong Kong Environmental Protection Department (HKEPD) introduced their strengthened emissions control programme utilising remote sensing to identify high emitting gasoline and liquified petroleum gas (LPG) vehicles (Hong Kong Government, 2014), the vehicle repair industry reaction to the remote sensing programme was of concern as detailed knowledge for repairing emissions failures had not been a major focus previously and there was concern vehicle owners or operators could be unfairly impacted financially if vehicles failed to pass testing after repairs with the possibility of vehicles being deregistered. To address this situation, the HKEPD had begun an engagement exercise earlier financially supporting a series of testing and evaluation programmes to engage with transport operators, repair industry associations and other stakeholders to identify which hardware failure types impacted the transport industry performance and emissions. The most frequent and worst case failures were determined from the programmes and the information shared with all stakeholders. With a list of hardware failures identified, planning was undertaken to manage industry concerns and deliver an acceptable outcome which would improve the emissions performance of the on-road vehicle fleet. This outcome was that a programme would be established before the implementation of the remote sensing enforcement programme to build up a test vehicle which could be used to simulate a comprehensive range of commonly observed engine and exhaust component failures as worst case scenarios. The list of failures was to be determined by consultation and agreement of all key stakeholders. These failures could then be demonstrated under repeatable test conditions using a chassis dynamometer where the automotive repair industry members/audience could learn firsthand about the impact of different failed components and which repairs were needed to ensure vehicles would be compliant with emissions regulations.

Studies conducted on failure simulations have focused on specific elements of vehicles. Toma et al. (2019) tested fault simulations created by disconnecting the electrical connector from either the MAP sensor, a fuel injector or the oxygen sensor. The testing was performed on four Dacia Logan cars at low and high idle and 50 km/h steady state speed. They observed significant increases of THC and CO for the MAP sensor and higher again for the oxygen sensor fault. Each of these observed results are a product of the ECU using open loop operation when sensor signals are not available. Nevius et al. (2012) conducted emissions measurements using PEMS and FTIR recording the outcome of EGR valve failure. The effectiveness of the EGR valve when working correctly to reduce THC, CO and all $NO_x$ gas species to the vehicles Euro 4 emissions limits was shown. Lee et al. (2002) studied the impact of variations to engine ignition such as ignition retard, ignition timing, excess air or fuel and misfire on close coupled TWC at various engine loads from 1500 to 4000 rpm. They identified the damage that can occur to TWC from misfire, too much retard and excess air ratio all of which lead to higher temperatures above 1050°C which will damage the precious metals in the TWC wash coat. Zheng et al. (2018) conducted testing on taxis with deactivated

TWCs showing the significant emissions difference between these vehicles and ‘China 4’ regulation taxis with active catalysts. Comprehensive studies generally have not been conducted to cover a complete range of common failures to determine their emissions impact, except for a recent study on a diesel Euro VI medium goods vehicle (Huang et al., 2019a). As the combustion and emissions aftertreatment technologies between diesel and spark ignition engines differ considerably, so the outcomes of that study vary from the results of this study. The value and novelty of this study cannot be understated as it unique in demonstrating a broad range of emissions failures for spark ignition engines and will help professionals in the automotive repair industry quickly and effectively identify emissions faults for repair.

The aim of this research is to simulate the different engine faults and their impacts on vehicle emissions, fuel consumption and drivability. In total 15 different malfunctions/faults (targeting worst case) were simulated using a chassis dynamometer, which were grouped into the following functional areas: air intake, fuel delivery, ignition and exhaust after treatment systems. This study provided essential knowledge for the automotive repair and maintenance industry to effectively identify and repair emission-related faults of LPG and gasoline vehicles. It also established a higher and more comprehensive level of research undertaken to address improving knowledge and its delivery to industry, which was a prerequisite for introducing the HKEPD remote sensing enforcement program. In addition, it provided further value in outlining a proven research and training framework that could be utilised in other cities and regions to characterise and address failures producing high emissions from their vehicle fleets regardless vehicle type, age or emissions standards.

## 2 Experimental section

### 2.1 Test vehicle and methods

Identifying a vehicle that many automotive repairers were familiar with and one that could easily be worked on by many workshops led to the selection of the Toyota Crown Comfort LPG taxi (Figure 1) as the vehicle of choice for the demonstration programme. It was the dominant vehicle (>95% of 18,163 licensed taxis) of the local taxi fleet and thus was a common extensively utilised vehicle accumulating high mileage and likely to have also deteriorated quickly thus contributing to serious air quality problems in Hong Kong. It also contained the target emissions control technologies gasoline and LPG vehicles had in common.

Figure 1. Toyota Crown Comfort Taxi under test.

Testing for this study was conducted at the Jockey Club Heavy Vehicle Emissions Testing and Research Centre in Hong Kong. The test vehicle specification is shown in Table 1. The Toyota Crown Comfort taxi had a kerb or unladen weight of 1400 kg and for testing a reference weight of 1470 kg was used in line with UNECE Regulation 83 simulated inertia and dyno loading requirements. It was equipped with a 1.988 l naturally aspirated LPG fuelled 4-cylinder engine. The specified maximum power and torque ratings for the engine are 58kW @ 4400 rpm and 160 Nm @ 2400 rpm respectively. This vehicle was built to meet the requirements of Euro 2 emissions standard and was representative of the dominant model of LPG taxi on road in Hong Kong in 2014 before the HKEPD began their ‘Strengthened emissions control of gasoline and LPG vehicles’ programme to identify high emitting gasoline and LPG vehicles. The vehicle had a TWC, oxygen sensor and EGR valve installed in the exhaust after treatment system to reduce emissions and meet the required standard.

Table 1. Specification of the vehicle used in this study.

| | |
|---|---|
| Vehicle make | Toyota |
| Vehicle model | Crown Comfort – YXS10RAESBN |
| Manufacturing year | 2000 |
| Engine model | 3Y-PE |
| Working Principle | Spark Ignition |
| Type of fuel used | Liquefied Petroleum Gas |
| Number of cylinders | 4 |
| Layout of cylinders | In line formation, Front Mounted Longitudinally |
| Bore (mm) | 86.0 mm |
| Stroke (mm) | 86.0 mm |
| Swept volume (litre) | 1.998 litre |
| Compression ratio | 10.5:1 |
| Rated maximum power output | 58 kW @ 4400 rpm |
| Rated maximum torque output | 160 Nm @ 2400 rpm |
| Exhaust aftertreatment | TWC & EGR |

The testing was conducted utilising a Euro 5 compliant and certified emissions chassis dynamometer, specifically a 48-inch 150 HP Mustang (Model: MIM48-150) single roller chassis dynamometer and Signal Maxsys900 emissions measurement system with a constant volume sampler (CVS). The emissions system was used to measure the concentrations of THC, $NO_x$, CO and $CO_2$. THC was measured using a flame ionisation device (FID), $NO_x$ was measured by a chemiluminescence analyser (CLA), and CO and $CO_2$ were measured by Non-Dispersive InfraRed (NDIR) analysers. The accuracy specification of these analysers is shown in Table S1. Modal emissions measurements were recorded at 1 Hz and emissions factors in g/km were calculated for each test cycle using the method defined in the Regulation 83 of the Economic Commission for Europe of the United Nations (UNECE, 2015). The fuel consumption rate was calculated in l/100km using the method defined in Regulation 101 of the Economic Commission for Europe of the United Nations (UNECE, 2013). The test cycle used to assess each simulated failure condition is the Hong Kong Transient Emissions Test (HKTET) cycle (Commissioner for Transport, 2012; Huang et al., 2019b). This test cycle is based on the TÜV Rheinland TUV-A short drive cycle (Samaras and Kitsopanidis, 2001; Samaras et al., 2001) which has been selected by the HKEPD as suitable for a short hot start

I/M transient emissions test. As shown in Figure S1, the test cycle has a duration of 200 s with a total distance of 1969 m and a maximum speed of 90.0 km/h.

It is to be noted that the HKTET test cycle is derived from the New European Drive Cycle (NEDC) which is used to determine compliance with the European standards for a vehicles' type approval. The HKTET is the I/M emissions certification test for Hong Kong's in-use vehicles which can be applied in a rapid, economic manner to a large number of vehicles that have been identified as high emitters. The results provide a reliable indication if a tested vehicle does or does not comply with its given European standard (for I/M emissions conformity, not type approval compliance).

The results of the testing for each malfunction/fault simulation have been collated, followed by the calculation of the average and standard deviation for each test malfunction simulation. The standard deviation results in the form of error bars show the range of variation.

