EXPERIMENTAL INVESTIGATION ON THE FEASIBILITY AND DURABILITY OF A NOVEL DIESEL PARTICULATE FILTER

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The increasing concerns on fuel prices, lowest fuel consumption, higher operating efficiency and low levels of carbon monoxide and unburned hydrocarbon during cold start have generated noticeable interest on diesel engine as a prime mover with expected higher soot and NO\textsubscript{X} emissions. In order to reduce the emission from diesel fuelled vehicle, some control technologies were introduced. One of the technology is diesel particulate filter (DPF) which consists of a porous substrate that permits exhaust to pass through but traps particulate matter (PM) or carboneous soot. Conventional DPFs are manufactured using expensive materials. In this study, alternative material based on alumina and zeolite was used to form porous ceramics filter installed in diesel fuelled vehicle exhaust system and named as novel diesel particulate filter (NDPF). The NDPF elements were arranged in line with 1cm spacing inside an enclosed casing. The NDPF showed potential as DPF to curb soot emissions. Pressure drop for the NDPF was in the range of 89% - 93% at every given flow rate during pressure drop test. Effective soot reduction was in the range of 60% - 70%. As predicted, trapped soot were accumulated mostly at the front and middle of NDPF. Scanning electron microscope (SEM) and energy dispersive xray (EDX) analysis confirmed the trapping ability of carbon elements in the range of 19% - 70% for each filter. Brake specific fuel consumption (BSFC) and brake mean effective pressure (BMEP) was slightly affected when NDPF was installed in the exhaust system and resulted to drops in engine efficiency in the range of 2% - 26%. Nevertheless, further reinforcement steps for the NDPF are needed to prolong its filtering capacity.
ABSTRAK

Peningkatan kebimbangan terhadap harga minyak, penggunaan minyak yang terendah, kecekapan pengoperasian dan tahap karbon monoksida dan hidrokarbon yang rendah semasa permulaan enjin dihidupkan telah menimbulkan minat terhadap enjin diesel sebagai penggerak utama dengan kesan pengeluaran asap dan NO\textsubscript{X} yang tinggi. Dalam usaha untuk mengurangkan pencemaran dari kenderaan berenjin diesel, beberapa teknologi untuk mengawalnya telah diperkenalkan. Salah satu teknologi adalah penapis partikel diesel (DPF) yang terdiri dari liang-liang berlubang yang pelepasan gas tetapi akan memerangkap partikel halus (PM) atau jelaga berkarbon. DPF konvensional dibuat menggunakan bahan-bahan yang mahal. Dalam kajian ini, satu bahan alternatif berdasarkan alumina dan zeolite telah dihasilkan untuk membentuk penapis seramik berliang dan dipasang pada sistem ekzos kenderaan berenjin diesel dan dinamakan sebagai penapis partikel diesel baru (NDPF). Elemen NDPF telah disusun sebaris dengan dipisahkan jarak sebanyak 1cm di dalam perumah. NDPF telah menunjukkan potensi sebagai DPF untuk mengurangkan pencemaran asap. Kejatuhan tekanan untuk NDPF adalah di dalam julat 89\% - 93\% dari setiap kadar alir yang dikenakan semasa ujian kejatuhan tekanan. Pengurangan asap pula di antara 60\% - 70\%. Seperti yang dijangka, asap yang ditapis kebanyakkannya berkumpul pada elemen hadapan dan pertengahan. Mikroskop pengimbas electron (SEM) dan analisis xray sebar tenaga (EDX) mengesahkan kemampuan untuk menapis elemen karbon dalam julat 19\% - 70\% untuk setiap penapis. Penggunaan bahan api tentu (BSFC) dan tekanan min berkesan (BMEP) sedikit terkesan apabila NDPF dipasang pada sistem ekzos dan menyebabkan pengurangan kecekapan enjin sebanyak 2\% - 26\%. Walaubagaimanapun, langkah pengukuhan lanjut untuk NDPF diperlukan untuk memanjangkan kapasiti penapisannya.
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<td>NDPF</td>
<td>Novel Diesel Particulate Filter</td>
</tr>
<tr>
<td>DPF</td>
<td>Diesel Particulate Filter</td>
</tr>
<tr>
<td>ΔP</td>
<td>Pressure Drop</td>
</tr>
<tr>
<td>λ</td>
<td>Lambda</td>
</tr>
<tr>
<td>sfc</td>
<td>Specific Fuel Consumption</td>
</tr>
<tr>
<td>HC</td>
<td>Hydrocarbon</td>
</tr>
<tr>
<td>CO</td>
<td>Carbon Monoxide</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon Dioxide</td>
</tr>
<tr>
<td>NOₓ</td>
<td>Nitrogen Oxide</td>
</tr>
<tr>
<td>SOₓ</td>
<td>Sulphur Oxide</td>
</tr>
<tr>
<td>ppm</td>
<td>Parts per million</td>
</tr>
<tr>
<td>rpm</td>
<td>revolution per minutes</td>
</tr>
<tr>
<td>PM</td>
<td>Particulate Matter</td>
</tr>
<tr>
<td>BSFC</td>
<td>Brake Specific Fuel Consumption</td>
</tr>
<tr>
<td>SCR</td>
<td>Selective catalytic converter</td>
</tr>
<tr>
<td>NSR</td>
<td>NOₓ storage-reduction</td>
</tr>
<tr>
<td>CRT</td>
<td>Continuously regeneration trap</td>
</tr>
<tr>
<td>CI</td>
<td>Compression Engine</td>
</tr>
<tr>
<td>TSP</td>
<td>Total suspended particulates</td>
</tr>
<tr>
<td>UTHM</td>
<td>Universiti Tun Hussein Onn Malaysia</td>
</tr>
<tr>
<td>BMEP</td>
<td>Brake mean effective pressure</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning Electron Microscope</td>
</tr>
<tr>
<td>EDX</td>
<td>Energy dispersive Xray</td>
</tr>
<tr>
<td>SOF</td>
<td>Soluble organic fraction</td>
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<tr>
<td>PAH</td>
<td>Polycyclic aromatic hydrocarbons</td>
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<tr>
<td>DI</td>
<td>Direct injection</td>
</tr>
<tr>
<td>TDC</td>
<td>Top death center</td>
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EGR - Exhaust gas recirculation  
CAAA - Clean air act amendments  
NHOG - Non-methane organic gas  
NMHC - Non-methane hydrocarbons  
TLEV - Transitional low emission vehicle  
LEV - Low emission vehicle  
ULEV - Ultra low emission vehicle  
SULEV - Super ultra low emission vehicle  
PZEV - Partial zero emission vehicle  
HSU - Hartridge smoke unit  
rw - Reference mass  
AWASI - Area watch and sanction inspection program  
IFQC - International fuel quality center  
ASTM - American society for testing and materials  
DOC - Diesel oxidation catalyst  
ARB - Air resource board  
DPNR - Diesel particulate NO\textsubscript{X} reduction  
Pt - Platinum  
K - Kalium  
Al\textsubscript{2}O\textsubscript{3} - Alumina  
TiO\textsubscript{2} - Titanium dioxide  
Rh - Rhobium  
ZrO\textsubscript{2} - Zirconium oxide  
ANN - Artificial neural network  
FTP - Federal test procedure  
NH\textsubscript{3} - Ammonia  
LNT - Lean NO\textsubscript{X} trap  
EEC - European economic community  
PAZ - Porous alumina zeolite  
Pu - Polyurethane  
MOHE - Ministry of Higher Education, Malaysia
Cu-Zsm - Types of zeolite
AFR - Air fuel ratio
HP - Horse power
XRD - X-ray diffraction
LHV - Low heating value
Al - Aluminum
C - Carbon
O - Oxygen
Si - Silica
CPSI - Cells per square inch
$\eta_e$ - Engine efficiency
# LIST OF APPENDICES

