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Technical Report: Engine and Emission System Technology

Spark Ignition Petrol
Euro 5 & Beyond
Light Duty Vehicles

August 2016
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EXECUTIVE SUMMARY

Scope:

This technical report is intended as an education and information tool. It explains how a spark ignition petrol engine works, with a focus on designs used for light duty vehicles conforming to current Euro 5 emission standard in Australia and those technologies which are necessary to meet future emissions standards.

It is intended to encourage consideration of the link between vehicle emissions, fuels and the impact that these have on the operation of petrol engine passenger cars and light vehicles in the Australian market.

The document provides the reader with the foundation knowledge necessary to understand the impact that fuel quality may have on engine design and how engines are designed to meet emissions and fuel efficiency targets. This will enable industry and policymakers to make informed decisions based on a holistic impact analysis.

Summary:

Since 2003 Australia has harmonised vehicle emissions standards with those of Europe through implementation of the Australian Design Rules (ADR) legislation. As each set of Euro standards has been enacted they have been adopted domestically, typically lagging European adoption by approximately three years. Revisions of emission standards encourage automotive manufacturers to progressively reduce vehicle pollutant emissions, which are known contributors to the greenhouse effect, and detrimental to air quality.

Japan, USA and Europe use carbon dioxide (CO$_2$) emission and/or fuel economy regulations as part of their respective policies aimed at tackling climate change and conservation of energy. It is difficult to compare these three standards on a like for like basis as each region uses different parameters, units, calculation methods and drive cycles to determine fuel consumption or CO$_2$. A common approach by all is that there is increasing pressure on vehicle manufacturers to produce more fuel efficient vehicles that emit less CO$_2$ and harmful pollutants.

A spark ignition engine requires fuel, air and a spark plug as a source of ignition to initiate combustion. Accurate control of the quantity and timing of these three items is essential to maximise the power and torque that an engine produces and limit its pollutant and CO$_2$ emissions.

Air and fuel within the engine is compressed prior to being ignited, with the amount of compression being quantified by the compression ratio. Increased engine efficiency can be achieved by using a higher compression ratio. There has been a tendency for engine compression ratio to increase as more stringent demands have been placed on fuel efficiency and CO$_2$.

A fuel’s octane rating limits the compression ratio that can be used as lower octane rating fuels are more prone to engine knocking which can damage the engine, ultimately leading to engine failure. The octane rating of fuel used in Australia is determined by its RON rating; Research Octane Number. Use of 95 RON fuel enables higher compression engines to be designed than 91 RON, resulting in higher fuel efficiency and therefore a reduction in CO$_2$ production.

In order to enable the use of lower octane fuels with high compression ratio engines, a common strategy is to adjust the spark timing. By delaying the firing of the spark plug, engine knocking can be prevented at the expense of reduced power and increased fuel consumption.

Valves are used to control the timing of air entering and exhaust gas leaving the engine. Traditionally the timing of valves opening and closing was fixed for a given engine design. Modern engines use Variable Valve Timing (VVT) to provide much greater flexibility in the operation of an engine. VVT can allow increased compatibility for lower octane fuels, reduce production of oxides of nitrogen (NO$_X$), increased power and improved fuel efficiency.

If perfect combustion of petrol fuel were possible it would result in the production of only CO$_2$ and water (H$_2$O) vapour emitted at the exhaust tailpipe. In reality, this seldom occurs. Combustion of fuel is imperfect due to many reasons including impurities in the fuel, non-perfect mixture and quantity of fuel and air, physical constraints on the combustion of fuel due to engine mechanical design and a short time duration for combustion at high engine speeds. Consequently, pollutant emissions other than CO$_2$ and water are produced by an engine in practice. These include oxides of nitrogen (NO$_X$), sulfur oxides (SO$_X$), carbon monoxide (CO), unburnt hydrocarbon fuel (UHC) and particulate matter. These are all substances which are harmful to human health and/or the environment, and consequently are regulated pollutants.
The proportion of CO, NOx and UHC produced by an engine depends to a great extent on the air:fuel ratio during combustion. A compromise must be made to achieve low levels of CO and UHC whilst mitigating the production of NOx. As a result, very accurate control of air, fuel and combustion is required to limit the production of pollutants.

Traditionally, engines were designed to pre-mix fuel with air before entering the engine combustion chamber; this is known as Port Fuel Injection (PFI). Most modern engines use Direct Injection (DI) of fuel into the combustion chamber prior to the spark plug initiating combustion. Direct Injection of fuel offers an improvement in timing and quantity of fuel injection, with subsequent fuel economy improvement and CO₂ reduction. A side effect is the increased production of particulate matter.

Exhaust Gas Recirculation (EGR) is an engine technology used to reduce the production of NOx by replacing some of the fresh air entering the engine with previously burnt exhaust gas. As exhaust gas is more inert than fresh air, the flame temperature is reduced during combustion which reduces the production of NOx. The use of EGR increases fuel consumption, CO₂ and the production of particulate matter.

Secondary air injection provides a small reduction in CO and UHC levels by injecting fresh air into the hot exhaust gas immediately at the exit of the engine. This promotes the oxidation of carbon monoxide and unburnt hydrocarbon fuel, with the side effect of increased CO₂ production.

The advancement of engine technology has enabled significant reduction in CO₂ and pollutant emissions. However, the emission of pollutants at the exhaust tailpipe are still too high to satisfy stringent emissions standards. A reduction of pollutants produced by the engine is required to lower the levels measured at the exhaust tailpipe. Exhaust aftertreatment is necessary to meet these targets. For many years, Three Way Catalytic Converters (TWC) have been used in light duty petrol cars to convert pollutant gases formed during combustion into less harmful compounds that are emitted at the exhaust tailpipe. A catalytic converter situated in the exhaust system promotes three main chemical reactions to occur; oxidising CO and unburnt hydrocarbon fuel as well as the reduction of NOx to harmless nitrogen (N₂). A by-product of all three chemical reactions is the production of CO₂. The engine must maintain the exhaust gas mixture within a very narrow band of air: fuel ratio in order for the oxidation and reaction reactions to occur simultaneously.

The Euro 6 emissions standards, currently in force in Europe, introduces limits on particulate matter, forcing the use of particulate filters for engines which use direct injection as a means of reducing CO₂. As a result, particulate filters are required in the exhaust aftertreatment system of DI engine vehicles. Although these trap around 90% of the mass of particulates produced by a petrol engine, they must be periodically regenerated to burn off the carbon based soot inside the filter and reduce the resistance to exhaust gas flow, otherwise engine power and fuel economy would suffer. The regeneration of petrol particulate filters introduces a small penalty in CO₂ production due to two reasons; firstly, from the temporary increase of engine fuel flow rate and secondly the CO₂ produced as a direct result of the oxidation of carbon-based particulates within the filter. High quality fuel and oil is required to prevent the build-up of ash within a particulate filter over successive regeneration events. Ash is formed from non-organic compounds which do not oxidise at the temperatures used for soot particulate oxidation and tend to block the pores of the filter. If left unchecked for extended periods of time, this can increase fuel consumption, reduce power and result in the Malfunction Indicator Lamp (MIL) illuminating on the dashboard.

TWC pollutant conversion efficiency is degraded by incorrect air: fuel ratio, excessive temperature and deactivation by sulfur compounds. Advanced engine management systems controlling technologies such as Multi Port Fuel Injection (MPFI) and Direct Injection (DI) fuel systems combined with variable valve and ignition timing improve combustion, hence the exhaust air/fuel ratio and temperature can be maintained within satisfactory limits for optimum Three Way Catalytic Converter pollutant conversion. However, these developments in engine technology have no impact on the production of sulfur compounds within the engine. To mitigate this detrimental impact on pollutant conversion by the TWC, reduction of sulfur compounds can only be achieved by limiting the concentration of sulfur in the fuel.

In Europe, the USA and Japan the emissions regulations have been aligned with fuels standards as regulators treat fuel quality and emissions standards as a system in order to maximise real world emissions reductions. From 2017, Europe, the USA and Japan will all require petrol to have a maximum sulfur content of 10 ppm. In Australia, fuel standards are not currently aligned with emissions standards. The most notable variation is the maximum allowable fuel sulfur concentration. Currently, standard Unleaded Petrol (ULP) has a maximum sulfur concentration of 150 ppm which is higher than that allowable in Europe for Euro 4 vehicles.

This misalignment in fuels and emission standards is more apparent when compared to European regulations. Figure 1 shows that in Europe, maximum sulfur fuel content was reduced from 50 ppm to 10 ppm to facilitate the introduction of Euro 5 emissions standard for all vehicles. In Australia the maximum sulfur content of ULP used today is more representative of levels allowed during the Euro 3 emissions standard period. Australian market fuel quality is therefore hindering the ability of vehicles to conform to current Euro 5 and (if adopted) future Euro 6 standards in the real world.
Studies have shown that higher sulfur concentration in fuel results in higher pollutant emissions.

A by-product of exhaust aftertreatment is increased CO₂ production; the reactions that occur within a catalytic converter all ultimately produce CO₂. This highlights that at times, emissions standards and fuel economy/CO₂ standards can place conflicting pressure on the design of vehicles. A compromise is made during engine development to meet both requirements. The design and operation of a petrol vehicle is extremely complex and must be considered as a whole system to obtain a balance between pollutant emissions, CO₂ production and fuel economy.
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ACRONYMS

ARB  Californian Air Resources Board
AS  Australian Standards
ASTM  American Society for Testing and Materials
AUX  Auxiliary
Avg  Average
BSFC  Brake Specific Fuel Consumption
CFR  Code of Federal Regulations (United States of America)
CO  Carbon Monoxide
CO₂  Carbon Dioxide
Cells/in²  Cells Per Square Inch
DI  Direct Injection
US EPA  United States Environmental Protection Agency (United States of America)
ECU  Engine Control Unit
EGR  Exhaust Gas Recirculation
EU  European Union
FTP  Federal Test Procedure (United States of America)
GDI  Gasoline Direct Injection
GPF  Gasoline Particulate Filter
LEV  Low Emissions Vehicle Emissions Standard (United States of America)
LNT  Lean NOₓ Trap
MBT  Mean Brake Torque Timing
MIL  Malfunction Indicator Lamp
MPFI  Multi Point Fuel Injection
N/A  Not Applicable
NATA  National Association of Testing Authorities, Australia
NMHC  Non-Methane Hydrocarbons
NMOG  Non-Methane Organic Gases
NO  Nitric Oxide
NOₓ  Oxides of Nitrogen
NO₂  Nitrogen Dioxide
OEM  Original Equipment Manufacturer
PEMS  Portable Emissions Measurement System
PM  Particulate Mass
PN  Particulate Number
PPM  Parts Per Million
PULP  Premium Unleaded Petrol
RDE  Real World Driving Emissions
RON  Research Octane Number
RPM  Revolutions Per Minute
S  Sulfur
SI  Spark Ignition
SOₓ  Sulfur Oxides
SULEV  Super Ultra Low Emissions Vehicle Emissions Standard (United States of America)
Temp.  Temperature
THC  Total Hydrocarbons
TWC  Three Way Catalyst
UHC  Unburnt Hydrocarbons
ULEV  Ultra Low Emissions Vehicle Emissions Standard (United States of America)
ULP  Unleaded Petrol
US  United States of America
UTEX  Unit Exchange
WHO  World Health Organisation
WLTP  Worldwide Harmonised Light Vehicle Test Procedures
WOT  Wide Open Throttle
GLOSSARY OF TERMS

Aftertreatment: The reduction of gaseous and particulate pollutant emissions produced by an engine by the use of catalytic converter and filter technologies placed in the exhaust system.

Charge Air: Intake air.

Chassis Dynamometer: Commonly referred to as a “rolling road”. Equipment that allows the vehicle to remain stationary whilst its wheels drive on rollers at various speeds, with resistance applied to the rollers to simulate road conditions.