### 2.2 Malfunction simulation

Before the testing began, the Toyota Crown Comfort taxi underwent significant maintenance work with the engine being rebuilt to as new condition with machining of the engine block, the cylinders, replacement of pistons, bearings, machining of the cylinder head, valve replacement and all gaskets and seals. All filters, fluids and consumable parts were replaced. The transmission was serviced along with the drivetrain, suspension and new tyres were fitted. The vehicle was then independently checked by a third party to certify all work had been properly conducted and the vehicle was in a fully functional and roadworthy condition after completion of all work and before any testing was conducted. The vehicle was then tested with all hardware functioning properly on the chassis dynamometer (as shown in Figure 1) and this condition was utilised as the baseline for comparison with the simulated faults.

Following the baseline testing, each of the 15 simulated malfunctions was investigated one at a time with all other system hardware being in good condition. These malfunctions covered the faults that could occur in the intake, fuel, ignition and exhaust after treatment systems. Malfunctions were simulated by either switching, disconnecting, mechanically disabling or electrically simulating an alternate output signal of the engine hardware or emissions system component. For each of these simulated malfunctions there were a minimum of three test results collected for evaluation purposes, It is noted that in the real world environment wear and tear failures do not occur in isolation. Normally multiple systems can wear and have deteriorated performance in tandem. The goal of testing in isolation is to provide a foundation knowledge on the magnitude of the effect of a particular failure. Which experienced automotive repair professionals can then use to assess the likely combined emissions impact of deterioration of the systems that they analyse and identify as faulty whilst conducting maintenance and repairs.

### 2.2.1 Intake system

#### 2.2.1.1 Worn Shaft Bushings in Throttlebody Butterfly Valve

The butterfly valve in the throttlebody (Figure S2 of the Supplementary Information) is used to control the airflow into the engine, pending the drivers speed/power demand via the throttle pedal. For efficient operation this must open and close smoothly at all times. The butterfly shaft runs on bushings and over time these can wear and the operation can become rough and the throttle plate can stick or jam in place which results in poor driveability for the vehicle. For simulation of the failure, the bearing bushings were lightly filed and scored so the butterfly shaft did not move smoothly and would momentarily stick in place when opening or closing.

#### 2.2.1.2 Sticky mixture control valve in the fuel mixer

The mixture control valve (Figure S3) is installed in the throttlebody assembly of the vehicle and controls the flow of LPG into the inlet manifold. In normal operation the mixture control valve moves smoothly and can deliver the fuel quickly as needed. To simulate failure, a used/worn mixture control valve which was sticking/not moving smoothly was installed in the throttlebody. The resultant impact on vehicle performance was a deterioration of the vehicle drivability, smoothness of acceleration and engine response.

#### 2.2.1.3 Sticky idle control valve in the fuel Mixer

The idle control valve (Figure S3) in the throttlebody regulates the required fuel injection when the engine is idling, i.e. when the butterfly valve and the main fuel mixing valve are closed. To simulate a malfunction an idle control valve which was sticking when operating to open or close was utilised. The sticky idle control valve impacts the engine idle stability resulting in poor/rough engine idling.

### 2.2.2 Fuel system

#### 2.2.2.1 Overly Rich/Lean Air-fuel Ratio Adjustment in Vapouriser

The vapouriser (Figure S4) is where the LPG is converted from liquid phase into a gas phase for mixing with the air into the intake manifold. The vapouriser has a diaphragm which is spring loaded to control the gas pressure and in turn the amount of LPG delivered to achieve stoichiometric air-fuel ratio for combustion. Adjusting the spring pressure either higher or lower alters the control pressure and the air fuel ratio adjustment. This will result in higher or lower fuel flow rates which can result in rich or lean biased fuel supply and potentially rich or lean combustion if it is outside the range of the closed loop feedback control for fuel supply. It can also result in fuelling control switching from closed loop feedback control to open loop control adding another variable element which further impacts the emissions and could produce a large variation in a set of test results.

#### 2.2.2.2 Restricted main fuel line in Vapouriser

Once the fuel has become a gas in the vapouriser it travels from there to the mixing valve on the throttlebody where it is metered into the intake manifold. Blockages can occur in the vapouriser and restrict the flow of fuel. To simulate this failure a line from the vapouriser to the mixing valve had an adjustable stop valve installed which could be used to restrict the fuel flow. When the fuel flow is restricted the vehicle loses power under heavy acceleration and load.

#### 2.2.2.3 Restricted idle fuel supply line

The idle fuel supply is also subject to blockages before it arrives at the idle injector in the throttlebody. Similar to the main fuel supply in the vapouriser the idle supply can be restricted as well. Simulation of this failure was by an adjustable stop valve installed in the fuel line which was used to restrict fuel flow. When the fuel flow is restricted the vehicle experiences rough idling conditions.

#### 2.2.2.4 Faulty Fuel Cut Solenoid Value in Vapouriser

The fuel cut solenoid valve (Figure S5) is used to stop the fuel flow from the vapouriser to the main mixture control valve and the idle control valves in the throttlebody. It opens when the fuel system primes before the engine starts and stays open while the engine is running. When the engine is turned off it closes and shuts off fuel supply to the vapouriser. The fault is simulated using a valve that is sticking when opening or closing. This results in the gas flow not stopping or starting when required and the engine operation not being controlled as needed.

### 2.2.3 Ignition system

#### 2.2.3.1 Faulty Spark Plug

The spark plug is essential in a spark ignition engine to provide the ignition source for the air fuel mixture in the cylinder. The spark plugs used in the Toyota Crown Comfort LPG taxi have been selected to optimise performance under the combustion conditions of the Toyota 3Y-PE engine used in these vehicles. As spark plugs wear over time, i.e. electrode(s) deteriorating, spark gap increasing, deterioration of the insulator, etc., the amount of energy required to form the spark increases, the duration of the spark and the quality of the ignition are impacted. These factors will impact the driving performance (fuel economy, misfire, rough idle, reduced acceleration power) and emissions of a vehicle. Worn spark plugs were utilised to simulate the malfunction.

#### 2.2.3.2 Faulty Distributor Cap and Rotor

The distributor functions to provide the required ignition timing to each cylinder at the correct time. The rotor is moving when the engine is running and touching the rotor contacts to provide the high voltage current from the coil to the spark plug to allow ignition of the air fuel mixture in the cylinder. Over time the rotor and distributor cap can wear due to vibration, exposure to high temperature and voltage, cracking and carbon deposits building up. To simulate failure in the testing a distributor cap with worn contacts was used in conjunction with a worn rotor. The Faulty Distributor Cap and rotor are shown in Figure S6 of the Supplementary Information.

### 2.2.4 Exhaust system

#### 2.2.4.1 Worn /Aged TWC

The TWC works to convert emissions of THC and CO by oxidation reactions to $CO_2$ and $H_2O$ using the precious metals Platinum and Palladium. NO and $NO_2$ are converted by a reduction reaction using the precious metals Platinum and Rhodium to $N_2$ and $H_2O$ (Chatterjee et al., 2001). The conversion reactions are represented by equations 1 – 3. A simulated malfunction has been produced by utilising a worn/aged TWC which has reduced effective surface area of the catalyst materials within the substrate for effective pollutant reduction. To be able to quickly compare the performance of a good and worn/aged TWC, the exhaust system was modified so both catalysts could be installed at the same time, with flow valves being used to select either the good or the worn/aged catalyst for a test. This dual catalyst installation is shown in Figure S7 of the Supplementary Information. The worn/aged TWC malfunction was the most commonly observed failure mode. Another failure mode also observed less frequently was blockage of the TWC. When this occurred the TWC substrate effectively acted as plug when under higher load and acceleration and the vehicle driveability was severely in impacted with loss of power, reduced top speed and engine stalling occurring in some instances.

$$CO + \frac{1}{2}O_2 \rightarrow CO_2 \qquad (1)$$

$$C_nH_m + \left(n + \frac{m}{4}\right)O_2 \rightarrow nCO_2 + \frac{m}{2}H_2O \qquad (2)$$

$$CO + NO \rightarrow CO_2 + \frac{1}{2}N_2 \qquad (3)$$

#### 2.2.4.2 Faulty Oxygen Sensor

The oxygen sensor (Figure S8) monitors the oxygen content in the exhaust gas before it enters the TWC. The sensor installed in this vehicle provides a variable voltage signal. If the exhaust is rich (high THC or CO) the voltage is around 0.9 V and if lean (high $NO_x$) the voltage is 0.1 V or when the mixture is at stoichiometric (balanced) the voltage is 0.45 V. The signal is utilised by the ECU to modulate and trim the fuel supply to try to achieve stoichiometric combustion conditions. The ECU either supplies additional fuel when the signal is lean or reduces the supply when it is rich. To simulate failures in this study, a breakout box was installed so that a fixed voltage signal from a power supply could be sent to the ECU. Constant voltage signals of 0.1 V and 0.9 V were utilised to simulate a faulty oxygen sensor. Additionally, when the oxygen sensor maintains a voltage signal that is excessively high or low for an extended period, the ECU can switch from using this signal in closed loop control to open loop control where fuel is supplied at predetermined settings for a given acceleration or driving demand. This can increase emissions by impacting the rich or lean conditions that already exist in the engine and could also produce a possible large variation in a set of test results.