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<td>B</td>
<td>Environmental Quality (Control of Petrol and Diesel Properties) Regulations 2007</td>
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INTRODUCTION

In this chapter, the background and premise of the research is explained in details. It consists of the research background focusing towards the research study, problem statements, research objective, research scope and the significance of the research.

1.1 Research Background

Malaysia is a rapidly developing country working hard towards achieving its Vision 2020, of becoming a developed country. The increase in economic activities has also resulted to an increase in the country pollution problem. One of the main sources of the pollutants is emissions from motor vehicles, which is originated from incomplete fuel combustion; either diesel or gasoline. Statistic from Malaysia Road Transport Department shows that from 2003 until 2008, the total number of vehicle registered is 4.7 million. Mobile sources or motor vehicles include passenger cars, motorcycles, goods vehicles, taxis and buses which are among the contributors to air pollution especially in major cities. The same reports show that the numbers of vehicles registration in 2008 were increase than 2007 as show in Figure 1.1. These numbers will
definitely increasing in coming years. The presence of these vehicles bring along the problem of air pollution because of the incomplete combustion by product that is emitted from engine exhaust pipe such as carbon monoxide (CO), hydrocarbon (HC), nitrogen oxide (NOX), sulphur oxide (SOX) and carbon soot (Department of Environment, Malaysia, 2008)

![Graph showing number of registration vehicles in 2007 and 2008](image)

Figure 1.1: Number of registration vehicles in 2007 and 2008 (Department of Environment, Malaysia, 2008)

Air pollutant sources in Malaysia can be classified under four main sectors; motor vehicles, power stations, industries and other sources like open burning and trans-boundary sources (Department of Environmental, 2008). Motor vehicles are the main contributor for the CO and NOX emission as show in Table 1.1. Meanwhile industrial sources are main contributor for PM about 40% and power station main contributor for SO2 emission about 48%. Although Malaysia have a good environment to stabilize the pollutant, it has reached a critical level as witnessed during the past haze crisis (Zulkifli et al., 2002).
Table 1.1: Emissions load by motor vehicles 2008 (Department of Environment, Malaysia, 2008)

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<th>Emissions</th>
<th>Metric Tonnes</th>
<th>Percentage of others sources</th>
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<tr>
<td>SO₂</td>
<td>12,865</td>
<td>8</td>
</tr>
<tr>
<td>PM</td>
<td>4,557</td>
<td>14</td>
</tr>
<tr>
<td>NOₓ</td>
<td>203,235</td>
<td>49</td>
</tr>
<tr>
<td>CO</td>
<td>1,410,134</td>
<td>97.1</td>
</tr>
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</table>

Increasing concerns on the fuel prices, lowest fuel consumption, higher operating efficiency and low level of CO and HC during cold start have generated noticeable interests on diesel engine as a prime mover. It is classified as powerful, durable and reliable than gasoline engine. Nevertheless, diesel exhaust contain several pollutants that are harmful to public health and can also effect the environment through HC, NOₓ, fine PM, CO and combination with other substance (Department of Environment, 2004).