Cold Start: Starting of an engine with the coolant temperature (or equivalent temperature) less than or equal to 35 °C and if measurement is available, less than or equal to 7 °C higher than ambient temperature.

Compression Ratio: The ratio between the maximum volume of fuel/air introduced into the engine and the minimum volume compressed inside the combustion chamber.

Gaseous Emissions: Engine emissions in gaseous form. Includes oxides of nitrogen (NOx), carbon monoxide (CO), carbon dioxide (CO2) and total hydrocarbons (THC).

Hot Start: Starting of an engine after a recent period of engine running or with coolant temperature greater than 35 °C.

Injector Timing: The points at which the start and end of fuel injection occurs, often reported in the number of degrees before or after the piston reaches top dead centre.

Injector Timing Advance: Refers to the start of injection being advanced (occurring earlier) relative to the piston reaching top dead centre.

Injector Timing Retard: Refers to the start of injection being retarded (occurring later) relative to the piston reaching top dead centre.

Particulate Emissions: Sometimes referred with the generic term Particulate Matter (PM) which can be ambiguous due to use of the acronym PM for Particulate Mass. A complex mixture of small solid and liquid particles suspended in the exhaust gas, often visible as soot and smoke being ejected from the exhaust. In emission standards for internal combustion engines, PM is defined as the material collected when the exhaust gas is diluted to a temperature of not more than 52°C and passed through a filter.

Particulate Mass: The mass of particulate matter collected when the exhaust gas is diluted and collected on a filter. With the advent of Euro 6c legislation the term PM refers to Particulate Mass (measured in mg/km) to avoid confusion with Particulate Number (PN).

Particulate Number: The number of particles collected when the exhaust gas is diluted and collected on a filter. In Euro emissions standards terms, this is measured in number of particles per km (#/km).
<table>
<thead>
<tr>
<th>Symbol</th>
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<tr>
<td>ºC</td>
<td>Degrees Celsius</td>
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<td>g</td>
<td>Gram</td>
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<td>J</td>
<td>Joule</td>
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<td>J/L</td>
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<td>m/s</td>
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TECHNICAL

OVERVIEW OF THE SPARK IGNITION ENGINE

COMPRESSI ON RATIO
ENGINE KNOCK
SPARK TIMING
VALVE AND FUEL INJECTION TIMING
TORQUE AND POWER
COMBUSTION OF PETROL
FUEL DELIVERY METHODS

EXHAUST EMISSIONS REDUCTION

ENGINE TECHNOLOGY FOR EMISSIONS REDUCTION
EMISSIONS AF TERTREATMENT SYSTEMS
FUEL DELIVERY METHODS: EFFECTS ON EMISSIONS

UNLEADED VERSUS PREMIUM UNLEADED PETROL

IMPACT ON EFFICIENCY
IMPACT ON POWER AND TORQUE
IMPACT ON REGULATED POLLUTANTS
EMISSIONS SYSTEMS PERFORMANCE & DURABILITY
OVERVIEW OF THE SPARK IGNITION ENGINE

The internal combustion engine remains the default choice of power plant for light duty vehicles due to the very high energy density of fuel used and the well-established infrastructure of fuel stations. This high fuel energy density provides a very long driving range for a relatively small weight penalty.

Since its inception 100 years ago, there has been a continuous development in technology used by the petrol engine enabling power increase, fuel consumption reduction and emissions reduction.

In a 4-cylinder engine at an engine speed of 2000 rpm there are 66 combustion events occurring every second!

Three items are required for combustion within an engine; Air, Fuel, and an Ignition Source.

- Air and Petrol Fuel enter the combustion chamber via the Inlet Port and Inlet Valve.
- The mixture is compressed by the Piston moving upwards, reducing the cylinder volume to that of the Combustion Chamber.
- A Spark Plug ignites the fuel/air mixture.
- The rapid expansion of hot gases creates high pressure, forcing the Piston to move. This motion is harnessed by the engine and driveline to propel the vehicle.
- The Exhaust Valve opens to allow the combusted gases to exit the engine before a fresh charge of fuel and air enters.

Source: ABMARC

Figure 2 – The Spark Ignition Petrol Engine
Compression Ratio

Compression Ratio is the ratio between the maximum volume of fuel/air introduced into the engine and the minimum volume compressed inside the combustion chamber.

The higher the volume of air and fuel that can be inducted into the engine and compressed into a small space, the more energy can be introduced into the engine and then released during combustion. Typical engine compression ratios have been around 8:1 in older engines but in modern engines the norm is around 9:1 or 10:1. Current production cars can have compression ratios as high as 13:1. Figure 3 demonstrates the concept of a 10:1 engine compression ratio.

Higher compression ratio benefits engine efficiency

Engine Knock

Engine Knock is a term used to describe the uncontrolled, rapid combustion of fuel which causes shock waves of pressure to be transmitted through the engine. This is observed as rough engine running accompanied by a knocking sound, with the driver perceiving a reduction in driving quality. The rate of combustion when engine knock occurs is many times faster than that of normal, controlled combustion.

Although raising compression ratio is advantageous for efficiency, there is a limit to the amount of compression that can be applied in a petrol engine. High compression ratio engines are more prone to engine knock occurring. The exact cause of engine knock is highly complex, but two main mechanisms are used to explain the occurrence of engine knock; Autoignition and Surface Ignition.

Autoignition

Once the spark plug has initiated combustion, the fuel and air mixture burns with an advancing flame front. As the hot gases expand, the unburned mixture ahead of the flame becomes compressed with an accompanied increase in temperature. Autoignition occurs when these compressed gases spontaneously combust before the flame front reaches them, causing a rapid pressure rise with accompanied shock waves.

Surface Ignition

In this scenario, fuel and air are ignited due to localised hot spots in the combustion chamber such as overheated valves, spark plugs or combustion deposits. Again, the rapid combustion that occurs before the flame front reaches the fuel causes erratic combustion with shock waves of pressure that are transmitted into the engine structure.
Continued operation of an engine suffering from knock can be damaging to its durability.

Knock sensors are used to detect the physical vibration of knocking occurring so that the Engine Control Unit (ECU) can adapt engine operating conditions to prevent its occurrence.

Modern engines monitor and control engine knock to operate most efficiently

Spark Timing

The combustion process is very complex, and a single combustion event takes place over a very short time period. Precise timing of when the spark initiates combustion is critical to both the power that an engine produces and the tailpipe emissions.

Combustion of petrol in an engine is slow relative to the speed at which an engine runs. If combustion was instantaneous, the spark to initiate combustion would occur when the piston reaches the top of the cylinder. At this point, the fuel/air mixture is compressed at its highest pressure.

However, as the fuel burns relatively slowly the spark is timed to occur whilst the piston is still travelling upwards and compressing the fuel/air mixture. This is known as spark advance.

The time required for the air/fuel mixture to burn (combust) is similar whether the engine is running at low or high speed, therefore at higher speeds the spark must occur even earlier. Modern engines are able to vary the spark timing to suit the mode of operation of the engine. Stored on the ECU are a number of calibration tables which allow the optimum spark timing to be chosen based on operating parameters such as speed, load, air flow rate, charge air temperature, engine coolant temperature and fuel flow rate.

Spark timing is used as a mechanism during a cold start to ensure the exhaust aftertreatment system warms-up quickly. This helps the catalytic converter reach its operating temperature quickly for efficient operation.

<table>
<thead>
<tr>
<th>SPARK TIMING INFLUENCE ON ENGINE OPERATION</th>
<th>Advance timing</th>
<th>Retard timing</th>
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<tbody>
<tr>
<td>Efficiency</td>
<td></td>
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<tr>
<td>Cold-start emissions</td>
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Source: ABMARC

Table 1 – Spark Timing Influence on Engine Operation
Valve and Fuel Injection Timing

Valves allow the air and/or fuel to enter the engine and allow exhaust gas to exit. As the quality and timeliness of fuel/air mixing has a direct impact on combustion, precise control of valve and fuel injection timing is critical to the power and emissions produced.

During induction of fresh air, the inlet valve opens.

To maximise power and torque, both the inlet and exhaust valve must be closed during combustion to allow the greatest pressure to form.

After combustion, the exhaust valve opens allowing the exhaust gas to flow through the exhaust system.

At points during engine operation, exhaust and inlet valves may be open at the same time; this is known as valve overlap. The length of time that a valve is open is referred to as its duration.

Most modern engines use a cam mechanism on a rotating shaft (camshaft) to actuate the valves by overcoming the resistance of a spring that holds the valve closed. The profile, or shape, of the cam would determine both when the valve opens and closes (timing and duration), as well as by how much the valve opens (lift). The greater the lift, the more inlet or exhaust gas can flow into or out of the engine.

Traditionally, engines were limited to fixed timing, duration, and lift of the valves. Engines are still in production today with this type of non-variable design. As an engine operates at a range of different speeds this means that valve timing can only be optimised within a narrow speed range. As a result, the emissions, power and fuel economy may be compromised at other operating conditions.

Variable Valve Timing (VVT)

Variable Valve Timing is a technology employed by many modern engines that provides full flexibility of valve timing throughout the engine’s speed range. This offers improved fuel economy, power and emissions when compared to fixed valve timing.

The inlet and exhaust valves are actuated via a complex mechanism controlled by the ECU which, determines the optimum timing, duration and lift for the operating conditions experienced.

Fuel Injection Timing

Direct Fuel Injection (DI) offers more ability to vary the timing and duration of fuel injection into the cylinder. DI provides engine designers greater flexibility to control combustion, leading to potential power, fuel economy and emissions benefits.
Potential in-service issues with VVT and Direct Fuel Injection

VVT technology relies on oil pressure for control of the actuation mechanism which means that oil viscosity and cleanliness is of high importance. During long-term operation, a reduction in oil viscosity and an increase in contamination in the oil can eventually affect the operation of the VVT system, with adverse impact on power, fuel efficiency and emissions.

Direct Fuel Injection technology is highly sensitive to the quality of fuel used. As the fuel injector nozzles are situated inside the combustion chamber they are exposed to the combustion process and very high temperatures which can lead to coking of the nozzle. Nozzle coking restricts the diameter of fuel flow passageways due to soot accumulation, which can reduce fuel flow and therefore power. Nozzle coking also impacts on the injector spray pattern and can prevent proper fuel atomisation and mixing of the fuel and air. Within the injectors, lacquers can accumulate which could result in a reduced response of injector timing, adversely affecting power or emissions. Lacquers are formed by the decomposition of fuel at higher temperatures, which, when left to cool, can harden and form a varnish-like coating.

In either of these cases, incorrect operation of valve or fuel timing can be recognised by the ECU leading to a Malfunction Indicator Lamp (MIL) illuminating on the dashboard.

As a result, technologies used in future engine designs become more reliant on high quality fuel and engine oil to ensure acceptable long term performance.

Torque and Power

Within an engine, the piston moves up and down in the cylinder and its linear motion is converted into a turning effect by mechanical linkages. The magnitude of the turning effect is quantified as Torque. It is this torque which is used to turn the wheels of a vehicle and propel it forwards. The heavier the payload, larger the vehicle, or steeper the (uphill) gradient, the more torque is required to propel the vehicle.

The rate at which an engine combusts fuel and creates torque is quantified by the Power produced by the engine. The faster a vehicle must accelerate, the more power is required from the engine.
Combustion of Petrol

Spark Ignition engines most commonly use Petrol fuel. Other fuel examples are Liquefied Petroleum Gas (LPG) and Natural Gas. Petrol is a hydrocarbon fossil fuel; it consists mostly of molecules made up of hydrogen (H) and Carbon (C) atoms. During complete combustion the fuels react with the Oxygen (O) atoms in the air to produce Carbon Dioxide (CO$_2$), and Water (H$_2$O). Figure 8 shows the regulated engine pollutants for Petrol vehicles.