#### 2.2.4.3 EGR Valve Jammed Open/Closed

The EGR valve (Figure S9) is utilised to allow a controlled/metered amount of exhaust gases back into the intake manifold which in turn reduces or dilutes the amount of available oxygen in the intake air available for combustion and lowers the temperature of combustion to reduce $NO_x$ formation. The EGR valve in this vehicle opens and closes utilising manifold vacuum and is controlled by an ECU controlled solenoid valve. To simulate a jammed open EGR valve, the vacuum line was disconnected and reconnected to a manually operated vacuum pump to keep the valve open. Conversely to simulate a jammed closed valve, the vacuum line was disconnected from the EGR valve so it would remain closed during testing.

## 3 Results and discussion

The results analysis and discussion are separated into the following sub-sections. Sub-section 3.1 covers the effect of malfunctions on regulated gaseous emissions. Sub-section 3.2 is covering the effect of the malfunctions on emissions of $CO_2$ and fuel consumption. Sub-section 3.3 discusses which malfunctions impact the driveability performance of the vehicle. Sub-section 3.4 outlines how the industry training programme was organised utilising the results of the study for improving the knowledge and experience of the repair industry.

### 3.1 Regulated gaseous emissions

The European emissions regulations for light duty (<3.5 t) positive (spark) ignition engine vehicles have emissions factor limits specified in g/km. The Toyota Crown Comfort Taxi tested in this study was built to the Euro 2 standard. The UNECE Regulation 83 Euro 2, type 1 test emissions limits for these vehicles were 0.5 g/km for $THC+NO_x$ and 2.2 g/km for CO (Australian Government, 2018). Figures 2 and 3 show the effect of the simulated engine malfunctions on THC and CO, respectively. For reference, the Euro 3 emissions limits have been included in these tables as the Euro 3 standard vehicle was similar in construction to the test vehicle used in the study. The differences for the Euro 3 model are a larger TWC, upgraded mixture control valve, throttlebody venturi and ECU software to improve cold start and hot emissions performance. A summary showing the comparison of the relative changes of emissions factors for each simulated malfunction and the baseline test are shown in Table S3.

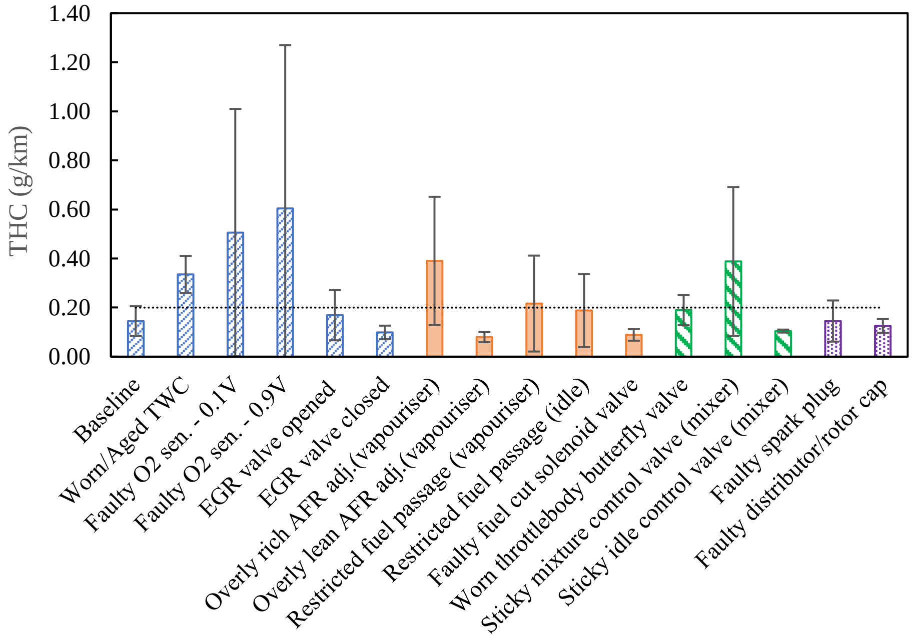

Figure 2: THC emissions results for malfunctions. Error bars indicate standard deviations and the dotted black line indicates Euro 3 THC emissions limit. (For Euro 2 standard, THC emissions are combined with $NO_x$)

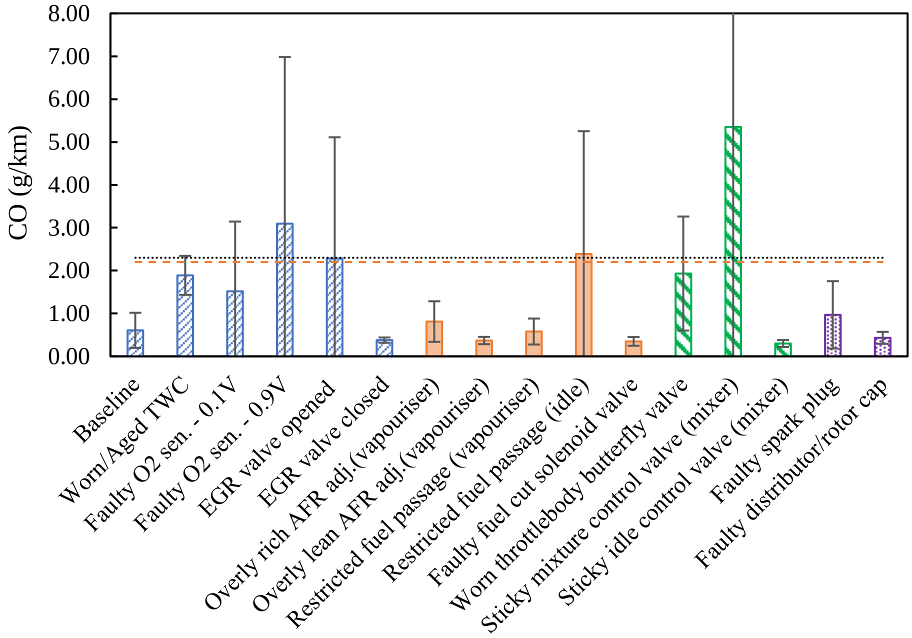

Figure 3: CO emissions results for malfunctions. Error bars indicate standard deviations and the dashed orange line indicates Euro 2 CO emissions limit. Dotted black line indicates Euro 3 CO emissions limit.

Reviewing the results for the simulated malfunctions, the majority of the THC and CO emission factors are lower than both the Euro 2 and 3 emissions limits (Figures 2 and 3 and Table S2 of Supplementary Information). The impact of the simulations shows for many of the failures there is little effect on the emissions or there are slight reductions from the baseline result. The THC results (Figure 2) show that for 6 out of the 15 simulated malfunctions the emissions factors are similar to or lower than that of the baseline result. The CO results (Figure 3) show a similar pattern as the THC for these 6 simulated malfunctions (5 are the same as THC) having similar or lower emissions factors as the baseline result. This consistency is not unexpected as THC and CO emissions often have similar trends in positive ignition vehicles. When these results are compared to the THC+$NO_x$ and $NO_x$ results (Figures 4 and 5) it can be seen in some instances the simulated malfunctions have trends that are opposite to the results observed for THC and CO. This also is expected when the balance of fuelling has been biased either rich or lean by the simulations. These results provide support to the different/conflicting emission formation mechanisms of THC/CO vs NO: THC and CO are results of unburnt and partial combustion respectively (mainly rich fuel combustion) while NO is formed in high temperature rich-oxygen condition (slightly lean fuel combustion) (Huang et al., 2018a).