Diesel engine operate with excess air ($\lambda > 1$) across their entire operating range, an insufficient quantity of excess air results in increased of PM (soot), CO and HC emission due of mixture formation. Others factor sources from engine compartment are combustion temperature, design of combustion chamber, injection timing, the rate of discharge curve, atomization of fuel and etc (Bosch, 2000).

In the diesel engine case, the major concern are about NOₓ and PM. The development effort have been focused on reduction of engine out, exhaust aftertreatment and fuel formulation. The big challenges on this strategies are to maintain reduction formula. In the case of retarding injection timing would be effective in reduction of formation of NOₓ, but it usually results in an increase in soot emissions and higher brake specific fuel consumption (BSFC) (Pundir, 2007). In other case, increasing fuel injection pressure can decrease soot emission but it can result in higher NOₓ emissions (Pierpont & Reitz, 1995).

Another strategies by using advanced exhaust aftertreatment such as selective catalytic converter (SCR), NOₓ storage-reduction (NSR) catalysts, diesel particulate filter (DPF) and continuously regenerating trap (CRT).
The DPF is a typical aftertreatment device for trapping soot particles contained in diesel engine exhaust gas. DPF is becoming an indispensable device to diesel engine vehicle. Numerous design of DPF involving different filter media and geometric configuration have been invented in the last 20 years (Konstandopoulos et al., 2000). It traps the particles when exhaust gases passed the porous structure. The filtration efficiency is more than 90%. Although some sort of clogging always occurs due to the particle trap, the consequent rise in backpressure could increase fuel consumption and reduce available torque (Konstandopoulos et al., 2000).

Porous ceramic filter is an alternative structure to the honeycomb monolith which offered higher degree of porosity and larger surface area. It is brittle with closed, fully open or partially interconnected porosity and commercially accepted in many fields with variety of products such as catalysis, filtration, impact absorbing structures and biomechanical implants. In automotive industries, ceramic foams have received particular interest in the development of diesel particulate traps and catalytic converters. Meanwhile, in hydrocarbon absorber, zeolites are known for its ability to selectively absorb molecules based primarily on a size exclusion process (Amirnordin et al., 2007).

Novel diesel particulate filter (NDPF) is a combination of DPF and porous ceramic filter in the aim to curb soot and others gases from diesel engine. The potential of porous ceramic filter based on alumina and zeolite give higher reduction in emission from gasoline engine as a motivation to apply the filter as a new exhaust aftertreatment device for diesel engine.
1.2 Problem Statements

Carbon soot emission is one of the by products from exhaust tailpipe especially from diesel fuelled vehicle. It is also included in one of the sources of environmental problems and human health. The emission of soot is higher for old vehicle especially more than 10 years due the lack of engine maintenance and incomplete combustion. At present, Malaysian government do not have regulation to dismiss old vehicle and don’t have requirement for diesel fuelled vehicle to be install with exhaust after treatment system. The current technology of the exhaust is expensive. The alternative system with economical, user friendly and effectiveness are the best way in order to control the emissions of carbon soot in Malaysia. Some local researchers have done lot of research in term of developing new alternative filter to get close into those criteria. One of the products that successfully developed is alumina-zeolite porous ceramic filter which shows good performance as catalytic converter for gasoline fuelled vehicle. Therefore, this research used the same alumina-zeolite porous ceramic filter but installed on diesel fuelled vehicle and known as novel diesel particulate filter (NDPF). This research investigated the NDPF feasibility and durability using laboratory and on-road condition in order assess the ability and effectiveness of NDPF to curb exhaust emissions and carbonaceous soot.
1.4 Research Objectives

The objectives of this research are:

i. To investigate the soot reduction performance of the NDPF, through engine parametric studies using chassis dynamometer

ii. To assess the feasibility of NDPF to curb exhaust emissions and soot

iii. To assess the durability of NDPF during on road tests

1.5 Research Scopes

The scopes for this research are:

i. The vehicle for this research was a medium duty diesel fuelled with cubic capacity of 2.5L and aged at least 10 years

ii. The emission analysis for exhaust tailpipe were in two conditions; with and without NDPF

iii. Two types of test for every condition; steady state test and on-road test

iv. Steady state test was carried out using chassis dynamometer

v. On road test covered 1,000 km
1.6 Research Significances

The significances of this research are as follows:

i. This research comes out with new finding about the use of alumina-zeolite porous ceramic filter as an alternative filter for diesel fuelled vehicle.

ii. The feasibility of the filter not only for automotive purpose but it will also be applicable for curbing emissions for stationary sources (power plant, boiler, accumulator and etc).

iii. The usage of NDPF as retrofit emissions control technology for Malaysia light duty diesel fuelled vehicles.
2.1 Emissions from Diesel Fuelled Engine

Diesel engines commonly called compression ignition (CI) engines is an internal combustion engine that converts chemical energy in fuel to mechanical energy that moves pistons up and down inside the enclosed spaces called cylinders. The pistons are connected to the engine crankshaft, which changes linear motion into rotary motion to propel the vehicle wheels. Energy is released in a series of small explosions as fuel react chemically with oxygen from the air.