In reality, engine combustion is rarely perfect. Imperfect combustion can lead to unburnt fuel (hydrocarbons) being emitted, generally when there is insufficient localised oxygen present. Air contains a large amount of Nitrogen (N) atoms. Petrol generally is refined from crude oil which consists of a spectrum of organic compounds as well as Sulfur (S).

A single combustion event in an engine may last only a matter of milliseconds. Due to the very high temperatures, pressures and the short time period for combustion to occur, other harmful pollutants can be created during combustion. Some of these such as Hydrogen Sulphide (H$_2$S) and Methane (CH$_4$) are created in very small amounts and can be mitigated by accurate control of the engine operation, whereas others are produced in sufficient quantities to have strict limits placed on their emission from vehicles. Pollutant emissions and CO$_2$ or fuel efficiency standards provide these limits. Table 3 lists some of the globally regulated emissions covered by Greenhouse Gas, CO$_2$ and pollutant emissions standards.

<table>
<thead>
<tr>
<th>REGULATED POLLUTANTS</th>
<th>Pollutant</th>
<th>Reason for production</th>
<th>Hazard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide CO$_2$</td>
<td>Always present during combustion; production is proportional to the fuel consumption rate</td>
<td>A greenhouse gas with Global Warming Potential of 1</td>
<td></td>
</tr>
<tr>
<td>Carbon Monoxide CO</td>
<td>Insufficient oxygen during combustion</td>
<td>Harmful to human health</td>
<td></td>
</tr>
<tr>
<td>Nitrogen Oxides NO$_x$</td>
<td>Excess oxygen during combustion &amp; very high combustion temperature</td>
<td>Harmful to human health</td>
<td></td>
</tr>
<tr>
<td>Nitrous Oxide N$_2$O</td>
<td>Excess oxygen during combustion &amp; very high combustion temperature</td>
<td>A greenhouse gas with Global Warming Potential of 310</td>
<td></td>
</tr>
<tr>
<td>Sulfur Oxides SO$_x$</td>
<td>Sulfur present in fuel and/or oil</td>
<td>Harmful to human health</td>
<td></td>
</tr>
<tr>
<td>Methane CH$_4$</td>
<td>Insufficient oxygen during combustion</td>
<td>A greenhouse gas with Global Warming Potential of 21</td>
<td></td>
</tr>
<tr>
<td>Particulate Matter PM</td>
<td>Incomplete combustion and/or insufficient oxygen during combustion</td>
<td>Harmful to human health</td>
<td></td>
</tr>
<tr>
<td>Unburnt hydrocarbons UHC</td>
<td>Incomplete combustion and/or insufficient oxygen during combustion</td>
<td>Contains Volatile Organic Compounds (VOCs) that are harmful to health</td>
<td></td>
</tr>
</tbody>
</table>

Sources: EPA, WHO & ABMARC

Table 3 – Key Petrol Engine Pollutants
Air/fuel ratio

In order to achieve the best combustion of petrol fuel, there is an ideal ratio of air to fuel. Lambda (\(\lambda\)) is used to denote this ratio.

When \(\lambda=1\), complete combustion of fuel is possible. The mass of air present is 14.7 times that of fuel.

When \(\lambda<1\) the exhaust gas is said to be fuel rich and \(\lambda>1\) means that the exhaust gas is lean (excess oxygen).

Combustion can still occur if the air to fuel ratio varies either side of \(\lambda=1\) but it affects both the power output of the engine and the emissions.

Formation of NOx is highest when the engine is under the most load, producing high torque, power and temperature. Carbon monoxide production is highest when there is insufficient air for combustion, which is accompanied by the highest production of unburnt hydrocarbons.

Due to practicalities of engine design, even when the air: fuel ratio is at \(\lambda=1\), incomplete combustion can still occur, with pollutants such as NOx, CO and UHC being produced by the engine. The Three Way Catalytic Converter (TWC) is used to convert these pollutants into less harmful substances emitted at the tailpipe.

The TWC only functions effectively when subjected to exhaust gas with a narrow range of air: fuel ratio. An oxygen sensor is placed in the exhaust before the TWC and provides a signal to the ECU to allow it to determine fuelling adjustments that are required to maintain the exhaust flow in the optimum range for TWC operation.

The TWC is able to reduce NOx to Nitrogen (\(N_2\)) and Oxygen (\(O_2\)) when the exhaust gas is rich, and it is able to oxidise Carbon Monoxide (CO) and Unburnt Hydrocarbons (UHC) to Carbon Dioxide (\(CO_2\)) and water (\(H_2O\)) during lean conditions (excess oxygen).
Fuel Delivery Methods

The technology used to deliver fuel to the engine has developed greatly since carburettors were phased out due to the introduction of stricter emissions legislation in the 1990s. Unable to provide the fine control in fuel quantity required for effective catalytic converter operation, carburettors were replaced by a simple fuel injector. Fuel injection enabled much improved fuelling control in terms of quantity and timing, enabling a reduction in vehicle emissions. As emission standards have become stricter, the complexity of fuel injection systems has increased accordingly.

Today all light vehicles use some form of fuel injection, and the fuel system is integrated with the Engine Control Unit (ECU) which controls it. Various parameters are measured and used as an input by the ECU to determine the correct fuelling. The components of a generic vehicle fuel and control system are shown in Figure 9.

Vehicle Fuel System Overview

![Figure 9 – Overview of a Typical Petrol Vehicle Fuel System](image)

### COMPONENTS OF A TYPICAL VEHICLE FUEL SYSTEM

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Injectors</td>
<td>Inject fuel either into the air inlet ports or directly into the combustion chamber. Precision machined nozzles ensure consistent atomisation of fuel</td>
</tr>
<tr>
<td>2. Fuel Pressure Sensor</td>
<td>Ensures a steady fuel pressure is delivered to the fuel injectors</td>
</tr>
<tr>
<td>3. Accelerator Position Sensor</td>
<td>Determines driver torque demand from pedal position and sends this to the ECU</td>
</tr>
<tr>
<td>4. Fuel Supply Module</td>
<td>Contains the fuel pump, fuel pump controller, fuel level sensor and fuel filter</td>
</tr>
<tr>
<td>5. Fuel Tank</td>
<td>Contains Fuel Supply Module</td>
</tr>
<tr>
<td>6. Exhaust Oxygen Sensor</td>
<td>Provides exhaust gas oxygen content measurement data to the ECU to maintain correct air: fuel ratio</td>
</tr>
<tr>
<td>7. Engine Control Unit (ECU)</td>
<td>Computer that determines fuelling rates and other engine control functions based upon the sensor signals provided to it</td>
</tr>
</tbody>
</table>

Table 4 – Components of a Typical Petrol Vehicle Fuel System
There are two types of fuel injection methods currently used in petrol cars; Port Fuel Injection (PFI) and Direct Fuel Injection (DI). In the quest for reduction of CO₂ emissions, Port Fuel Injection technology is increasingly being replaced by Direct Injection in modern petrol engines.

### PETROL ENGINE FUELLING TECHNOLOGY

<table>
<thead>
<tr>
<th>Generation 1</th>
<th>Generation 2</th>
<th>Generation 3</th>
<th>Generation 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Delivery Method</strong></td>
<td>Carburettor</td>
<td>Port Fuel Injection</td>
<td>Direct Injection</td>
</tr>
<tr>
<td><strong>Description</strong></td>
<td>Fuel is drawn from the carburettor into the air flow due to the low pressure in the air intake. A complex assembly of jets and needles provides limited mechanical fuelling control.</td>
<td>This design uses one fuel injector. Fuel sprayed into the intake mixes with air before splitting into separate intake runners that feed each cylinder of the engine.</td>
<td>One fuel injector per inlet port. A timed and precise quantity of fuel is injected into each inlet port and is mixed with the incoming air before entering the combustion chamber.</td>
</tr>
<tr>
<td><strong>Key characteristics</strong></td>
<td>Limited control of fuel.</td>
<td>Control of fuelling at a wide range of conditions. Poor fuel mixing.</td>
<td>Improved control of fuel quantity and timing. Improved fuel mixing.</td>
</tr>
<tr>
<td><strong>Emissions Compliance</strong></td>
<td>Does not meet current requirements</td>
<td></td>
<td>Move to DI as CO₂ limits reduce</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Trend</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increasing use of Direct Injection fuel technology</td>
<td>Reduction in CO₂ and fuel consumption</td>
</tr>
<tr>
<td></td>
<td>Increase in NOₓ produced by engine</td>
</tr>
<tr>
<td></td>
<td>Increase in Particulate Matter (PM) produced by engine</td>
</tr>
<tr>
<td></td>
<td>Improved control of engine fuelling</td>
</tr>
</tbody>
</table>

Source: ABMARC

Table 5 – Types of Petrol Fuelling Technology
Chart 1 shows the percentage of petrol engine light duty vehicles sold in Australia that use Direct Injection fuel systems. From 2010 to 2015 the proportion of all petrol vehicles using Direct injection increased from 12 % to 39 %. In 2010, 39 % of vehicles sold which require the use of Premium Unleaded Petrol (PULP) used DI fuel systems, increasing to 81 % in 2015. Correspondingly, for light duty vehicles requiring standard Unleaded Petrol (ULP), from 2010 to 2015 the proportion using DI increased from 8 % to 28 %.

Some manufacturers use a combination of DI and MPFI in their engines in order to minimise the compromise between reduced CO₂ production (through improved fuel efficiency) and acceptable emissions during all operational phases such as cold start and Wide Open Throttle (WOT). This increased complexity allows Direct Injection of fuel at low engine loads such as idle and decelerations, switching to Multi Port Fuel Injection at high engine loads for heavy accelerations. The sales of vehicles in Australia that use this combination of DI and MPFI are included in the data presented in Chart 1.

Source: ABMARC based on VFACTS and Redbook

Chart 1 – Percentage of Petrol Engine Light Duty Vehicles using Direct Injection by Year
EXHAUST EMISSIONS REDUCTION

During the design phase, reduction of vehicle emissions is achieved by treating the vehicle as a system made up of three categories: Fuel, Engine and Exhaust Aftertreatment. Each of these categories is critical to the operation of the vehicle and as they interact they must be controlled precisely to ensure acceptable tailpipe emissions.

Before the introduction of vehicle emission control in the 1970s, tuning of an engine was focussed on only a few key considerations:

- Attaining an adequate spark to initiate combustion
- Correct air: fuel ratio to produce
  - Sufficient power at high load,
  - Limited smoke
  - Acceptable idle speed

The introduction of emissions legislation has resulted in the need to improve the control of fuelling, ignition and combustion within an engine in order to reduce the harmful pollutants that are produced. The use of new technology has enabled vehicles to produce a small fraction of the emissions compared with the 1970s. This has increased engine complexity, requiring higher quality fuels, a multitude of sensors, more advanced and expensive materials and complex calibration of systems.

No longer can the engine be considered separately from fuel it uses or the aftertreatment system required in the exhaust to convert harmful pollutants. Figure 10 provides an overview of the three main systems that determine vehicle emissions; engine, fuel and exhaust aftertreatment system.
Petrol Spark Ignition Engine and Emission System Technology

Engine Technology for Emission Reduction

Engines are designed with a compromise between power, fuel efficiency, durability, drivability, emissions and cost. Engine development involves a highly complex and lengthy calibration of these items in order to meet the emissions limits and desired vehicle performance characteristics across all conditions experienced in the real world. Numerous sensors are used to provide inputs to the ECU which are then used to determine the optimum operating conditions for the engine. Thousands of parameters are processed by the ECU and it is capable of making hundreds of adjustments per second to these operating parameters. A fast response time of system control is critical to ensure low vehicle emissions.