The baseline test result with the new catalyst and all systems functioning properly shows this high mileage vehicle (odometer mileage of >436,000 km when tested) to be in good condition and repair to have relatively low emissions for each individual pollutant gas or combination of gases when tested using the HKTET transient emissions test.

The highest increases in the THC emissions factor is the result of a simulated faulty oxygen sensor signal which produces increases of 4.2 times for THC (206% of the THC+$NO_x$ limit) and 5.1 times for CO. This has occurred when the oxygen sensor signal voltage has been replaced by a constant input voltage (0.9 V). In this instance the ECU has trimmed/reduced the fuel supply as the supplied voltage simulating the sensor signal indicates the combustion is rich. When this reduction in fuelling has occurred, it produced misfire events and has resulted in high THC and CO levels being produced. The highest increases in the CO emissions factors are the result of a sticky mixture control valve which produces increases of 8.8 times for CO (243% of the CO limit) and 2.7 times for THC. This has occurred when the mixture control valve sticks when operating. In this instance there has been excess fuel resulting in rich combustion. Further faults producing significant increases are the low oxygen sensor supply voltage malfunction (0.1 V) with THC and CO being 3.5 and 2.5 times higher. In this instance when the fuel trim has added more fuel, the combustion becomes rich and delivers unburnt THC as well as CO. The restricted idle fuel delivery fault simulation has also produced CO emissions 3.9 times higher (109% of the limit) when the fuel supply is unstable at idle, this produced rough idle and impacted the completeness of combustion. The other fault simulations which produced higher THC and CO emissions than the baseline were either just greater than the Euro 2 emissions limits or just below them. The faulty/aged TWC produced THC and CO emissions that are 2.3 and 3.1 times higher than the baseline. In this instance only when THC+$NO_x$ results (Figure 4) are combined does the result exceed the Euro 2 emissions limit (214% of the limit). Further noticeable increases that occurred are the overly rich Air Fuel ratio adjustment producing THC and CO emissions 1.2 and 3.8 times the baseline result (104% of CO limit). Other increases greater than the baseline result but lower than the emissions limits were from the EGR valve jammed open, restricted fuel passages for main and idle fuel supply and the worn throttlebody valve.

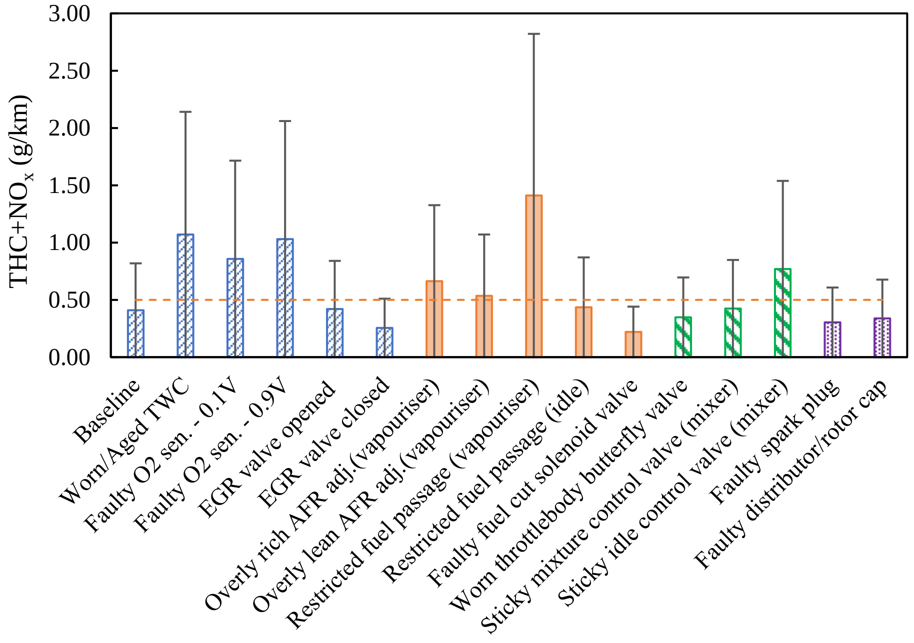

Figure 4: THC+NO$_x$ emissions results for malfunctions. Error bars indicate standard deviations and the dashed orange line indicates Euro 2 THC+NO$_x$ emissions standard.

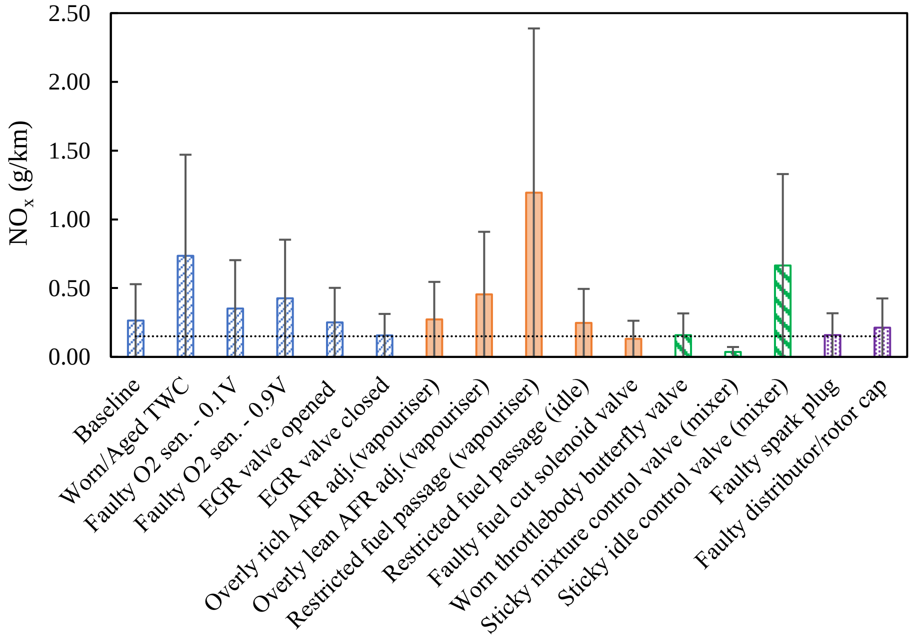

Figure 5: NO$_x$ emissions results for malfunctions. Error bars indicate standard deviations and the dotted black line indicates Euro 3 NO$_x$ emissions limit.

The highest increase of $NO_x$ emissions (Figure 5) resulted from the restricted fuel supply passage in the vapouriser malfunction producing significantly lean conditions with $NO_x$ emissions 4.5 times higher than baseline result (282% of THC+$NO_x$ limit). The worn/aged catalyst follows with $NO_x$ emissions 2.8 times higher than the baseline (214% of THC+$NO_x$ limit, as mentioned previously). The faulty oxygen sensor high voltage 0.9 V $NO_x$ emissions were 1.6 times higher and when combined with THC exceeded the limit (206% of THC+$NO_x$ limit). The sticky idle control valve produces 2.5 times higher $NO_x$ emissions above the baseline (154% of THC+$NO_x$ limit). When the EGR valve was jammed open (maximum EGR), $NO_x$ emissions were similar to the baseline, but when considering the combined emissions of THC+$NO_x$ the result exceeds the limit (133% of THC+$NO_x$ limit).

Of these increased emissions results, the ones that attracted the most interest from government representatives, the trade and industry were the impact of the worn/aged TWC and the faulty oxygen sensor. The worn/aged TWC produced significant increases for each pollutant and with the results exceeding the respective reference emissions limit. The oxygen sensor results were more significant for THC and CO with the increased emissions of both of these pollutants with the results exceeding the respective emissions limits. The assessment of these particular malfunction simulation results reinforced support for the effectiveness a programme the HKEPD had undertaken from August 2013 to April 2014 to provide a one off subsidised replacement catalyst and oxygen sensor for taxis and light buses (Government, 2012; Yao et al., 2019). This was significant as the impact of worn/aged catalysts and faulty oxygen sensors were not apparent to all owners, vehicle operators and repairers as these faults were not impacting driveability, downtime and operating costs for vehicles.

What is clearly observable from the malfunction simulation results is that there are a number of failures which produce unacceptably high results for all of the emissions gases in the roadside environment. In numerous cities worldwide the concentration of $NO_x$ at the roadside is major problem. Whilst a significant portion of this can be traced to diesel vehicles (Grange, 2017), it should not be ignored that gasoline and LPG fuelled vehicles can also contribute to this problem as well being that they are the major portion of vehicles on road. Being able to quantify the impact and magnitude of failures for each individual part of these vehicle engine systems, the critical focus can then be moved to ensuring these parts are properly understood and maintained by the repair industry and vehicle owners/operators.