The different about CI engines than gasoline engine in the way of explosions occur. Gasoline engines start explosion with sparks from spark plugs. Meanwhile in CI engines, fuel ignites by heat produced by compressed air in the combustion chamber. This is the reason for diesel engine called compression ignition engine. The history of this engine start when German engineer Rudolph Diesel try to proved that fuel can be ignited without a spark. Figure 2.1 shows basic structure of CI engine.
In a perfect combustion, oxygen in the air would convert all the hydrogen in the fuel to water and all the carbon in the fuel to CO$_2$. Nitrogen in the air would remain unaffected. In reality, the combustion process cannot be perfect. Not only CO$_2$ and water produced but unburned HC, CO, SO$_X$, PM and NO$_X$ also produced in that combustion. All the gases produced by incomplete combustion called primary pollutants. This primary pollutant will spread in atmosphere and change to the other harmful chemical called secondary pollutant. The secondary pollutants are oxidants like ozone, NO$_2$ and total suspended particulates (TSP). The resulting transformations of emissions to air pollution are shown in Figure 2.2.

Figure 2.1: Basic structure of CI engines (US Department of Technology, 2008)

<table>
<thead>
<tr>
<th>Emissions</th>
<th>Pollutants</th>
</tr>
</thead>
<tbody>
<tr>
<td>HC</td>
<td>Oxidants</td>
</tr>
<tr>
<td>NO$_X$</td>
<td>NO$_2$</td>
</tr>
<tr>
<td>SO$_X$</td>
<td>SO$_2$</td>
</tr>
<tr>
<td>PM</td>
<td>TSP</td>
</tr>
<tr>
<td>CO</td>
<td>CO</td>
</tr>
</tbody>
</table>

Figure 2.2: Vehicle emissions and resulting air pollution (Pundir, 2007)
Table 2.1: Adverse impact of principal pollutants (Pundir, 2007)

<table>
<thead>
<tr>
<th>Pollutants</th>
<th>Short term health effects</th>
<th>Long term health effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxidants</td>
<td>Difficulty in breathing, chest tightness, eye irritation</td>
<td>Impaired lung function, increased susceptibility to respiratory function</td>
</tr>
<tr>
<td>Ozone</td>
<td>Soreness, coughing, chest discomfort, eye irritation</td>
<td>Development of emphysema, pulmonary edema</td>
</tr>
<tr>
<td>TSP</td>
<td>Increased susceptibility to other pollutants</td>
<td>Many constituents especially poly-organic matter are toxic and carcinogenic, contribute to silicosis, brown lung</td>
</tr>
<tr>
<td>NO(_X)</td>
<td>Similar to those of ozone but at a higher concentration</td>
<td>Development of cyanosis especially at lips, fingers and toes, adverse changes in cell structure of lung wall</td>
</tr>
<tr>
<td>CO</td>
<td>Headache, shortness of breath, dizziness, impaired judgement, lack of motor coordination</td>
<td>Effects on brain and central nervous system, nausea, vomiting, cardiac and pulmonary functional changes, loss of consciousness and death</td>
</tr>
</tbody>
</table>

Diesel fuel is heavier than gasoline because of it require less refining and has higher energy density. It is become a good choice and economically through its price. Meanwhile CI engine can give lowest fuel consumption, higher operating efficiency, less maintenance, powerful, durable and reliable than gasoline engine. It is good for the user but it gives bad impact to the environment especially human health that gives adverse impact as shown in Table 2.1. the pollutant occurs through the exhaust gas is composed of a large number of organic and inorganic solid, liquid and gaseous chemical species that are pollutants as shows in Table 2.2.

Table 2.2: Pollutant in diesel engine (Pundir, 2007)

<table>
<thead>
<tr>
<th>Solids</th>
<th>Liquids</th>
<th>Gases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soot</td>
<td>Soluble organic fraction (SOF)</td>
<td>Nitric oxide (NO)</td>
</tr>
<tr>
<td>• Primary particles</td>
<td>• Fuel derived</td>
<td>Nitrogen dioxide (NO(_2))</td>
</tr>
<tr>
<td>• Agglomerated particles</td>
<td>• Oil derived</td>
<td>Unburned hydrocarbons (HC)</td>
</tr>
<tr>
<td>• Sulphates</td>
<td>Poly nuclear aromatic hydrocarbons (PAH)</td>
<td>Carbon monoxide (CO)</td>
</tr>
<tr>
<td>Ash</td>
<td>Sulphuric acid</td>
<td></td>
</tr>
<tr>
<td>• Oil additives</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Engine wear particles</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inorganic fuel and air contaminants</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2.1.1 Sources of Exhaust Emissions

2.1.1.1 Compression Ratio

An increasing in compression ratio results in a shorter ignition delay and higher combustion temperatures which tend to oxidize the unburned HC. A longer delay increases the fraction of fuel burned during the premixed phase resulting in higher peak pressure and temperature at the end of rapid phase of combustion, which causes an increase in NO\textsubscript{X} formation. However if the ignition delay is too long the combustion may begin in the expansion stroke reducing combustion pressure and temperature. It leads to lower NO\textsubscript{X} emission of “white smoke”. For the lowest particulate and NO\textsubscript{X} emissions an optimum compression ratio generally exists.