To demonstrate the complexity of modern engines, a typical Euro 5 or Euro 6 engine may use the following list of sensors:

- Engine Position
- Manifold Absolute Pressure
- Exhaust Gas Oxygen Content
- Exhaust Filter Back Pressure
- Inlet Air Temperature
- Air Mass Flow Rate
- Engine Coolant Temperature
- Vehicle Speed
- Crankshaft Position
- VVT Phase Position
- Throttle Position
- Fuel Temperature and Pressure
- EGR Lift Position
- EGR Back Pressure
- Engine Knock Sensor

Exhaust Gas Recirculation

From the 1980s Exhaust Gas Recirculation (EGR) has been used to reduce the emissions of NO\(_X\) produced by spark ignition engines.

NO\(_X\) is formed during combustion by high temperatures created by the available oxygen in the air. To lower the oxygen content in the air inducted into the engine, exhaust gas is recycled from the exhaust port back into the intake port. As the exhaust gas has already been burnt it contains a much lower proportion of oxygen and so is more inert than fresh air.

By recycling a proportion of the exhaust gas into the air intake, the flame temperature during combustion is reduced, lowering the NO\(_X\) production.

To control the amount of exhaust gas recirculated, an EGR valve is typically used. Other methods are possible such as opening the inlet valves whilst the exhaust valves are open to allowing mixing of some exhaust gas with incoming fresh air.

Figure 11 gives a schematic overview of an exhaust gas recirculation system.

Impact of EGR on Engine Operation & Emissions

As NO\(_X\) emission limits reduce there is a requirement to increase the volume of exhaust gas recirculated into the engine. The hot exhaust gas limits the amount of EGR that can be used. There is an increasing trend to cool the EGR gas before it is re-ingested into the engine. This increases its density and allows a higher volume of EGR to be used, lowering NO\(_X\) emissions further.

The recirculation of exhaust gas into the engine compromises durability. Use of EGR increases particulates of soot, metallic ash from lubricants, and unburnt hydrocarbons. These can form carbonaceous deposits on the inlet valves and EGR valves as well as increasing the likelihood of catalyst and filter plugging. Table 6 summarises the key impacts of increased EGR on engine operation and pollutant emissions.
### IMPACT OF EGR ON ENGINE OPERATION & EMISSIONS

<table>
<thead>
<tr>
<th>Action</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increased amount of EGR</td>
<td>Reduces NO&lt;sub&gt;x&lt;/sub&gt;</td>
</tr>
<tr>
<td></td>
<td>Reduced power</td>
</tr>
<tr>
<td></td>
<td>Increased CO&lt;sub&gt;2&lt;/sub&gt;/fuel consumption</td>
</tr>
<tr>
<td></td>
<td>Potential of EGR valve blocking</td>
</tr>
<tr>
<td></td>
<td>Increased Particulate Matter</td>
</tr>
</tbody>
</table>

Sources: ABMARC and Platinum Metals Rev., 2013, 57, (2), 157–159

Table 6 – Impact of EGR on Engine Operation & Emissions

### Secondary Air Injection

Secondary Air Injection systems reduce CO and UHC emissions before they reach the catalytic converter.

Fresh oxygen from the air intake is injected into the exhaust gas immediately after the combustion chamber causing the exhaust gases to be re-burnt.

As well as the fresh oxygen causing CO and UHC to be converted to carbon dioxide and water, the heat produced by this reaction aids the warm-up of the catalytic converter, further benefiting pollutant conversion.

Source: ABMARC

Figure 12 – Secondary Air Injection

### Engine Downsizing

Engine downsizing is a response to the requirement to reduce CO<sub>2</sub> emissions by improving vehicle fuel economy with smaller capacity engines. Improved fuel consumption is achieved by reducing the engine capacity and increasing its efficiency via a range of mechanisms as outlined in Table 7 below:

### METHODS EMPLOYED TO ENABLE ENGINE DOWNSIZING

<table>
<thead>
<tr>
<th>Category</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forced Air Induction</td>
<td>Turbocharging</td>
</tr>
<tr>
<td></td>
<td>Supercharging</td>
</tr>
<tr>
<td></td>
<td>Turbocharging + Supercharging</td>
</tr>
<tr>
<td>Mass Reduction</td>
<td>Structural design</td>
</tr>
<tr>
<td></td>
<td>Design for duty cycle rather than design for life</td>
</tr>
<tr>
<td></td>
<td>Cylinder reduction</td>
</tr>
<tr>
<td>Reduced Frictional Losses</td>
<td>Improved lubricants</td>
</tr>
<tr>
<td></td>
<td>Cylinder reduction, e.g. 3-cylinders replacing 4-cylinder</td>
</tr>
<tr>
<td></td>
<td>Cylinder deactivation at part load conditions</td>
</tr>
<tr>
<td></td>
<td>Low-friction coatings for engine parts</td>
</tr>
<tr>
<td>Improved Engine Control</td>
<td>Combustion research</td>
</tr>
<tr>
<td></td>
<td>Improved engine sensors</td>
</tr>
<tr>
<td></td>
<td>Fuel, air and ignition systems</td>
</tr>
</tbody>
</table>

Source: ABMARC

Table 7 – Methods Employed to Enable Engine Downsizing
Emissions Aftertreatment Systems

During the design of an engine or vehicle a compromise between engine power, fuel efficiency, durability and cost can be reached at the expense of emissions or the engine technology may not be currently available to meet the required emissions targets. Emissions aftertreatment systems are employed in these situations to reduce the harmful emissions produced by the engine and emitted from the vehicle tailpipe to an acceptable level.

Since the 1970s, catalytic converters have been utilised to improve the tailpipe emissions of vehicles. Originally oxidation catalysts offered a solution to reducing emission of carbon monoxide and unburnt fuel, with further development leading to the Three Way Catalytic Converters (TWC) which also reduce emission of Oxides of Nitrogen (NO\textsubscript{X}).

Today, TWCs form the back bone of petrol emission aftertreatment systems which have progressively become more complex and technologically advanced in the effort to meet ever more stringent emissions legislation.

Aftertreatment technology is developed in conjunction with engine technology in order to achieve the greatest emission reduction benefits and so their operation is inter-related. The fine control of engine operation is vital to the performance of the aftertreatment system in order to ensure tailpipe emissions targets are met.

Figure 13 shows an overview of a typical emissions aftertreatment system for a Direct Injection petrol engine. An Oxygen sensor is placed in the exhaust gas after the engine and before a catalytic converter. After exhaust gas flows through the catalytic converter it passes through a particulate filter before continuing through the exhaust system to leave the vehicle at the tailpipe.

Catalytic Converter

A catalytic converter is a device that is placed within the exhaust system to encourage the harmful engine exhaust gases to react and form safer by-products which are emitted at the tailpipe.

The catalyst coating lowers the energy required for reactions to occur between the exhaust gases, but remains unchanged at the end of the reactions. It is a non-consumable component and providing it operates within its design limits, will continue to function for a lifetime of use.

Catalytic converters are made of either a ceramic or metallic foil substrate with many hundreds of cells creating passageways for the exhaust gases to flow through.

Figure 15 shows a sectional photograph of a ceramic catalytic converter typical of the type used in light duty petrol vehicles.
Cell density is quoted in cells per square inch, cells/in². Figure 14 shows a close-up view of the cells within a catalytic converter with ceramic substrate.

The substrate is coated with catalyst compounds containing precious metals including platinum, palladium, rhodium or iridium.

**Three-Way Catalytic Converter (TWC)**

A TWC promotes the oxidation of Unburnt Hydrocarbons (UHC) and Carbon Monoxide (CO) as well as reducing oxides of Nitrogen (NOₓ). The three chemical reactions can be represented by:

**Oxidation:**

\[
2 \text{CO} + \text{O}_2 \rightarrow 2 \text{CO}_2
\]

\[
4 \text{HC} + 5 \text{O}_2 \rightarrow 4 \text{CO}_2 + 2 \text{H}_2\text{O}
\]

**Reduction:**

\[
2 \text{NO}_x \rightarrow \text{N}_2 + x \text{O}_2
\]

Since the inception of Euro 1 emissions legislation, three-way catalytic converters have been fitted to petrol light duty vehicles. Figure 15 demonstrates the function of a TWC converting engine emissions into tailpipe emissions.

**Factors Affecting Catalytic Converter Performance**

**Catalytic Converter Design**

Catalytic converter design can be optimised for different engine applications by choice of precious metal coatings, coating distribution through the catalyst substrate and the number of cells per unit area for the exhaust gas to flow through.

**Temperature**

Below a minimum temperature known as the “Light-Off Temperature” there is negligible conversion of pollutants as the catalyst has insufficient activation energy to initiate the required chemical reactions. Excessive temperature can reduce the activity of the catalyst coatings, negatively impacting conversion of pollutants. The temperature fluctuations that occur during normal operation over the lifetime of a vehicle cause the catalytic converter efficiency to reduce. This is one of the factors contributing to catalyst ageing.

**Air: Fuel Ratio**

Catalytic converters promote conversion of pollutants only if the Oxygen content of the exhaust gas is maintained within tight limits. Oxygen sensors are used in the exhaust to quantify Air : Fuel ratio and their signal is fed back to the Engine Control Unit (ECU) which then adjusts fuelling.

**Fuel and Oil**

Impurities in fuel and oil lead to the production of compounds during combustion which may inhibit the performance of the catalytic converter. The continual exposure of a catalytic converter to some of these compounds over its lifetime is another factor contributing to catalyst ageing.
**TRENDS IN CATALYTIC CONVERTER TECHNOLOGY**

Catalytic converters have in the past used cell densities around 200 cells/in\(^2\). Late model vehicles have cell densities of 600 cells/in\(^2\), with densities as high as 1200 cells/in\(^2\) possible.

Increased cell density increases the active surface area where pollutants can be converted, as well as reducing the wall thickness of the substrate. This reduces thermal mass of the catalyst, enabling it to reach working temperature more quickly and therefore improve tailpipe emissions, particularly during cold-start.

Catalyst coatings have been improved, with better high temperature resistance and pollution conversion attributed to the chemistry employed and strategic placement of coatings within the catalyst substrate.


### Fuel Delivery Methods: Effects on Emissions

The fuel delivery method used in a petrol engine has a direct effect on the emissions it creates. This places different requirements on the exhaust aftertreatment system used, which in turn changes the way in which an engine must function in order to stay within legislative emissions limits.

PFI systems produce exhaust gases that are generally rich or around Lambda = 1 which is perfectly suited to TWC technology, ensuring their correct function and acceptable emissions.

Direct Injection (DI) systems have improved control of fuelling compared to PFI systems and consequently offer reduction of CO\(_2\) emissions due to improved fuel atomisation and timing control. However, as the fuel is injected directly into the cylinder there is less time available for fuel and air to mix than with PFI systems so the particulate emissions of DI engines are higher.

#### Particulate Filters

Direct Injection of fuel increases production of particulates when compared with Port Fuel Injection. With the introduction of particulate matter emission limits, particulate filters are a solution. A particulate filter is part of the exhaust system and is usually situated after the catalytic converter.

Use of Particulate filters with Direct Injection engines is necessary to satisfy Euro 6b Particulate Mass (PM) and Euro 6c Particulate Number (PN) emission legislation.

Exhaust gas flows through a series of small passageways which prevent flow directly through to the exit.

The gas must pass through porous side walls with very small pores that trap soot particles whilst allowing cleaner gas to pass through to the tailpipe.

Pore sizes can be as small as 9 µm, allowing filtration of up to 90% of particulate matter by mass to be achieved. 9 µm is approximately equivalent to 10,000 times smaller than the width of a human hair.