### 3.2 Fuel consumption and $CO_2$ emissions

The fuel consumption of any vehicle is constantly being assessed by owners and fleet operators as it impacts the economic cost of operation. Likewise, the $CO_2$ emissions from vehicles are directly representative of fuel consumption and additionally they impact our environment by contributing to ambient $CO_2$ levels rising and which adds to greenhouse effects in the environment. The results for fuel consumption (l/100km) and $CO_2$ emission factor (g/km) are shown in Figures 6 and 7 respectively. Table S4 shows the relative change from the baseline result for fuel consumption and $CO_2$.

The emissions factor results show that the majority of the fuel has been burnt in the engine and converted to $CO_2$. The fuel economy and $CO_2$ follow the same pattern and magnitude in almost all of the fault simulations. Where there are variances in the pattern it can be traced to higher emissions of CO produced as a result of the fault simulations. Malfunctions producing higher CO emissions were the sticky mixture control valve and the high oxygen sensor voltage (as discussed in Figure 3).

Overall increases in fuel consumption figures compared to the baseline result were moderate with the highest increase of 15.5% from the worn throttlebody valve. This was followed by 11.4% for the EGR valve jammed open, 10.8% for the sticky idle control valve and low oxygen sensor voltage. The next highest increases were 10.1% from the faulty fuel cut solenoid and 8.9% for the high oxygen sensor voltage. The remainder of the increases ranged between 3.3% to 7.7% higher than the baseline. These results show the impact of malfunctions in normal operations will consume additional fuel. There were no results better than the baseline fuel economy. It was the lowest fuel consumption result of the study. The closest was a 3.3% increase for the sticky mixture control valve. This result could be considered representative of normal testing variation.

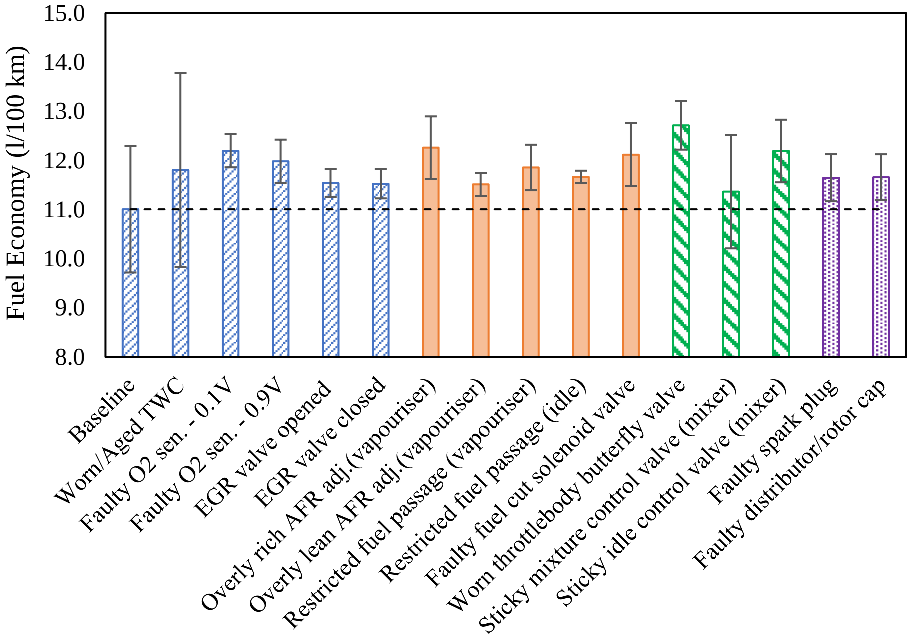

Figure 6: Fuel economy results for malfunctions. Error bars indicate standard deviations and the black dashed line represents the baseline fuel economy.

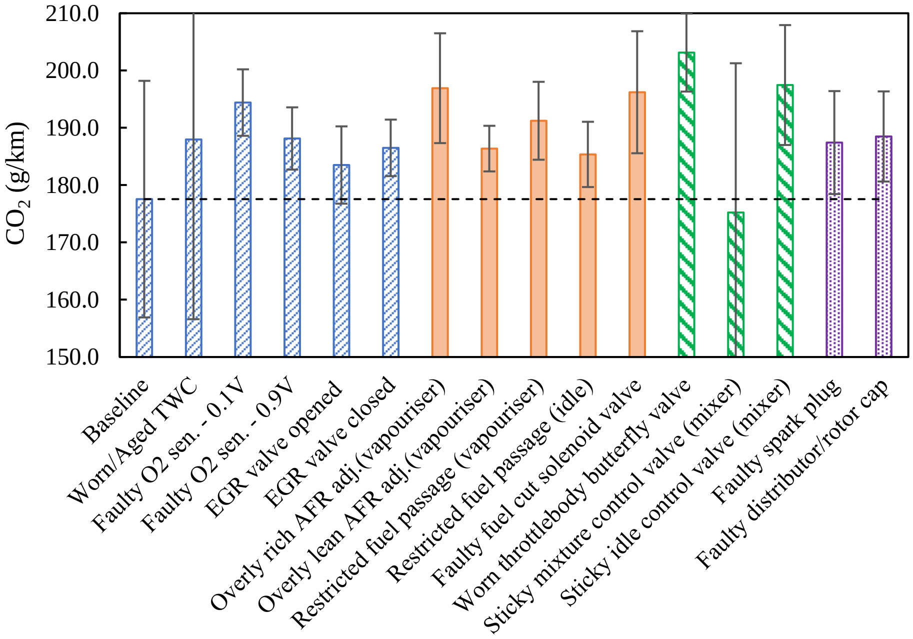

Figure 7: $CO_2$ emissions results for malfunctions. Error bars indicate standard deviations and the black dashed line represents the baseline $CO_2$ emissions.

### 3.3 Impact on drivability

The impact on drivability of these malfunctions was variable. If the emissions increased as a result of the malfunction simulation, the drivability was not necessarily affected in a negative fashion.

From the exhaust system malfunctions, the impact on driveability was not noticeable for the worn/aged TWC, oxygen sensor faults and the EGR valve jammed closed. The vehicle responded as expected and drove in the manner anticipated for a vehicle running normally. When the EGR valve was jammed open the performance of the vehicle at idle was impacted. Idle stability was poor and acceleration from a standing start was rough.

The fuel system malfunctions which impacted the emissions also had an impact on the drivability. The restricted main fuel supply in the vapouriser produced increased $NO_x$ emissions as well as having an impact on the performance. There was a speed response lag when the vehicle accelerated. The restricted fuel to the idle control valve in the mixer produced rough idle with misfire occurring when insufficient fuel was available for ignition. The resultant poor idling reduced the quality of the driving experience.

Two of the intake malfunctions impacted drivability. The worn bushings on the throttle body butterfly valve resulted in the valve not moving smoothly and sticking at points when accelerating and decelerating. This impacted the drivers' ability to maintain smooth accelerations, decelerations and maintaining the desired/stable test speeds. The sticky mixture idle control valve produced rough idle as the valve opening time was longer than normal when activated. Both of these malfunctions reduced the quality of the driving experience. The sticky idle control valve also produced increased $NO_x$ emissions which exceeded the regulation emissions limit.

The ignition system spark plug malfunction produced misfire events, whilst these were noticeable, the impact to the driving performance was limited to reduced driving quality. This malfunction produced increased CO emissions by 5.3 times.

For the malfunction simulations tested in which the driveability is affected there can be significant variations in results which can be attributed to rough and or unstable engine idle and running. This significant variability leads to large error bars for the results.

### 3.4 Impact on industry training and knowledge

The results of the fault simulations from this study provided compelling evidence to show which failures would impact roadside emissions and air quality in faulty gasoline and LPG fuelled vehicles. It highlights the need to identify and deal with maintenance and repairs of malfunctioning vehicle engine and emissions control hardware. In Hong Kong utilisation of remote sensing has provided the mechanism to identify significant numbers of high emitting vehicles. A vehicle is identified as a high emitter when emissions exceed 2 times the emissions limit for its respective European regulation. Being able to effectively repair these vehicles is the required outcome to reduce emissions and improve air quality. To deliver this outcome after vehicles are identified as high emitters it is necessary to ensure vehicle mechanics have the requisite knowledge to effectively identify and repair emissions related faults. Developing a training/education programme to do this is a necessary prerequisite for delivering a successful I/M programme.