2.1.1.2 Combustion Chamber Dead Volume

Air in the combustion chamber volume is contained in several different volumes like piston bowl, top land crevice, piston lead clearance, valve recess and head gasket clearance volumes as shown in Figure 2.3. The air contained in top land crevice, head gasket clearance, valve recess, volume between piston head and cylinder head at top dead center has poor air utilization. Reducing the “poor air utilization” volume can give benefit to the PM emission and brake specific fuel consumption (BSFC) as shown in Figure 2.4.
Figure 2.3: Distribution of poor air utilization volumes in DI diesel engine combustion chamber (Richards & Sibley, 1988)

Figure 2.4: Engine fuel economy and PM emissions versus poor air utilization volumes in DI diesel engine combustion chamber (Gill, 1988)
2.1.1.3 In-Cylinder Air Swirl

High air swirl can increase fuel. Overmixing of fuel is an important source of HC emissions. An increasing in air swirl increases air utilization due to improved mixing. Swirl also reduces spray penetration and impingement of spray on combustion chamber walls in small engines. Reentrant shape of combustion bowls improves mixing during expansion stroke when the combustion products are flowing out of the bowl and leads to more complete combustion.

2.1.1.4 Multi-Valve

Use of multiple valves (3 or 4) per cylinder configuration increases flow area and volumetric efficiency of the engine. In four valve engines, symmetric air motion in the piston bowl and equal fuel distribution between different spray lead to optimal mixture formation and combustion with very low smoke levels. Centralized combustion system thus results in reduced formation of PM and NO\textsubscript{X}. Effect of injector inclination from vertical on increase in PM is shown in Figure 2.5. The particulate-NO\textsubscript{X} and fuel economy –NO\textsubscript{X} trade off with two valve and four valve engines are compared in Figure 2.6.

![Figure 2.5: Effect of injector inclination on PM emissions in a 2 valve, DI diesel engine (Monaghan, 1996)](image-url)
2.1.1.5 Fuel Injection Variables

Effect of injection timing on NOX, smoke and engine performance parameters are shown in Figure 2.7 with retarded injection timing, as expected the NOX emissions decrease sharply. An increase in smoke and decrease in HC results with retarded injection timing. However, if the injection timing retarded too much, HC emissions in naturally aspirated engines may increase sharply. Increase in injection pressure results in higher NOX and HC, but yield lower smoke and CO emissions.
2.1.1.6 Engine Load

Increase in engine load, air fuel ratio decrease and the combustion and exhaust temperatures increase. Dependence of smoke and HC on air fuel ratio for a direct injection diesel engine is shown in Figure 2.8. Increase in engine load (decrease in air fuel ratio), NO$_X$ and soot emissions increase. CO decrease with decrease in air fuel ratio until excess air reduces to about 70 percent. At maximum load, NO$_X$, CO and soot are also at their maximum level. HC however reduce with increase in engine load as higher gas temperature lead to their oxidation. Engine brake thermal efficiency increases with engine load as the ratio of friction to brake power goes down.
2.1.1.7 Engine Speed

The variable speed engines are designed to give lowest fuel consumption at about 2/3rd of maximum speed at which it is normally operated. At high speeds pumping losses increase, but cooling decrease and the residual gases are hotter. Both factors increase NO\textsubscript{X}. The HC and PM have optimum at an intermediate speed because time available for oxidation decreases as the speed resulting in higher NO\textsubscript{X}. But reductions in HC, PM and fuel consumption are obtained as the coolant temperature increases.

2.1.1.8 Exhaust Gas Recirculation (EGR)

EGR act as an inert diluents reducing oxygen concentration during combustion and as heat sink to reduce combustion temperatures. EGR has been used on diesel passenger cars since mid 1990s to reduce NO\textsubscript{X} emissions. Typical effect of EGR on NO\textsubscript{X}, HC and CO emissions as shown on Figure 2.9. At around 10 percent EGR, 50 percent reduction in NO\textsubscript{X} is obtained with little change in CO and HC. However as the EGR is increased beyond 15 percent NO\textsubscript{X} decrease more but CO, smoke and HC are increased. The excess air ratio declines with EGR causing sharp increase in smoke and loss in fuel economy compared to engine operation without EGR.
Exhaust gas recirculation (EGR) is one of the most effective engine control methods for reducing NOx emissions. EGR works by recirculation a portion of an engine's exhaust gas back to the engine cylinders (intake system) to lower the concentration and also increase the heat capacity of the air/fuel charge. Cooling the exhaust gas that is to be recirculated can be used to minimize combustion temperatures. This reduces peak combustion temperature and the rate of combustion, thus reducing the NOx emissions. Typically NOx reductions are about 50%.