Source: Corning

Figure 16 – Particulate Filter

There are three main types of particulate filter; ceramic wall flow filters, sintered metallic filters and open metallic filters. Table 9 compares their key characteristics.
### COMPARISON OF PARTICULATE FILTERS

<table>
<thead>
<tr>
<th></th>
<th>Ceramic Wall Flow</th>
<th>Sintered Metallic</th>
<th>Open Metallic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Robustness</td>
<td>Medium</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Weight</td>
<td>Light</td>
<td>Heavy</td>
<td>Heavy</td>
</tr>
<tr>
<td>Cost</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Filtration</td>
<td>High</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Adoption</td>
<td>Widely used</td>
<td>Low: Suited to heavy duty vehicles</td>
<td>Low: Suited to retro-fit to existing vehicles</td>
</tr>
</tbody>
</table>

Source: Gasoline Engine with Direct Injection, R. van Basshuysen, 2009
Table 9 – Comparison of Particulate Filters

### Regeneration of Particulate Filters

Particulate filters have a finite capacity to trap soot and other matter. As they capture particulates, there is an increased resistance to the exhaust gas flow, decreasing efficiency. If the filter is not cleaned (regenerated) at regular intervals this would result in a reduction in engine power and may cause rough running and the Malfunction Indicator Lamp (MIL) being illuminated on the car dash. In extreme cases it may be possible to only drive the vehicle at very low speeds.

Cleaning of the particulate filter is generally an automatic process. This cleaning process is known as *Particulate Filter Regeneration*.

Engines use two filter regeneration methods; Passive and Active Regeneration.

#### Passive Regeneration

Particulate matter consists mainly of carbon-based soot from the incomplete combustion of petrol and trace amounts of oil. During regeneration, soot is oxidised to form carbon dioxide gas which then passes through the filter to the tailpipe.

Passive regeneration is possible as petrol engines often produce exhaust gas up to 800 °C. If the filter is placed close enough to the engine, the high temperature enables soot to be oxidised whilst the engine is operating in its normal mode.

#### Active Regeneration

The engine alters its fuel and ignition timing to allow additional fuel into the exhaust stream. This raises the temperature of the filter and encourages the soot to oxidise, but increases fuel consumption.

Generally, an active regeneration is necessary under two circumstances:

- For packaging reasons, a particulate filter may be fitted under the floor of the vehicle. The lower exhaust temperatures cannot initiate oxidation of soot.
- Engines operating primarily at light load and so do not produce high temperature exhaust gas.

The regeneration of a particulate filter produces high exhaust gas temperatures, potentially >1200 °C. Control of air and fuel is critical to ensure that the filter does not suffer thermal shock and crack (ceramic filter) or melt (metallic filter).

The regeneration of a particulate filter can completely remove carbonaceous soot by the process of oxidation but a small proportion of ash remains in the pores of the filter. This originates from non-hydrocarbon compounds present in the fuel and oil, which usually become metallic based compounds after combustion in the engine.

Figure 16 shows the cross section of one cell of a ceramic particulate filter from a DI petrol engine. A thin layer of white coloured ash is trapped in the pores of the square shaped cell walls, and upon this the black soot particulates have agglomerated.

Source: Argonne National Laboratory
Figure 16 – Soot and Ash Accumulated Inside a Ceramic Particulate Filter Cell
Whilst a particulate filter can be regenerated hundreds of times over a vehicle’s life, the ash that remains after each regeneration slowly blocks the pores of the filter, reducing its effectiveness and creating an increase in resistance to gas flow. This increase in resistance reduces the power that the engine is able to produce and results in an increase in fuel consumption for a given power requirement. In order to ensure the most fuel efficient operation over the lifetime of a vehicle it is important to use fuels and oils that limit the production of ash in the particulate filter.

Potential Impact of a Blocked Particulate Filter
- More frequent active regeneration
- Reduction in engine power
- Malfunction Indicator Lamp (MIL) illumination
- Increased fuel consumption
- Inability to drive vehicle

Future Trends in Aftertreatment

In light of engine downsizing there is the potential to reduce the weight of the exhaust aftertreatment system by combining the separate TWC and particulate filter and applying a catalyst coating to the particulate filter substrate itself. This may allow placement of the filter close to the engine providing higher temperatures and therefore improved passive regeneration of the filter. A secondary effect is that the heat produced by the exothermic reaction in the TWC further increases filter temperature.

Alternatively, the increased heat offered by a catalysed filter may provide the ability to locate the filter further downstream in the underfloor position of the car aiding packaging within the engine bay.

An increase in the use of catalysed particulate filters in future Euro 6 vehicles is anticipated.

Impact of Lean Burn Mode on Emissions

Engines calibrated to run in Lean Burn mode have not been widely adopted in Australia, whilst in Europe and Japan it has been facilitated by the provision of 10 ppm sulfur petrol. Adoption of lean burn direct injection reached around 2% of European vehicles in 2010. Lean Burn engines can provide significant improvements in fuel consumption when compared to engines that operate at Lambda 1. Global adoption of vehicles calibrated to run in Lean Burn mode has not been as high as anticipated, and this is believed to be due to durability challenges associated with its use.

In Japan, the limit for Particulate Mass emissions from petrol vehicles only applies to engines that run in Lean Burn mode.

Direct Injection technology offers potential fuel consumption (CO$_2$) or power improvements by enabling air: fuel ratios as high as 50:1 to be achieved. When the engine runs at air: fuel ratios greater than 14.7:1 this is known as running in ‘Lean Burn’ mode. An engine may benefit from running in this mode when it is under light load, for example at idle or during decelerations.

When operating in lean-burn mode, the excess oxygen in the exhaust gas prevents the TWC from efficiently reducing NO$_x$. These systems require the use of an additional aftertreatment catalyst.

Lean NO$_x$ Traps (LNT) or NO$_x$ Storage Reduction (NSR) catalysts are employed by Lean Burn DI Petrol engines to reduce tailpipe NO$_x$ emissions. They are fitted in the exhaust downstream of an oxidation catalyst.

They consist of a ceramic or metallic substrate, upon which a catalyst coating is applied that is different to that of a TWC.

A number of intermediate reactions occur during operation but these can be summarised by the following two modes of engine operation:

Lean Operation: NO$_x$ is stored on the catalyst surface as a nitrate.

Fuel - Rich Operation: Catalyst chemically reduces NO$_x$ to Nitrogen gas (N$_2$). N$_2$ is an inert gas which is safe for emitting at the tailpipe.

Lean NO$_x$ traps rely on the engine running under lean conditions for a finite duration of time before running for a short period of fuel-rich operation, during which the NO$_x$ trap is refreshed. If the exhaust mixture does not become rich then the NO$_x$ trap reduces in effectiveness and will eventually provide no useful function, resulting in tailpipe NO$_x$ emissions increasing. Frequent cycles of rich running are required to regenerate the NO$_x$ trap, with an associated small increase in fuel consumption.
UNLEADED VERSUS PREMIUM UNLEADED PETROL

Standard unleaded and premium unleaded fuels available at service stations in Australia have different properties which can potentially affect the operation of an engine.

RON

RON is an acronym for Research Octane Number, sometimes referred to as Octane Rating. It is a measure of a fuel’s ability to resist knocking when used in an engine.

Petrol can be compressed up to a limit when the pressure and temperature causes it to auto-ignite before the spark plug fires. If this occurs, it can be observed as a knocking noise from the engine and if allowed to continue for an extended period of time will damage the engine.

Higher RON fuels enable higher compression ratios to be used due to their higher resistance to engine knocking.

Fuel Sulfur

Standard 91 RON unleaded petrol (ULP) has a maximum permitted sulfur content level three times higher than that of 95 RON premium unleaded petrol (PULP). Australia’s petrol fuel quality standards lag behind European standards with regard to sulfur content. Fuel sulfur concentration is often referred to by either of the following equivalent units: mg/kg or ppm (part per million).

Table 10 summarises the minimum RON standard and maximum allowable fuel sulfur content for both Unleaded Petrol (ULP) and Premium Unleaded Petrol (PULP) available in Australia.

<table>
<thead>
<tr>
<th>RON AND SULFUR SPECIFICATIONS</th>
<th>Standard Unleaded Petrol (ULP)</th>
<th>Premium Unleaded Petrol (PULP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RON (Minimum)</td>
<td>91</td>
<td>95</td>
</tr>
<tr>
<td>Sulfur (Maximum)</td>
<td>150 mg/kg or ppm</td>
<td>50 mg/kg or ppm</td>
</tr>
</tbody>
</table>

Table 10 – RON and Sulfur Fuel Specifications of ULP and PULP in Australia

91 RON ULP versus 95 RON PULP: Impact on Efficiency

91 RON ULP and 95 RON PULP have similar energy content so neither offers a direct efficiency benefit through release of energy during combustion.

Engine efficiency is proportional to the compression ratio of the engine. As 95 RON fuel allows the use of a higher compression ratio, PULP enables engines to be designed with higher efficiency.

Vehicle manufacturers may state that a certain fuel RON rating is recommended for use or acceptable for use. This choice of language is key in understanding how the engine is expected to perform with different fuels.

A modern high performance vehicle may be recommended for use with 95 RON fuel because it has been optimised for use with this grade of fuel. Using the lower octane rating fuel of 91 RON may be acceptable for operation but it is likely that with these fuels the engine must retard the spark, valve and/or fuel timing to prevent knocking. This reduces engine efficiency as there is less time for combustion of fuel to occur.

Vehicles that have been designed and optimised for 91 RON ULP fuel may experience a small improvement in efficiency if 95 RON PULP is used if they have been calibrated by the manufacturer to operate on a range of fuel RON grades. Not all vehicles with an ECU and knock detection and control have this capability, particularly those that are a more than a few years old.

Longer term secondary impacts of fuel type on efficiency are the use of fuel detergent additives that maintain cleanliness of fuel injector and valves over a long duration. Use of fuel additives is independent of the RON rating and is specific to a fuel manufacturer’s particular fuel specification.
For new engines the benefits of detergent additives from fuel types is much less obvious than when compared with an aged vehicle which has been used for long period of time, as engine cleanliness is a gradual degradation in efficiency. For engines that have been run for a long duration on lower quality fuel, high fuel additive concentrations offer the potential to restore efficiency or power lost due to deposits on valves, inside the injectors and the combustion chamber.

<table>
<thead>
<tr>
<th>Impact</th>
<th>Attributed to</th>
<th>Mechanism(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increases Efficiency</td>
<td>RON rating</td>
<td>95 RON fuel enables higher compression ratio, hence higher efficiency. An engine designed for 95 RON fuel may de-rate its performance to prevent knocking when running on 91 RON fuel.</td>
</tr>
<tr>
<td>Maintains Efficiency</td>
<td>Fuel detergent additives</td>
<td>Use of fuel additives can maintain the cleanliness of injectors and valves, preventing a reduction in power or efficiency.</td>
</tr>
<tr>
<td>Decrease Efficiency</td>
<td>High fuel sulfur levels</td>
<td>De-sulfation of exhaust aftertreatment to maintain acceptable tailpipe emissions requires increased fuel use.</td>
</tr>
</tbody>
</table>

**Table 11 – Impact of Fuel Type on Efficiency**

**91 RON ULP versus 95 RON PULP: Impact on Power and Torque**

Torque is generated in an engine as the fuel and air combust and cause a rise in pressure, which forces the piston to move. Maximum torque occurs at the maximum pressure. The faster the rate that this torque can be generated, the more power is available.

At the design phase, a 95 RON fuel allows a higher compression ratio to be used, therefore enabling an increase in torque and power.

For engines that have been designed specifically for use with 95 RON fuel, using 91 RON will likely result in engine knock occurring. When this is detected by the ECU it automatically retards the ignition timing (reduces the spark advance) which lowers power and torque produced by the engine. It is not recommended that 91 RON fuel be used in vehicles requiring 95 RON.