The organisation of the technical training sessions began by advertisements being placed in popular local newspapers, information was circulated to all automotive industry groups, repair associations, by email and letter and it was advertised online on the HKEPD website. The advertised programme of free training sessions (funded by the HKEPD) were listed and interested automotive industry staff, repair industry staff or members of the public could enrol to attend (first priority was allocated to industry staff before members of the public). The training programme provided sessions broken into specialised half day sessions (a half-day session being chosen so as to minimise the impact on businesses when staff attended) which were conducted at various locations in the different regions around Hong Kong. The demonstration taxi was taken to each training location so that it could be used for testing demonstration and explanations during the sessions. The sessions were led by HKEPD technical staff with support from a mechanic with suitable knowledge and experience in emissions diagnosis and repair and support technicians to run HKTET emissions tests.

The utilisation of the emissions testing and fuel economy results of these simulated malfunctions along with the demonstration taxi provided a solid foundation for the local Hong Kong automotive and repair industries to develop their emission related knowledge for vehicles. Training sessions were able to highlight which malfunctions had the greatest potential to produce high emissions. There were two types of training sessions organised for the attendees to choose from. The first was a ‘Mechanic Service Session’ where the HKEPD technical staff worked with a mechanic who had been trained in emission repairs and was familiar with the vehicle and the components. They would display the hardware in question and demonstrate its function. The second consisted of a ‘Workshop Service Session’ where the taxi would be tested on a chassis dynamometer to demonstrate the simulated malfunctions which produced high emissions. Following this the support mechanic would then demonstrate the ways to reduce the emissions from the taxi by undertaking the necessary/proper maintenance to return a vehicle to normal/low emissions and fuel consumption ensuring that drivability and performance were achieved as well.

## 4 Conclusions

The aim of this study was to conduct a broad range of simulated malfunctions (15) testing them on a Toyota Crown Comfort LPG taxi to determine their impact. The simulated hardware malfunctions from a range of various engine systems known to fail or breakdown were thoroughly investigated to determine their effect on gaseous emissions, fuel economy and performance when tested on Euro 5 compliant chassis dynamometer and emissions measuring system. The test results were compared against a baseline result for the taxi in good mechanical order with the engine and all hardware functioning properly. The results of the study clearly show that when engine hardware and emissions control systems are working together properly, they are clearly capable of achieving emissions pollution control and vehicle driving performance targets. The main points are summarised as follows:

- For 6 of the malfunctions there were insignificant changes or lower results for THC and CO emissions factors. There were however increases for the high voltage faulty oxygen sensor signal of 317% (0.604 g/km) for THC and for the sticky mixture control valve of 782% (5.351 g/km) for CO. Other malfunction which produced high THC emissions were the low voltage oxygen sensor signal of 247% (0.506 g/km) and the EGR valve jammed open of 169% (0.369 g/km). High CO emissions were produced by high voltage oxygen sensor 410% (3.09 g/km), the restricted idle fuel supply of 293% (2.388 g/km) and the worn/aged TWC of 211% (1.89 g/km).
- The most significant $NO_x$ increase was for the restricted main fuel supply in the vapouriser of 352% (1.41 g/km). Other simulated malfunctions producing high $NO_x$ emissions were the worn/aged TWC 178% (0.735 g/km) and the sticky idle control valve of 151% (0.665 g/km).

- The fuel economy and $CO_2$ emissions produced moderate increases with the largest increase in fuel consumption being 15.5% for the worn throttlebody. Likewise, it had the highest $CO_2$ emissions increase of 14.4%. Eight of the malfunctions had fuel consumption and $CO_2$ emissions variations 5% higher which would noticeably impact the fuel economy and operation cost of the vehicle.
- Negative driveability impacts were not necessarily related to increases in emissions from malfunctions. The EGR open malfunction impacted the smoothness of the drivability under idle and acceleration conditions. Fuel system malfunctions in the main fuel and idle fuel delivery plus the worn throttlebody and sticky mixture idle control valve in the intake system impacted acceleration smoothness, driving stability and idle control which reduced the quality of the driving experience.
- An effective training programme was able to be implemented by the HKEPD using the demonstration taxi and the fault simulation results. The training utilised evidence supported testing with tailored sessions for the automotive and repair industry to learn which malfunctions have the greatest impact on emissions, fuel consumption and drivability. The training provided essential knowledge to the industry to successfully repair vehicles identified as high emitters to pass required emissions test standards.

## Acknowledgements

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# Supplementary Information

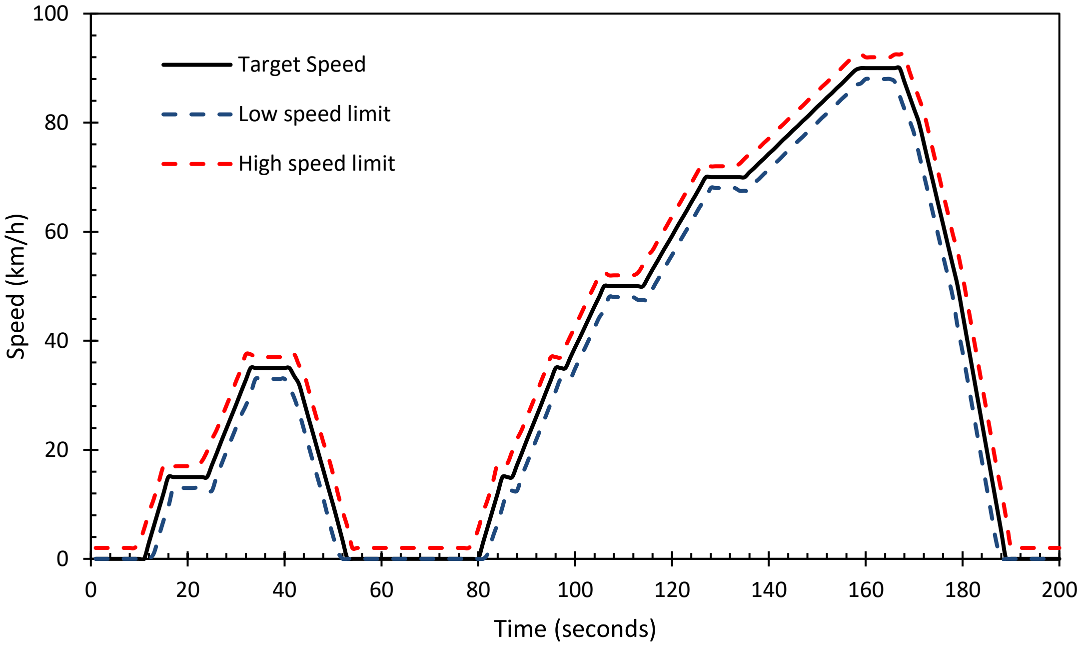

Figure S8. Speed Profile for HKTET Automatic Transmission Drive Cycle.

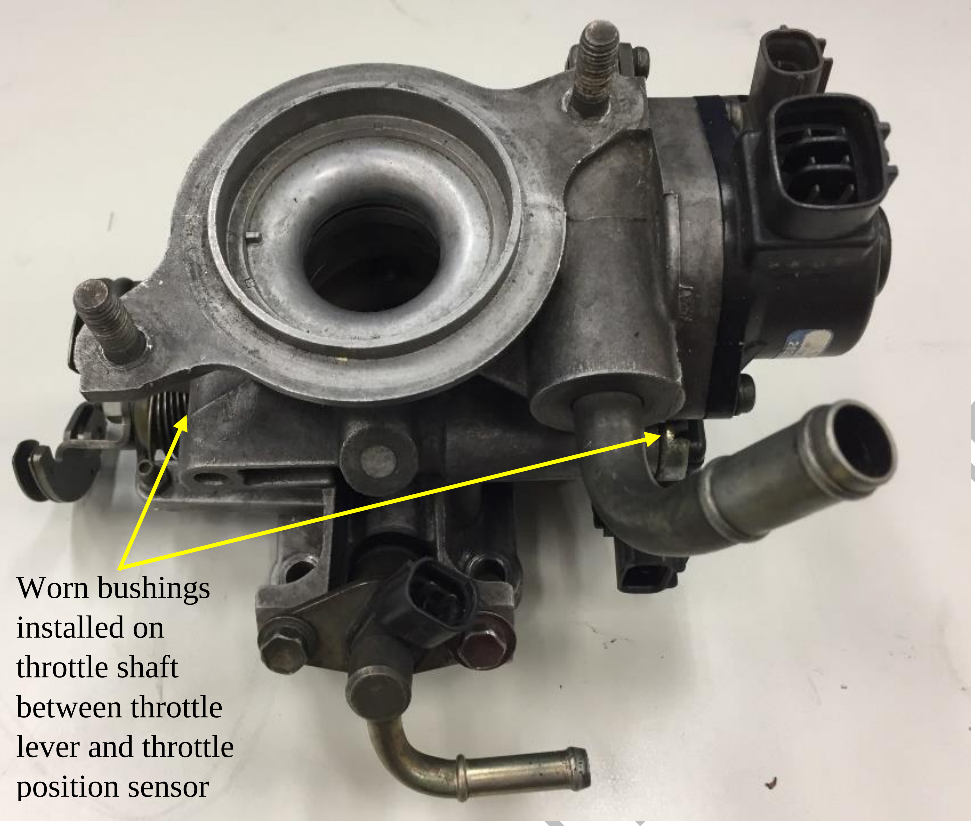

Figure S9: Throttlebody with worn shaft and bushings installed, also with mixture and idle control valves.