Figure 2.9: Typical effect of EGR on NOX, HC and fuel economy (Pundir, 2007)

2.1.1.9 Fuel Quality

The natural cetane number, volatility, viscosity, density and hydrocarbon composition are interdependent. A high cetane number results in ease of cold starting, faster warm up and reduced premixed burning. Thus a higher cetane number has beneficial effect on HC and NOX at all engine loads. Besides that, higher fuel volatility increases premixed burning. An increase in NOX as well as HC may be observed with more volatile diesel fuel. Fuel sulphur increases adsorption of sulfates on soot and hence the emission of PM increases.
2.1.2 Impact from the Emissions

During 1950s, studies in California were identified for the first time emissions from vehicle as a major contributor to urban pollution. All vehicles and combustion devices using hydrocarbon and their derivatives as fuel control to air pollution. The amount of emissions depends on design of engines, operating condition and the characteristic of the fuel (Pundir, 2007). Meanwhile, the vehicle population is projected to grow about 1300 millions by the year 2030 (Shah et al., 1997). The primary concerns for the diesel engine exhaust emission are CO, NO\textsubscript{X} and PM.

2.1.2.1 Carbon Monoxide (CO)

CO is formed due to decreasing of oxygen during combustion (Pundir, 2007) and when the carbon present in fuel is not burn completely (Wellington & Asmus, 2002). It is colourless, odourless and at high concentration is a poisonous gas. It enters the bloodstream through the lungs and reduces oxygen delivery to organs and tissues through forming carboxy-hemoglobin. The health threat from exposure to CO is most serious to those who suffer from cardiovascular diseases. At high level of exposure, CO can be poisonous even for healthy people. Visual impairment, reduced work capacity and poor learning ability are among the health effects associated with exposure to elevated CO levels (Pundir, 2007).
2.1.2.2 Nitrogen Oxide (NO\textsubscript{X})

NO\textsubscript{X} is the term used to describe the sum of NO, NO\textsubscript{2} and other oxides of nitrogen. Most of the NO\textsubscript{X} about 95 percent from combustion processes are emitted as NO and the rest as NO\textsubscript{2} (Pundir, 2007). NO as principle oxides and NO\textsubscript{2} is high in diesel engine ranging about 10 until 20 percent but less than 2 percent in spark ignition (SI) engine emission. It is formed during combustion at high temperature. NO\textsubscript{X} is a reddish brown, irritating odour and low solubility and when it reaches deep in lungs causing irritating and also results in destruction of red blood cells (Carel, 1998). The symptoms on exposure on NO\textsubscript{X} occur in slow but harmful. The major sign of exposure include development of bluish skin particularly of lips, finger and toes. A formation of NO\textsubscript{2} and ultraviolet radiations leads to form ozone (Pundir, 2007).

2.1.2.3 Particulate Matter (PM)

PMs are fine solid or liquid particles suspended in air emitted by the vehicles are largely made of carbonaceous matter (soot) consisting a small fraction of inorganic substances. The heavy HC in the exhaust gas may condense to form white smoke during engine start up and warming particularly in cold weather. Principle sources of soot emitted in air is the diesel engine. The PM from diesel engine consists of unburned soot, soluble organics from fuel and lubricating oil, ash particles coming from oil additive and wear particles. The major sources of PM in diesel engine are heterogeneous mode of combustion where fine soot particles are generated. These fine soot particles grow and agglomerate as the combustion progresses. During expansion and in the exhaust system heavy HC from fuel and oil, sulphates produced from combustion of fuel sulphur and water is absorbed on the soot core of particles (Pundir, 2007). Particulate pose health hazard due penetrate deep into lungs and deposit there affecting performance of lungs adversely and can have synergistic effect with other pollutants present in air. The combination can be carried to lungs and cause cancer (Pundir, 2007).
2.2 Emission Legislation and Enforcement

2.2.1 International Legislation

2.2.1.1 US Standard

First emissions standards were set in the Clean Air Act of 1968, which were amended later in 1970. Then a lot of amendment from 1975-76, 1977, 1979, 1980, 1981 and 1990 Clean Air Act Amendments (CAAA) covered a wide range of emission sources and air quality issues. The trends in US and California exhaust emissions standards for passenger car are shown in Table 2.3.

<table>
<thead>
<tr>
<th>Year</th>
<th>NMOG/NMHC</th>
<th>CO</th>
<th>NOₓ</th>
<th>PM</th>
<th>HCHO</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g/test</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>US FEDERAL</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pre-control</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1966</td>
<td>15</td>
<td>90</td>
<td>6.2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1970</td>
<td>4.1</td>
<td>34</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1975</td>
<td>1.5</td>
<td>15</td>
<td>3.1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1977</td>
<td>1.5</td>
<td>15</td>
<td>2.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1980</td>
<td>0.41</td>
<td>7.0</td>
<td>2.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1981-1993</td>
<td>0.41</td>
<td>3.4</td>
<td>1.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Tier1 1994</td>
<td>0.25 (0.31)</td>
<td>3.4 (4.2)</td>
<td>1 (1.25)</td>
<td>0.08 (0.10)</td>
<td>-</td>
</tr>
<tr>
<td>Tier 2 2004</td>
<td>0.125</td>
<td>1.7</td>
<td>0.2</td>
<td>0.02</td>
<td>0.018</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CALIFORNIA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TLEV 1996</td>
<td>0.125 (0.156)</td>
<td>3.4 (4.2)</td>
<td>0.4 (0.6)</td>
<td>(0.08)</td>
<td>0.015 (0.018)</td>
</tr>
<tr>
<td>LEV 2000</td>
<td>0.075 (0.09)</td>
<td>3.4 (4.2)</td>
<td>0.2 (0.3)</td>
<td>(0.08)</td>
<td>0.015 (0.018)</td>
</tr>
<tr>
<td>ULEV 2001</td>
<td>0.04 (0.055)</td>
<td>1.7 (2.1)</td>
<td>0.2 (0.3)</td>
<td>(0.04)</td>
<td>0.015 (0.018)</td>
</tr>
<tr>
<td>LEV2 2004</td>
<td>0.075 (0.09)</td>
<td>3.4 (4.2)</td>
<td>0.05 (0.07)</td>
<td>(0.01)</td>
<td>0.015 (0.018)</td>
</tr>
<tr>
<td>ULEV2 2004</td>
<td>0.04 (0.055)</td>
<td>1.7 (2.1)</td>
<td>0.05 (0.07)</td>
<td>(0.01)</td>
<td>0.008 (0.011)</td>
</tr>
<tr>
<td>SULEV2 2004</td>
<td>(0.01)</td>
<td>(1.00)</td>
<td>(0.02)</td>
<td>(0.01)</td>
<td>(0.00)</td>
</tr>
<tr>
<td>PZEV</td>
<td>0.01</td>
<td>1.0</td>
<td>0.02</td>
<td>0.01</td>
<td>0.004</td>
</tr>
</tbody>
</table>