Figure 18 demonstrates the relationship between engine torque and spark advance timing for an engine operating at a constant speed and wide open throttle.

![Maximum Brake Torque Timing (MBT)](image)

<table>
<thead>
<tr>
<th>Engine Torque</th>
<th>Spark Advance Increasing</th>
</tr>
</thead>
<tbody>
<tr>
<td>95 RON</td>
<td></td>
</tr>
<tr>
<td>91 RON</td>
<td></td>
</tr>
</tbody>
</table>

**Source:** ABMARC

**Figure 17 – Impact of Spark Advance on Torque**

Maximum Brake Torque Timing (MBT) is the spark advance timing that enables maximum torque to be developed by the engine.

Using 95 RON fuel enables the engine to operate more often at, or near the spark advance required for MBT.

When using 91 RON fuel the spark advance must be reduced to prevent engine knock, moving further away from MBT which reduces the engine torque.

**Source:** ABMARC
91 RON ULP versus 95 RON PULP: Impact on Regulated Pollutants

Only by considering the whole vehicle as an interactive system can the impact of fuel choice be assessed against the tailpipe emissions of passenger cars and light duty petrol vehicles.

The development of petrol engine technology to reduce CO\textsubscript{2} emissions has followed a similar path to that of diesel technology. The use of direct fuel injection reduces CO\textsubscript{2} but increases NO\textsubscript{X} and PM emissions. Increased use of exhaust gas recirculation reduces NO\textsubscript{X} with an increase in PM and a small increase in fuel consumption (and therefore CO\textsubscript{2}). Particulate filters offer a solution to reducing tailpipe particulate emissions.

Higher compression ratio engines have been developed which offer improved efficiency, lowering CO\textsubscript{2} emissions but they require higher RON fuels. Although able to run on lower RON fuel, doing so increases their actual CO\textsubscript{2} emission via the decreased efficiency associated with retarding spark timing. This highlights the importance of using the recommended RON fuel for the engine.

A constant throughout the development of petrol engine technology has been the use of Platinum Group Metals (PGM) in exhaust aftertreatment technology. As legislated emissions limits have decreased, increased importance is placed on the efficient operation of the aftertreatment system. In the USA and Europe, as Diesel emissions limits have decreased they have done so with an associated reduction in the sulfur content in the fuel. Australian Diesel sulfur limits have followed this trend too, with current Diesel sulfur limits at 10 ppm maximum.

Fuel Sulfur Impact on Catalytic Converter Efficiency

During combustion, fuel-borne sulfur is converted into oxides of sulfur (SO\textsubscript{X}).

SO\textsubscript{X} is more readily absorbed onto the active surfaces of Three Way Catalysts and Lean NO\textsubscript{X} traps than the other exhaust gases, resulting in tailpipe emissions increasing. The catalyst becomes contaminated by sulfation as the sulfates adsorbed onto the catalyst surface reduce the effective surface area required for conversion of other regulated pollutants, resulting in tailpipe emissions increasing.

This sulfate absorbed surface is thermally stable and so extended periods of rich running is required by the engine to produce the temperature needed to decompose the sulfates and refresh the catalyst. This process is known as de-sulfation. The increased fuel injected to cause rich running results in increased in fuel consumption with an associated increase in CO\textsubscript{2} production.

As NO\textsubscript{X} limits are reduced, fuel sulfur may become a limiting factor in achieving low emissions in real world driving in Australia that allows up to 150 ppm sulfur fuel.

Table 12 summarises the impact of fuel borne sulfur on the emission of regulated pollutants for petrol engines.

<table>
<thead>
<tr>
<th>IMPACT OF FUEL SULFUR ON REGULATED POLLUTANTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impact</td>
</tr>
<tr>
<td>Increased tailpipe emissions</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Reduced Fuel Economy</td>
</tr>
<tr>
<td>Increased CO\textsubscript{2}</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

Certification Fuel and Market Available Road Fuel: USA

If there is a difference in sulfur content between the fuel used to certify a vehicle and that normally used as a road fuel, then the real world vehicle emissions may be quite different from those measured during certification.

In the USA, certification fuels produce more repeatable results for vehicle emissions than commercially available road fuel. This is because the specification of certification fuel is much tighter and reduces the variability in quality seen in market fuel, particularly with regard to sulfur content. The future intent is to use certification fuel that more closely replicates commercially available fuel to reduce this difference.

91 RON ULP versus 95 RON PULP: Emissions Systems Performance & Durability

Long term effects on emissions due to the use of fuels containing 150 ppm sulfur concentration together with modern (Euro 5/ Euro 6) vehicles has not been tested and studied as it is not a situation experienced outside of Australia. In Europe, USA and Japan, maximum permitted fuel sulfur levels have since 2005 been reduced to 80 ppm or less and so 150 ppm sulfur fuel has no relevance to modern engine development in those markets. From 2017 onwards, maximum permitted sulfur content in petrol in USA, Europe and Japan is 10 ppm, with 20 ppm being permitted in California.

Various investigations have been made into the impact of sulfur levels on tailpipe emissions and economy with older vehicles at the time when fuel quality was under review in different regions. These studies can be used to gain an appreciation of a vehicle’s immediate sensitivity to fuel sulfur levels together with an understanding of the potential long term impact on durability.

Short and Long-term Fuel Sulfur Impact on Emissions

The following results are based on the testing of a fleet of 12 vehicles for the Coordinated Research Council (CRC) and CONCAWE in 2010. The vehicles were manufactured during 2000-2001 to USA Tier 2 LEV, ULEV and SULEV standards. They were tested with varying levels of fuel sulfur content with new and aged catalytic converters to investigate and understand the short and long-term effect of fuel sulfur on various pollutant emissions.

The drive cycles used to determine the vehicle emissions were the Federal Test Procedure (FTP) and US06; both used for approvals to emissions standards in the USA. The FTP and US06 cycles reflect conditions experienced during inner city and highway driving.

Chart 2 shows the production of regulated pollutants at various fuel sulfur concentrations using new catalytic converters to determine the short-term effect of fuel sulfur on tailpipe emissions. The data is based on the fleet averaged emissions across the 12 test vehicles.

It can be seen that as sulfur concentration is reduced from 150 ppm (Australian 91 RON ULP sulfur limit) to 50 ppm (Australian 95 RON PULP sulfur limit), a reduction in CO, NOX and NMHC is observed. This reduction continues as sulfur concentration decreases below 50 ppm, suggesting that further reduction of noxious emissions could be enabled by reducing fuel sulfur below the 50 ppm limit of PULP fuel used in Australia. It is reinforced by the decisions of USA, Europe and Japan to implement fuels standards with a maximum limit of 10 ppm from 2017 onwards.

Chart 3 shows the average emissions results based on the 12 vehicles tested with aged catalytic converters. This provides an indication of the impact that fuel sulfur has on a vehicle’s ability to conform to emissions standards throughout its useful life; which is a regulated requirement.
Although non-methane hydrocarbon emissions are virtually unchanged by the ageing of the catalytic converters, there is an increase in base level NO\textsubscript{X} and CO emissions compared with that with the new catalytic converters. It is also apparent that there is a greater reduction in NO\textsubscript{X} when reducing sulfur levels from 150 ppm sulfur fuel to 50 ppm for these used catalytic converters in Chart 3 than the new ones in Chart 2.

This suggests that aged vehicle emissions have a greater sensitivity to fuel sulfur content than new vehicles. Charts 2 & 3 also show that at very low sulfur concentration of 3 ppm the NO\textsubscript{X} emissions are very similar for used and aged catalysts, further highlighting the benefit that very low sulfur fuels offer to emissions reduction.

**Aged Catalytic Converters**

![Graph showing emissions vs fuel sulfur concentration for aged catalytic converters.](chart)

Sources: CRC E-60 NH\textsubscript{3} emissions from late model vehicles, 2010, & ABMARC

Chart 3 - Impact of fuel sulfur on emissions of vehicles using aged* catalytic converters

Chart 4 summarises the average reduction in emissions attributed to the reduction from 150 ppm to 50 ppm fuel sulfur across these 12 vehicles. This reflects the potential emissions reduction that could be achieved by using 50 ppm fuel as opposed to 150 ppm.

**Ageing of catalytic converter**

![Graph showing percentage change in emissions.](chart)

Sources: CRC E-60 NH\textsubscript{3} emissions from late model vehicles, 2010, & ABMARC

Chart 4 - Reduction in emissions for new and aged* catalytic converters with 50 ppm Sulfur Petrol.

*Catalysts were aged using 0.2 ppm Sulfur fuel to an equivalent of 192,000 km (considered useful vehicle life for USA Tier 2 durability standards).

A very low sulfur fuel was used for ageing the catalytic converters and therefore the ageing they were subjected to was primarily due to the cyclic temperatures experienced reducing the catalyst conversion efficiency. For Europe, Japan and the USA this may be acceptable due to the use of sub 20 ppm fuel sulfur levels but it is not representative of the real ageing that would be experienced if driven 192,000 km with 150 ppm sulfur Australian ULP. It is therefore
anticipated that the long-term impact of ageing with Australian 91 RON ULP with 150 ppm sulfur may be much more detrimental to vehicle emissions than indicated in this study.

Chart 4 shows that significant emissions reduction is offered by using PULP Australian fuel rather than ULP due to the lower sulfur concentration. It also shows that this benefit increases with vehicle age, promoting the long-term benefit that the use of lower sulfur fuel would have over the entire lifetime of vehicle use.

The Manufacturers of Emission Controls Association (MECA) commissioned a separate study with similar outcomes, in their 2013 publication “The impact of gasoline fuel sulfur on catalytic emission control systems”.

In this study, 12 different vehicles conforming to Tier 2 LEV standards in the USA were tested with various fuel sulfur levels including 50 ppm and 150 ppm. Two sets of catalytic converters were tested in each vehicle; the first aged to the equivalent of 16,000 km and the second aged to the equivalent of 160,000 km. 160,000 km is a durability requirement introduced with Euro 5 and is therefore the regulated service life for Euro 5 emissions standard onwards.

Chart 5 summarises the fleet averaged reduction in NO\textsubscript{X} emissions attributed to the reduction from 150 ppm to 50 ppm fuel sulfur for two different ages of catalytic converter.

In both cases, the study demonstrates that the reduction in NO\textsubscript{X} emission is enabled by the reduction in fuel sulfur from 91 RON ULP to 95 RON PULP levels. The percentage reduction is greater in magnitude than that measured by the CRC in their study shown in Chart 4, and reinforces the significance of fuel sulfur to efficient catalytic converter operation and its impact on real world emissions. As in the previous study, the benefits of using lower sulfur fuel are greater for older vehicles that have accumulated greater distance and is due to the catalyst ageing increasing its sensitivity to sulfur.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{chart5.png}
\caption{Ageing of catalytic converter}
\end{figure}

\textbf{Sources:} CRC Sulfur/LEV Program, CEC Project No. E-42, Coordinating Research Council, 1997 & ABMARC

\textbf{Euro 6c: Use of Market Fuel for Real World Driving Emissions}

The impact of ULP versus PULP on emissions will be more significant if Euro 6c emission standards are adopted in Australia. Euro 6c will determine NO\textsubscript{X}, UHC, CO and Particulate emissions using Real Driving Emissions (RDE) measurement as well as a laboratory based drive cycle. RDE is enabled by new Portable Emissions Measurements Systems (PEMS) technology which provides accurate measurement of emissions on the road, with the system fitted to the vehicle during test.

For the first time, Euro 6c will require light vehicle emissions to be measured whilst driving on public roads. The legislation surrounding how RDE testing will be applied to the Euro 6 standard is currently being finalised. However, the interim (draft) European Commission document G3 1515125 PE RDE Annex 1 Part 1/3 states that the fuel used for the RDE testing “shall be within the specifications issued by the manufacturer for vehicle operation by the customer”. Europe has a minimum fuel standard of 95 RON with a maximum 10 ppm fuel sulfur concentration.