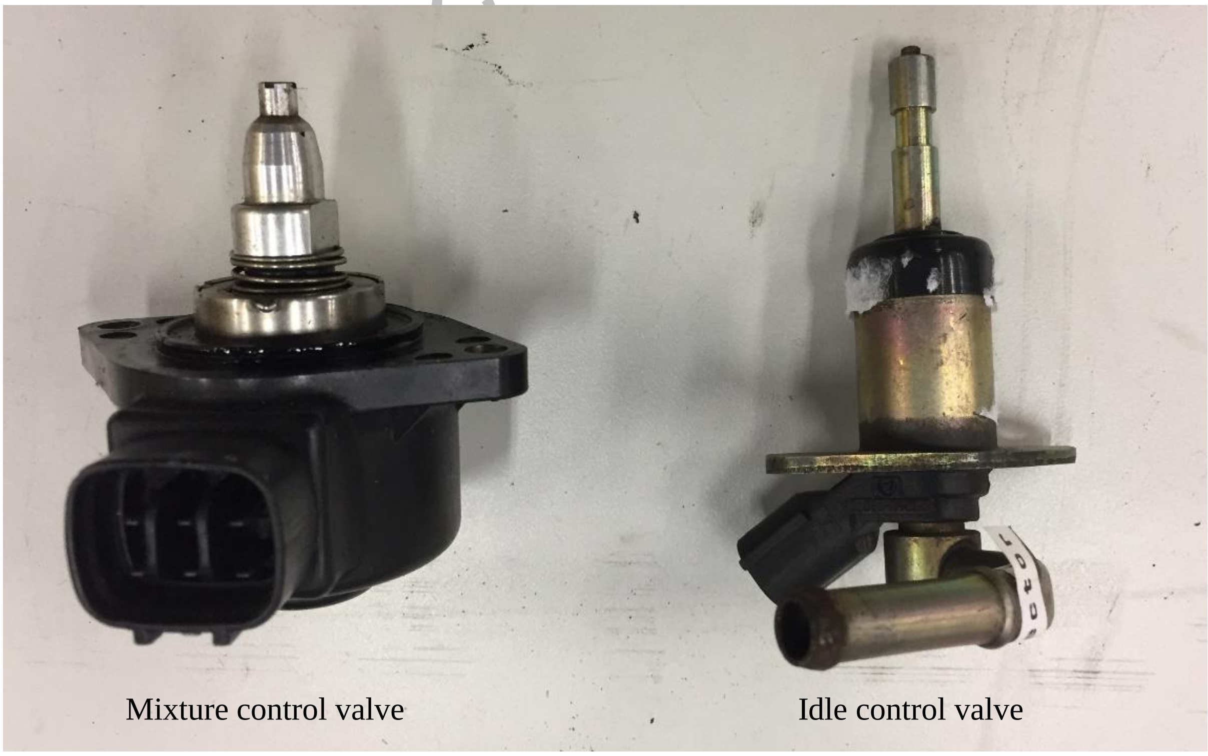

Figure S10:Mixture and idle control valves.

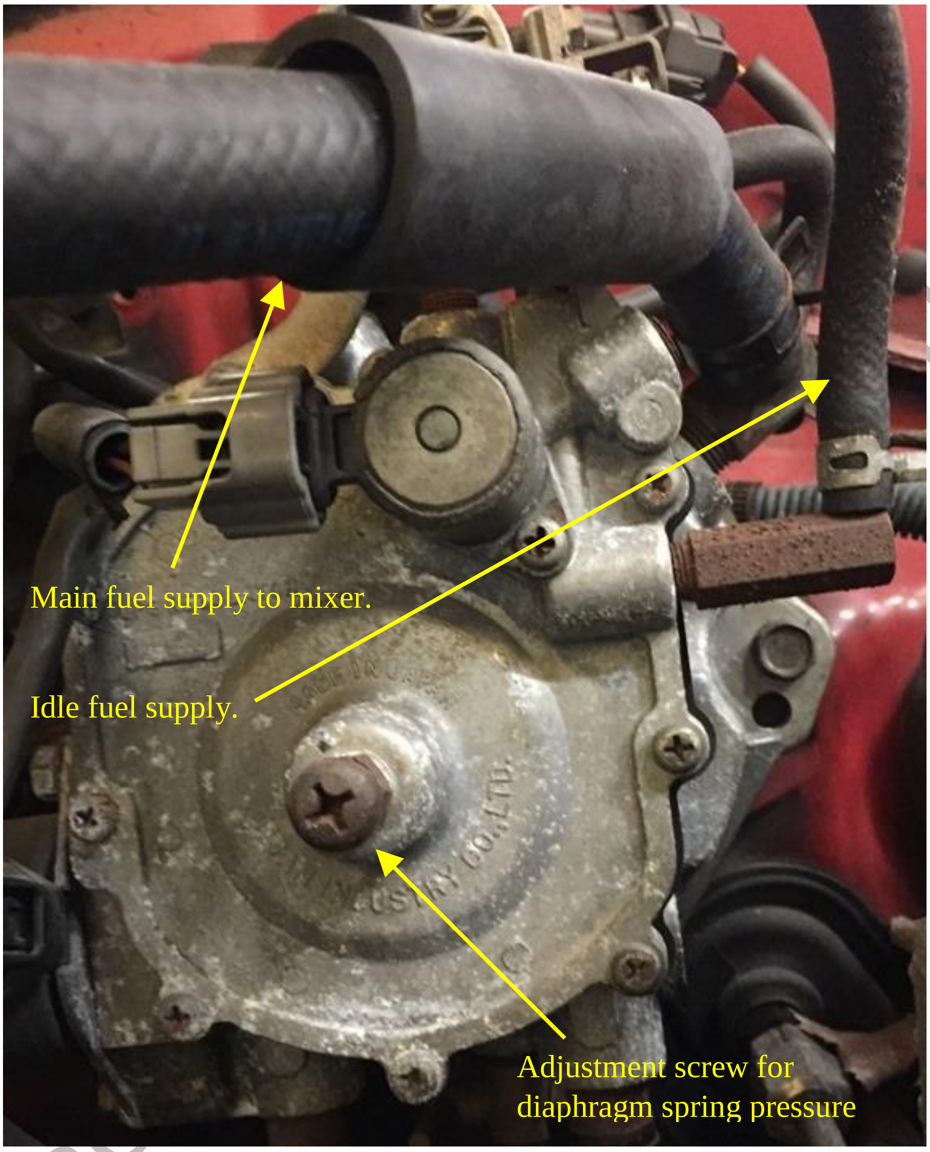

Figure S11: LPG fuel vapouriser.

Figure S12: Fuel Cut Solenoid Valve.

Figure S13: Distributor Cap and Rotor Button.