Table 2.3: US federal and California emission standard for passenger cars (g/mile) (Pundir, 2007)
2.2.1.2 European Standard

European emission regulations for new light duty vehicles were specified for the first time in the Directive 70/220/EEC. The base directive has been amended from time to time. The most important amendments are:

- Euro 2 standard (1996): Directives 94/12/EC or 96/69/EC

European emission standards for the light duty vehicle are shown in Table 2.4. Before 1992, ECE-15 regulations emission limits were based on the vehicle reference weight, higher values permitted for the heavier passenger cars. Starting 1992, the same limits irrespective of weight of the passenger car were introduced and called as “consolidated emission directives”. EU standards up to Euro 3 stage require durability demonstration for 80,000km or 5 years whichever occurs first.

Euro 4 standards require durability of 100,000km or 5 years, while the Euro 5 stage proposes durability of 160,000km or 5 years, whichever occurs first. The emission standards for the light duty truck and medium duty vehicle also have been laid down and can be found in the European regulations.

Table 2.4: European emission standard for diesel passenger cars (g/km) (Pundir, 2007)

<table>
<thead>
<tr>
<th>Stage</th>
<th>Year</th>
<th>CO</th>
<th>HC+NOx</th>
<th>NOx</th>
<th>PM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>g/km</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Euro 1</td>
<td>1992</td>
<td>2.72 (3.16)</td>
<td>0.97 (1.13)</td>
<td>-</td>
<td>0.14 (0.18)</td>
</tr>
<tr>
<td>Euro 2</td>
<td>1996</td>
<td>1.0</td>
<td>0.70</td>
<td>-</td>
<td>0.080</td>
</tr>
<tr>
<td>Euro 3</td>
<td>2000</td>
<td>0.64</td>
<td>0.56</td>
<td>0.50</td>
<td>0.050</td>
</tr>
<tr>
<td>Euro 4</td>
<td>2005</td>
<td>0.50</td>
<td>0.30</td>
<td>0.25</td>
<td>0.025</td>
</tr>
<tr>
<td>Euro 5</td>
<td>2009</td>
<td>0.50</td>
<td>0.23</td>
<td>0.18</td>
<td>0.005</td>
</tr>
<tr>
<td>Euro 5a</td>
<td>2011</td>
<td>0.50</td>
<td>0.23</td>
<td>0.18</td>
<td>0.005</td>
</tr>
<tr>
<td>Euro 6</td>
<td>2014</td>
<td>0.50</td>
<td>0.17</td>
<td>0.08</td>
<td>0.005</td>
</tr>
</tbody>
</table>
2.2.2 Malaysian Legislation and Enforcement

Emission legislation for diesel fuelled vehicles is included in Environmental Quality Act 1974 (Act 127). Under this legislation, two regulations are specific for diesel fuelled cases. Emissions of smoke and gaseous pollutants from motor vehicle exhausts are controlled under the Environmental Quality (Control of Emission from Diesel Engines) Regulations 1996 and diesel properties under the Environmental Quality (Control Petrol and Diesel Properties) Regulations 2007.

2.2.2.1 Environmental Quality (Control of Emission from Diesel Engines) Regulations 1996

This regulation was enforced beginning 1 September 1996. Part II contains regulations for control of diesel engines on motor vehicle registered after 31 August 1996. Motor vehicle is already registered but which has a new engine system to replace an existing system they need to obey the standard prescribed in the First Schedule and Second Schedule (refer appendix) for any new model of motor vehicle on or after 1 January 1997. Emission standard of pollutant of motor vehicle for used or new model before and after 1 January 1997 are shown in Table 2.5 and Table 2.6. Test to be conducted by assembler or manufacturer may be determined by the Director General of Road Transport Department, in the presence of an authorized officer, at any approved facility at the cost of the assembler or manufacturer. The test samples of not more than one per centum of the annual projected number of motor vehicles shall be selected at random and they shall submit periodically the results of such tests to the Director General of Road Transport Department.