As both Australian ULP and PULP conform to many manufacturer’s specifications for current vehicles, it is assumed that for Euro 6c, the RDE test could be conducted using 91 RON ULP. If this were to be the case, pollutant emissions measured during the RDE test with 91 RON ULP could be much higher in Australia compared to Europe and conformance with the Euro 6c emissions standard may not be possible.
CONCLUSIONS
In the last 40 years the increasing complexity of engines and aftertreatment technology has enabled a dramatic reduction in harmful pollutants emitted from petrol light duty vehicles whilst improving the power output and fuel efficiency for a given engine size.

A commitment to reduce vehicle impact on the greenhouse effect through the use of GHG, CO₂ and Fuel Efficiency standards has resulted in new fuelling and engine technology being developed, with the additional benefit of improving fuel economy. The USA, Japan, and Europe each have their own separate Fuel Efficiency/CO₂ emission standards which cannot be directly compared due to differences in vehicle mix, drive cycle used to determine emissions, calculation methods and units. Although Japan does not formally have legislation that regulates CO₂ production, its use of energy conservation laws and its ‘Top Runner’ legislation aims to limit the production of CO₂ through use of a minimum target of fuel economy.

Japan, the USA, and Europe regulate the vehicle emissions of the following pollutants; NOx, unburnt hydrocarbons, CO, and particulates. In Japan, a particulate emission limit only applies to those petrol vehicles utilising lean-burn Direct Injection. The latest emissions standards have more stringent limits on the production of pollutant and CO₂ emissions, as well as increased durability requirements. Australia has adopted the European ‘Euro’ emissions standards and enacted these through the Australian Design Rules (ADR) regulation, typically lagging the Euro standards by around three years.

The introduction of more stringent emission legislation in the 1990s resulted in carburettors being replaced by fuel injection in order to improve control of combustion within an engine. Fuelling technology has since developed more complex systems that allow increasingly precise control of timing and quantity of fuelling. This enables a reduction in pollutant emissions and reduction in CO₂ from the engine through improved combustion and increased engine efficiency.

A spark ignition engine requires fuel, air and a spark plug as a source of ignition to initiate combustion. Accurate control of these three items is essential to maximise the power and torque an engine produces and limit the pollutant and CO₂ emissions.

Increased engine efficiency can be achieved by using a higher compression ratio, which raises the compression of the fuel and air mixture prior to combustion. An unwanted effect of increased compression ratio is engine knocking, a phenomenon which involves the fuel and air mixture igniting prior to the spark plug firing, causing combustion to occur before it was intended. This can damage the engine, ultimately leading to engine failure if left uncontrolled. A higher compression ratio is enabled by the use of higher octane fuels; higher RON fuels are more resistant to engine knocking. Therefore, higher octane fuels may be necessary to enable more fuel efficient engines to be produced.

If high compression ratio engines are fuelled with lower octane fuel, engine knocking can occur and is detected by a knock sensor. To eliminate knocking the ignition timing or fuel timing is retarded by the central Engine Control Unit (ECU) which has the impact of reducing power and torque. Therefore, for a given power requirement of the engine, fuel economy reduces and CO₂ production per unit of work will increase. 95 RON fuel is more resistant to engine knock than 91 RON and so the need to retard ignition or fuel timing is negated, offering CO₂ and fuel consumption reduction for modern engines when compared to 91 RON fuel.

Direct Injection (DI) has grown in use since 2004 due to the improved fuel efficiency it offers over Multi Point Fuel Injection (MPFI), enabling vehicle manufacturers to comply to more stringent CO₂ regulation. Currently, around 50% of petrol engine light duty vehicles sold in Australia utilise DI fuel systems. Further benefits of DI engines are possible through the use of lean burn combustion strategies but these have not been fully realised due to durability issues. The use of lean-burn strategies in DI engines appears to be confined to Japan at present.

Improvements in engine technology have reduced pollutant emissions and improved fuel efficiency but due to the very short time period for combustion of fuel, physical characteristics of an engine and the variable conditions that an engine is required to operate in, perfect combustion of fuel within an engine does not occur in practice. Consequently, harmful pollutants cannot be eliminated from the exhaust of an engine.

Exhaust Aftertreatment is required to reduce the pollutants emitted by the engine to lower levels at the tailpipe to satisfy emission standards. The key component of an exhaust aftertreatment system in a petrol engine is the Three Way Catalytic converter (TWC) which converts the harmful products of combustion into less harmful substances emitted at the tailpipe. The catalytic converter promotes the following chemical reactions which occur on the catalyst surface; oxidation of CO and unburnt hydrocarbons and reduction of NOx. Catalytic converters use precious metals acting as a catalyst, lowering the energy required for the harmful pollutant gases to react. A minimum operating temperature, known as the light-off temperature, is required to initiate these reactions and below the light-off
temperature the catalytic converter pollutant conversion is negligible. Fuel: air ratio of the exhaust gas must be within specific limits to ensure efficient conversion of pollutants, hence requiring the accurate and fast control of fuelling and combustion facilitated by modern engine designs.

A by-product of exhaust aftertreatment is increased CO₂ production; the reactions that occur within a catalytic converter all ultimately produce CO₂. This highlights the fact that at times emissions standards and fuel efficiency / CO₂ standards can place conflicting pressure on the design of vehicles. A compromise is made during engine development to meet both requirements, and optimise the overall outcome.

The use of Exhaust Gas Recirculation (EGR) is an engine technology which reduces NOₓ by recirculating inert exhaust gas back into the air intake, thereby reducing the flame temperature during combustion (high combustion temperatures contribute to NOₓ formation). This, however, has the effect of decreasing engine efficiency, increasing fuel consumption/ CO₂, and increasing particulate matter.

Modern engines utilise a number of sensors that provide information to the Engine Control Unit (ECU) which determines the optimum operating setting for improved combustion and pollutant conversion within the TWC. As a result of the increased particulate emission from DI vehicles compared to MPFI only engines, some manufacturers are using a combined system of MPFI and DI, offering improved performance in the compromise between reduced CO₂ and pollutant emissions. The increased use of Direct Injection has been accompanied by a Particulate Mass emission limit from Euro 5, and from Euro 6 an additional Particulate Number limit. Both of these promise to have further positive impact on public health but further increase complexity of engine operation. Exhaust aftertreatment systems have the addition of particulate filters to meet these standards, which although they can filter as much as 90% of particulate matter by mass from the exhaust gas, still allow very fine particles to pass through the filter pores into the environment. These small sized particles can be easily ingested into the human body, and have resulted in the particulate number limits being introduced into Euro 6c emissions standard.

Downsizing is an increasingly used term, signifying the improvement in engine efficiency through the use of a holistic design and optimisation process for all of an engine’s constituent parts. It enables engine size to be reduced whilst maintaining power and torque output and is increasingly being achieved by the use of turbocharging &/or supercharging. For many vehicles the result is an improved driver experience accompanied by an improvement in fuel efficiency and CO₂ reduction.

The result of developments in engine, fuelling, and exhaust aftertreatment technology is an increased reliance on higher quality fuel. High quality fuel is required for the engine to operate cleanly and efficiently, and engine operation has to be integrated with the needs of the aftertreatment system. If one of these three categories (fuel, engine or exhaust aftertreatment) has a reduction in quality or effectiveness, it will result in an increase in emissions.

In the USA, Japan, and Europe there has been an alignment of fuels standards with emissions standards, particularly with regard to the permitted maximum sulfur concentration in fuel. From 2017 all of these regions will have a maximum fuel sulfur concentration of 10 ppm or below, whereas Australian fuel quality standards allow sulfur of up to 150 ppm in 91 RON ULP.

The high sulfur concentration in 91 RON ULP is known to significantly increase tailpipe pollutant emissions through the mechanism of catalyst deactivation by sulfation. Although de-sulfation of a catalytic converter can restore its function of converting pollutants, it is achieved by increasing fuelling which reduces efficiency and increases CO₂ production. It also is a temporary solution, requiring frequent de-sulfation cycles during a vehicle’s lifetime. A side effect is also a reduction in catalytic converter durability due to the temperature aging effect. Studies have shown that even with catalytic converters aged with very low sulfur content fuel, vehicle emissions are more sensitive to fuel sulfur concentration than new vehicles. With the increased durability requirements of future emissions standards this may present an additional challenge to the 150 ppm sulfur content limit in the current ULP fuel standard.

The potential benefit of 95 RON PULP over 91 RON ULP fuel for improving vehicle emissions and CO₂ production can be significant, due to the benefits of reduction in fuel sulfur concentration and increased fuel octane rating. Reduction in NOₓ, CO and UHC emissions as great as 13 % for new catalytic converters and 29 % for end of life catalytic converters have been demonstrated and attributed to the lower sulfur concentration.

The increased octane rating of 95 RON PULP fuel enables higher compression ratio engines to be developed, increasing engine efficiency and therefore reducing vehicle CO₂ production. In Europe, the minimum octane petrol is 95 RON and so European vehicle manufacturers design engines with compression ratios that make use of its increased resistance to knocking. When these vehicles are fuelled using Australian 91 RON petrol the engine must de-rate its performance to prevent engine knock through the adaption of ignition timing, valve timing and/or fuel timing. The impact of these adaptions is that engine efficiency decreases, increasing the CO₂ production for a given engine power requirement.
A great challenge is posed by the introduction of the European Euro 6c standard. Its requirement to use real world driving emissions (RDE) for vehicle type approval places an increased importance on real world operation. Current evidence suggests that market relevant fuel shall be used for approval tests. Since Australia’s fuel sulfur concentration is up to 15 times that of Europe, this could pose a significant threat to demonstration of compliance with the standard in Australia if the Euro 6c emissions standard were to be adopted in full and 91 RON ULP fuel used.
APPENDIX: EMISSIONS AND FUELS REGULATIONS

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GLOBAL AND AUSTRALIAN OVERVIEW

Since the 1970s the harm caused by vehicle emissions has been well established, such that today this topic is now firmly embedded in the minds of the general public, health officials, and policy makers throughout the world.

Regulations for emissions and fuels standards have required vehicle manufacturers to develop new technologies that take advantage of the better fuel quality. Consequently today’s new vehicles emit a tiny proportion of the emissions produced when the first vehicle emissions legislation was introduced in the USA more than 40 years ago.

Development of the strictest legislation has mainly been led by the USA, Europe, and Japan, with many other countries adopting these regulations or developing their own regulations based on the knowledge gained from these regions. Australian emissions limits defined by the Australian Design Rules Regulations (ADRs) are equivalent with those defined in the European (Euro) regulations, albeit with a different timeframe for implementation.

Due to the variety in size and payload of different vehicles, emissions regulations are tailored to levels that are appropriate to the category of vehicle being considered. This summary concentrates on those regulations relevant to light-duty petrol engined vehicles, including passenger cars.

Emissions legislation is separated into two main branches: pollutants that are harmful in small concentrations (Oxides of Nitrogen (NOx), Particulate Matter, and Carbon Monoxide (CO)) and CO$_2$ (which although harmless to humans at low concentrations contributes to the greenhouse effect). In recent years Particulate Mass has been a focus as studies have suggested they have carcinogenic effects, and Oxides of Nitrogen have been shown to cause low level smog with resultant adverse health effects. Particulate Number is becoming more of a concern as the total Particulate Mass emitted from vehicles is reducing, with vehicles producing less large, wet, soot particles; those particles emitted by newer vehicles now tend to be of smaller size, and have been shown to be more easily ingested into the human body through respiration.