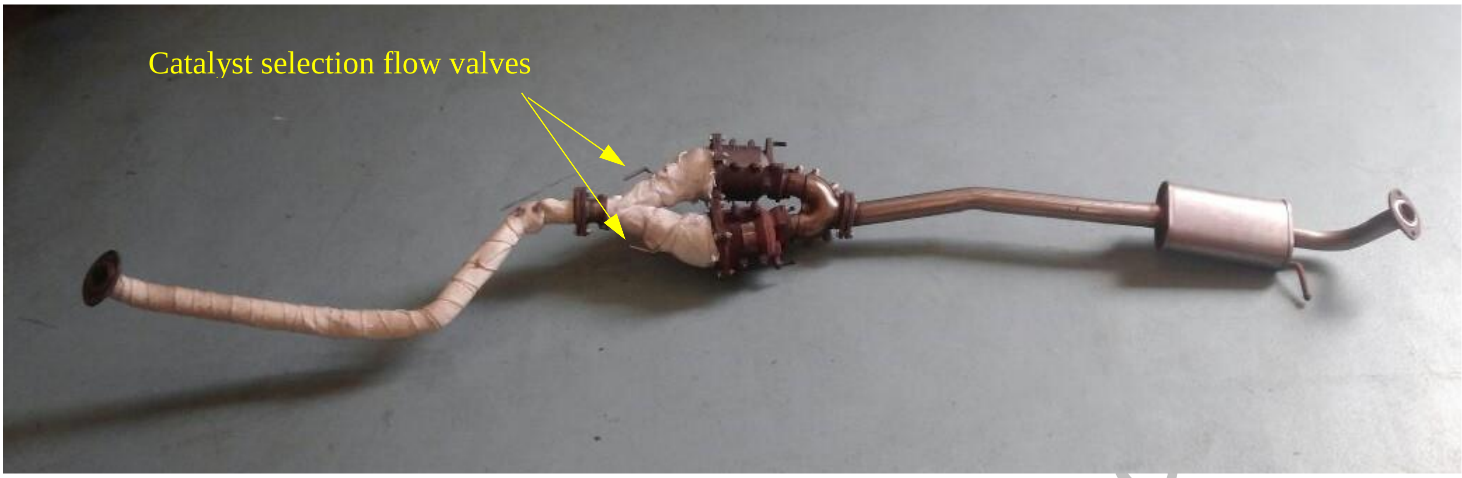

Figure S14: Dual Catalyst assembly for Toyota Crown Comfort Taxi with new and aged/worn TWCs. The two TWCs were installed under the vehicle instead of on the exhaust manifold due to size restrictions

Figure S15: Oxygen Sensor.

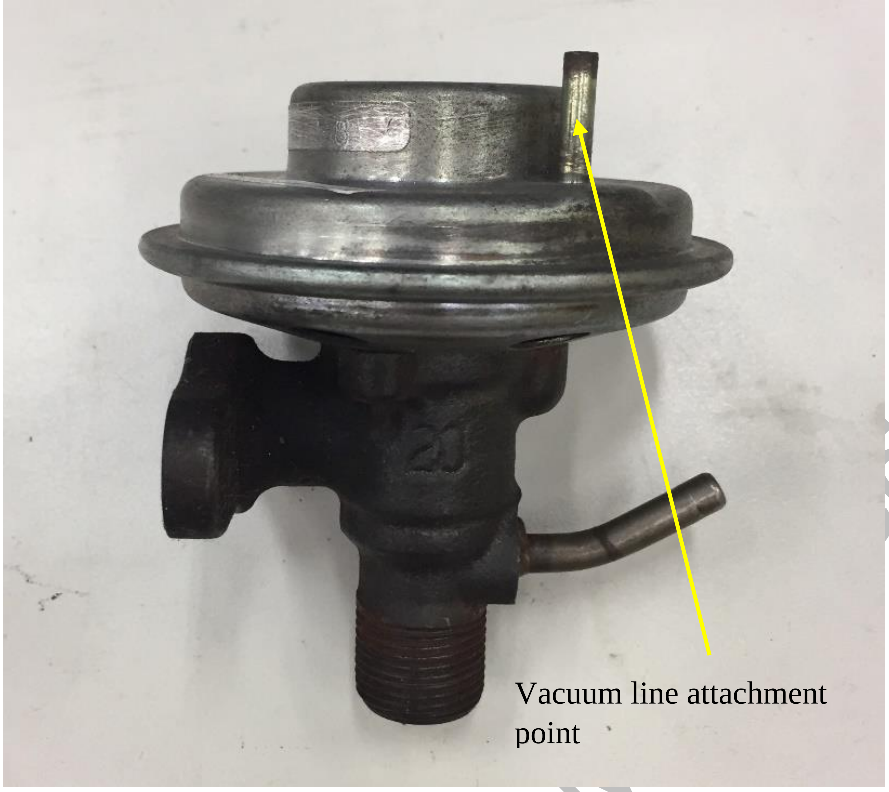

Figure S16: Exhaust Gas Recirculation (EGR) Valve.

Table S2. Signal Maxsys900 emissions analyser system accuracy

| Gas | Principle | Model | Accuracy |
|---|---|---|---|
| THC | FID | 3000HM | Better than ±1 % range or ±0.2 ppm whichever is greater |
| $NO_x$ | CLA | 4000VM | Better than ±1 % range or ±0.2 ppm whichever is greater |
| CO | NDIR | 7100FM | Better than ±1 % of range or ±0.5 ppm whichever is greater |
| $CO_2$ | NDIR | 7200FM | Better than ±1 % of range or ±0.5 ppm whichever is greater |

Table S3: Economic Commission for Europe Emissions Standards.

| | **Euro 1** | **Euro 2** | **Euro 3** |
|---|---|---|---|
| THC (g/km) | - | - | 0.200 |
| NO (g/km) | - | - | 0.150 |
| HC+NO(g/km) | 0.970 | 0.500 | - |
| CO (g/km) | 2.720 | 2.200 | 2.300 |
| PM (g/km) | - | - | - |
| **Hong Kong Implementation Dates** | | | |
| Petrol | 01/04/1995 | 01/04/1997 | 01/01/2001 |
| LPG | - | 01/08/2001 | 01/08/2001 |
| **Durability Requirements for maintaining emissions compliance** | | | |
| Durability (km) | 80,000 | 80,000 | 80,000 |

Table S4: Summary of relative change from baseline test of emissions factors of simulated malfunctions.

| System | Fault Description | (g/km) |  |  |  |
|---|---|---|---|---|---|
|  |  | THC | CO | $NO_x$ | $NO_x$ + THC |
| Exhaust system | Worn/Aged TWC | 131% | 211% | 178% | 161% |
|  | Faulty O2 sensor - 0.1V | 249% | 150% | 33% | 109% |
|  | Faulty O2 sensor - 0.9V | 317% | 410% | 61% | 152% |
|  | EGR valve open | 169% | 34% | 3% | 62% |
|  | EGR valve closed | -45% | -39% | 72% | 31% |
| Fuel system | Overly rich Air-fuel ratio | 17% | 276% | -5% | 3% |
|  | Overly lean Air-fuel ratio | -32% | -38% | -41% | -38% |
|  | Restricted main fuel | 49% | -5% | 352% | 245% |
|  | Restricted idle fuel | 30% | 294% | -6% | 6% |
|  | Faulty fuel cut valve | -39% | -43% | -50% | -46% |
| Intake system | Worn Throttlebody | 31% | 218% | -40% | -15% |
|  | Sticky mixture control valve | 168% | 782% | -86% | 4% |
|  | Sticky idle control valve | -28% | -51% | 151% | 88% |
| Ignition system | Faulty spark plug | 0% | 60% | -40% | -26% |
|  | Faulty distributor cap & rotor | -13% | -29% | -20% | -17% |

Table S5: Summary of relative change from baseline test of $CO_2$ emissions factors and fuel economy (l/100km) of simulated malfunctions

| System | Fault Description | $CO_2$ (g/km) | Fuel Economy (l/100 km) |
|---|---|---|---|
| Exhaust system | Worn/Aged TWC | 5.9% | 7.3% |
| | Faulty O2 sensor - 0.1V | 9.5% | 10.8% |
| | Faulty O2 sensor - 0.9V | 6.0% | 8.9% |
| | EGR valve open | 10.9% | 11.4% |
| | EGR valve closed | 5.0% | 4.6% |
| Fuel system | Overly rich Air-fuel ratio | 3.4% | 4.8% |
| | Overly lean Air-fuel ratio | 5.0% | 4.7% |
| | Restricted main fuel | 7.7% | 7.7% |
| | Restricted idle fuel | 4.4% | 6.0% |
| | Faulty fuel cut valve | 10.5% | 10.1% |
| Intake system | Worn Throttlebody | 14.4% | 15.5% |
| | Sticky mixture control valve | -1.3% | 3.3% |
| | Sticky idle control valve | 11.2% | 10.8% |
| Ignition system | Faulty spark plug | 5.6% | 5.8% |
| | Faulty distributor cap & rotor | 6.2% | 5.9% |