Part III contains regulations for smoke emission control of motor vehicle. This part shall apply to every motor vehicle irrespective of whether it is in use or stationary, or in any bus terminus, taxi stand or private premises or on any private road. Maximum concentration of smoke shall not exceed Ringelmann no.2 with the procedure as specified in the Third Schedule and Fourth Schedule (refer appendix). Maximum density
of smoke permitted when tested under the free acceleration test with a smoke meter shall not exceed 50 HSU or other equivalent smoke units or in percentages (%) or other units. The free acceleration test shall be conducted in accordance with the methods specified in the Fifth Schedule (refer appendix).

The establishment of the inspection centre was awarded to a private company, PUSPAKOM. Its establishment in under policy of the government to provide one integrated inspection which provides services such as initial inspection, routine inspection, re-inspection, special inspection, accident inspection, voluntary inspection and transfer of ownership.

Table 2.5: Emission standard of pollutants of motor vehicles before 1 January 1997

<table>
<thead>
<tr>
<th>Gross vehicle weight of not exceeding 3.5 tonnes</th>
<th>Reference Mass (rw) (kg)</th>
<th>CO (g/test)</th>
<th>Combined emission of HC and NOX (g/test)</th>
</tr>
</thead>
<tbody>
<tr>
<td>rw ≤ 1020</td>
<td>58</td>
<td>19.0</td>
<td></td>
</tr>
<tr>
<td>1020 &lt; rw ≤ 1250</td>
<td>67</td>
<td>20.5</td>
<td></td>
</tr>
<tr>
<td>1250 &lt; rw ≤ 1470</td>
<td>76</td>
<td>22.0</td>
<td></td>
</tr>
<tr>
<td>1470 &lt; rw ≤ 1700</td>
<td>84</td>
<td>23.5</td>
<td></td>
</tr>
<tr>
<td>1700 &lt; rw ≤ 1930</td>
<td>93</td>
<td>25.0</td>
<td></td>
</tr>
<tr>
<td>1930 &lt; rw ≤ 2150</td>
<td>101</td>
<td>26.5</td>
<td></td>
</tr>
<tr>
<td>2150 &lt; rw</td>
<td>110</td>
<td>28.0</td>
<td></td>
</tr>
</tbody>
</table>

Gross vehicle weight over 3.5 tonnes

<table>
<thead>
<tr>
<th>Mass of CO (g/kWh)</th>
<th>Mass of HC (g/kWh)</th>
<th>Mass of NOX (g/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>3.5</td>
<td>18</td>
</tr>
</tbody>
</table>

Table 2.6: Emission standard of pollutants for new models of motor vehicles on or after 1 January 1997

<table>
<thead>
<tr>
<th>Gross vehicle weight of not exceeding 3.5 tonnes</th>
<th>Reference Mass (rw) (kg)</th>
<th>CO (g/test)</th>
<th>Combined emission of HC and NOX (g/test)</th>
<th>Mass of PM (g/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>rw ≤ 1250</td>
<td>2.72</td>
<td>0.97</td>
<td>0.14</td>
<td></td>
</tr>
<tr>
<td>1250 &lt; rw ≤ 1700</td>
<td>5.17</td>
<td>1.4</td>
<td>0.19</td>
<td></td>
</tr>
<tr>
<td>1700 &lt; rw</td>
<td>6.90</td>
<td>1.7</td>
<td>0.25</td>
<td></td>
</tr>
</tbody>
</table>

Gross vehicle weight over 3.5 tonnes

<table>
<thead>
<tr>
<th>Mass of CO (g/kWh)</th>
<th>Mass of HC (g/kWh)</th>
<th>Mass of NOX (g/kWh)</th>
<th>Mass of PM (g/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5</td>
<td>1.1</td>
<td>8.0</td>
<td>0.36</td>
</tr>
</tbody>
</table>
Any offences under these regulations except the offense under regulation 4 which may be compounded accordance with the procedure prescribed in the Environmental Quality (Compounding of Offences) Rules 1978 [P.U.(A)281/78]. Excessive black smoke emissions from diesel vehicle exhaust are implemented under the Area Watch and Sanction Inspection (AWASI) program. This programme involves patrols by Department of Environment mobile squad. Observation and testing of diesel vehicles belching excessive smoke is carried out. On the spot compounds are issued to drivers and owners if their vehicles fail to comply with stipulated smoke limit of 50 HSU, and a prohibition order (prohibiting vehicle usage) is issued if the smoke limit exceeds 70 HSU. The compound not exceeding RM20,000 and maximum RM100,000 if the cases prosecuted in court or not exceeding 5 years in prison (Jabatan Alam Sekitar, 2002).

2.2.2.2 Environmental Quality (Control of Petrol and Diesel Properties) Regulations 2007

This regulation was operated since 1 April 2007 and applies to fuel used in any internal combustion engine (mobile or stationary applications) and in industrial plants. Fuel which is produced, stored, distributed, transported, supplied, sold or offered for sale within Malaysia shall comply with the standard of properties as prescribed in the case of diesel in column (2) of the Second Schedule in the Federal Subsidiary Legislation under this regulation or shown as in the Table 2.7. This regulation must be followed by the fuel supplier (producer or importer of fuel). It is important because Bernama has reported that Malaysia ranked 78th per 100 country in the list trailing behind the several Asian countries by International Fuel Quality Centre (IFQC) according to the sulphur limits in diesel used by this country.
REFERENCES