Fuel Standards

In Europe, the USA, and Japan, as emissions limits have been reduced, fuel quality standards have been adjusted to allow vehicles to achieve the required emissions targets. In recent years a key amendment in US, European and Japanese fuels standards has been the reduction in sulfur concentration. Current Australian fuels standards permit the use of 150 ppm sulfur content which has not been allowed in the USA, Japan or Europe since prior to 2005.

The introduction of 80 ppm Sulfur maximum and 30 ppm Sulfur average by the US EPA facilitated the introduction in 2007 of Tier 2 vehicle emission legislation. Lower limits in California have been enforced by the Reformulated Gasoline Regulations, with a current 15 ppm average and 20 ppm maximum. In Europe, a 50 ppm Sulfur maximum was introduced facilitate the introduction of Euro 4 emission limits and a 10 ppm limit to facilitate the introduction of Euro 5.
Emissions Standards

In the USA, Japan, and Europe for many years there has been a commitment to reduce CO₂ and other harmful pollutant emissions from vehicles. CO₂ is known to contribute to climate change and particulate emissions from vehicle tailpipes are hazardous to human health.

In the quest to reduce CO₂ emissions and improve fuel consumption, a greater proportion of petrol vehicles now use Direct Injection fuel systems, which offer around 10% efficiency improvements on previous engine technology (see Multi Point Fuel Injection). Direct Injection introduced a new emissions challenge as they increase production of particulate emissions compared to MPFI. From Euro 5 emissions standard onwards, limits were introduced to control particulates. Originally these controls focussed on measurement of Particulate Mass (PM), but more recently, the number of particles (PN) that are emitted from an engine have been under scrutiny, as the smaller particulates also offer potential health risks (albeit constituting a very small mass). Consequently, the most modern legislation incorporates limits for Particulate Number and Particulate Mass emissions.

To compare the different emissions standards, data presented has been converted into units and parameters consistent with Australian emissions regulations wherever possible.

USA Emissions Standards

Since the 1970s Californian state legislation has enforced stricter emissions limits for vehicles in the USA. Today two parallel standards exist: US Federal legislation formed by the Environmental Protection Agency (EPA) and more stringent Californian state legislation formed by the Californian Air Resources Board (ARB). Table 13 provides an overview of the standards.

<table>
<thead>
<tr>
<th>Legislative Body</th>
<th>Standard</th>
<th>Vehicle Categories</th>
</tr>
</thead>
<tbody>
<tr>
<td>US Federal EPA (Environmental Protection Agency)</td>
<td>Tier 2 Tier 3</td>
<td>All Light Vehicles up to 8500 lbs</td>
</tr>
<tr>
<td>Californian ARB (Californian Air Resources Board)</td>
<td>LEV I LEV II</td>
<td>LEV (Low Emission Vehicle) ULEV (Ultra Low Emission Vehicle) SULEV (Super Ultra Low Emission Vehicle) PZEV (Partial Zero Emission Vehicle)</td>
</tr>
</tbody>
</table>

The ARB differentiates between vehicles emissions by categorising them as LEV (Low Emission Vehicle), ULEV (Ultra Low Emission Vehicle), SULEV (Super Ultra Low Emission Vehicle) or PZEV (Partial Zero Emission Vehicle). PZEV vehicles attain the same emission levels as SULEV but also exhibit near zero evaporative emissions when the vehicle is not in use.

Table 14 shows the timeline for implementation of emission standards by the EPA and ARB. From 2004 there was a phased introduction of Tier 2 legislation for light duty passenger cars, reaching full implementation in 2008. Tier 2 legislation groups CO, NOₓ, PM and NMOG emissions into classifications referred to as bins. Individual vehicles produce emissions that classify them as situated in one of these bins, from which a fleet average is determined for each manufacturer.

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</thead>
<tbody>
<tr>
<td>EPA</td>
<td>Tier 2 Phase-in</td>
<td>Tier 2</td>
<td>LEV II</td>
<td>LEV III Phase-in</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>ARB</td>
<td>LEV II Phase-in</td>
<td>LEV II</td>
<td>LEV III Phase-in</td>
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</table>

The Californian emissions standards are more stringent than those of the EPA. From 2005 to 2014 the ARB phased in the replacement of their LEV I standard with LEV II. Chart 7 compares the current EPA Tier 2 and ARB LEC fleet average emissions categories with forthcoming tighter Tier 3 limits.
Use of Non Methane Organic Compounds (NMOG) by the EPA and ARB rather than Non-Methane Hydrocarbons (NMHC) as used in European standards is because organic compounds contained in unburnt fuel (other than solely hydrocarbons) can also contribute to low-level ozone depletion.

The EPA set a fleet average NO\textsubscript{X} limit of 0.07 g/mile (0.044 g/km) for Tier 2, giving manufacturers the flexibility to produce some vehicle models that exceed the limit as long as their fleet average satisfies the requirement. During the phased introduction of Tier 2, a temporary limit of 0.3 g/mile NO\textsubscript{X} (0.188 g/km) was permitted from 2004 to 2007.

The forthcoming introduction of Tier 3 standards has harmonised the Federal emission standard with Californian emission standard LEV III, meaning vehicles sold in any of the US states will conform to the same effective standard in the future. CO limits have effectively been frozen at levels equivalent to Tier 2 and during the phase-in of Tier 3 there is a progressive reduction in allowable fleet average combined NO\textsubscript{X} + NMOG emissions to the final limit shown in Chart 8 below.
European Gaseous Emissions Limits Standards

Chart 9 shows the progressive reduction in emission limits allowed by the Euro 2 to Euro 6 standards. This is displayed on the same axis scales as that used for US and Japanese standards for ease of comparison.

![Euro Emissions Limits Chart](chart9.png)

Source: UN ECE

Chart 9 – Euro Emissions Limits

European Particulate Emission Limits for Direct Injection Petrol Vehicles

Chart 10 shows that there has been a large reduction in the limits of THC, NO\textsubscript{x} and CO emissions over the last 15 years such that the latest Euro 6 standard has no further reduction in limits for these pollutants. Euro 5 introduced a limit of particulate emissions by use of a mass limit in grams per km travelled on the New European Drive Cycle. A phase-in of Euro 5 legislation allowed an increased particulate mass emission of 0.05 g/km until the stricter limit of 0.045 g/km applied for Euro 5b. The introduction of the latest Euro 6 standard started with Euro 6b which introduced, in addition to particulate mass, a limit in the number of particulates emitted per km. Although exact timing is not yet finalised, Euro 6c drastically reduces this limit by an order of magnitude to $6 \times 10^{11}$ particles per km. This certainly will require the use of improved engine and aftertreatment vehicle technology to satisfy this criterion.

![European Particulate Limit Chart](chart10.png)

Source: UN ECE

Chart 10 – European Particulate Mass and Number Emissions Limits for Direct Injection Petrol Vehicles
Table 15 shows the timeline for implementation of the Euro emissions standards in Europe. Separate timings for type approval of new vehicles before all vehicles are required to comply allows phased introduction of the standards.

### European Petrol Emissions Standards Timeframe

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</thead>
<tbody>
<tr>
<td>New Vehicles</td>
<td>Euro 4</td>
<td>Euro 5a</td>
<td>Euro 5b</td>
<td>Euro 6b</td>
<td>Euro 6c</td>
<td></td>
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<tr>
<td>All Vehicles</td>
<td>Euro 3</td>
<td>Euro 4</td>
<td>Euro 5a</td>
<td>Euro 5b</td>
<td>Euro 6b</td>
<td>Euro 6c</td>
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</table>

Source: UN ECE

### Drive Cycles for Euro Standards

Up to Euro 5b, the NEDC (New European Drive Cycle) has been used as the legislated drive cycle to determine vehicle emissions in laboratory tests. This test cycle as used today was designed in 1990 and incorporates urban and extra-urban sections to emulate city, highway and freeway driving.

Over time the design of modern cars has been optimised for reducing emission according to the conditions experienced in the NEDC and yet real world traffic and driving conditions have changed. This has given rise to claims that fuel economy and emissions in the real world are not adequately reflected by the NEDC measurements.

The introduction of the WLTP (Worldwide Harmonised Light Vehicle Test Procedures) aims to address this and is the chosen laboratory drive cycle to be used for determining CO$_2$ and pollutant emissions from Euro 6c onwards. The WLTP has been developed by studying vehicle usage across a number of cities in the world and aims to provide a significantly more realistic drive cycle for testing and comparative analysis vehicles.

Euro 6c standards also sees the introduction of Real Driving Emissions (RDE) for NO$_x$, CO, and PN to measure emissions and ensure in-service conformity. The RDE concept is a departure from the traditional laboratory-based emissions measurement. It uses Portable Emissions Measurement Systems (PEMS) to measure pollutant emissions from a vehicle performing real-world driving. A schedule determines minimum durations that must be achieved at various speeds in order to qualify as a valid RDE test. RDE testing has only recently become enabled by the development of high accuracy and repeatable equipment that is portable enough to mount in, on, or behind a vehicle.

### Australian Emissions Standards Timeframe

From the early / mid 1970s through to 1999 Australia adopted the US FTP (Federal Test Procedure) emissions standards. Since 2003 Australia has harmonised its vehicle emissions standards with the European "Euro" standards through the Australian Design Rules (ADR), typically implementing the Euro standards with a lag of around three years.

Table 16 shows the timeline for adoption of Euro emissions standards. Implementation of Euro 6 emissions standards are currently under consideration at the time of publication.

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</thead>
<tbody>
<tr>
<td>New Vehicles</td>
<td>Euro 3</td>
<td>Euro 4</td>
<td>Euro 5a</td>
<td>Euro 5b</td>
<td></td>
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<tr>
<td>All Vehicles</td>
<td>Euro 2</td>
<td>Euro 3</td>
<td>Euro 4</td>
<td>Euro 5b</td>
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</table>

Source: Federal Register of Legislation
Japanese Emissions Standards

Japanese emissions standards have taken a different approach to the Euro standards. In 2000, very stringent limits of NMHC, NO\textsubscript{x} and CO were set. Over time, effective emissions reduction has been made by testing vehicles using drive cycles that are progressively more representative of actual use. From 2000 through to 2017, a combination of two drive cycles is used to test a vehicle under cold-start and hot-start conditions. The weighted mean of the emissions measured during these drive cycles is used to determine the overall vehicle emissions and are assessed against the limit values.

Although the absolute pollution limits have not changed over the period 2005 - 2016, choice of drive cycles used has been modified, effectively making it harder to achieve these limits.

Japanese PM limits for Lean Burn Direct Injection Petrol

A Particulate Mass emission limit of 0.05 g/km exists in Japan but applies only to Direct Injection Petrol engines that operate in Lean Burn mode requiring the use of NO\textsubscript{x} reduction catalysts. No particulate emissions limits apply to any other petrol engine passenger cars at present.

Japanese Emissions Standards Timeframe

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</tr>
</thead>
<tbody>
<tr>
<td>All Vehicles</td>
<td>11 mode &amp; 10-15 mode</td>
<td>10-15 mode &amp; JC08</td>
<td>JC08 &amp; JC08</td>
<td>WLTP</td>
<td></td>
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</tbody>
</table>
Alignment of Australian Fuels and Emissions Standards

Figure 18 below shows that in Europe, maximum fuel sulfur content has been reduced from 50 ppm to 10 ppm to facilitate the introduction of Euro 5 emissions standard for all vehicles. This has resulted in such a low sulfur content that subsequent Euro 6 standard has not required any further reduction.

In Australia, the maximum sulfur content of ULP used today exceeds that allowable in Europe during Euro 4 emissions standard, and is more representative of levels allowed during Euro 3. The fuel standard lags behind the introduction of successive emissions standards which in Europe were timed to enable their introduction. Although PULP fuel has a lower maximum sulfur content of 50 ppm, this is still equivalent to that allowable during Euro 4 standards in Europe. Australian market fuel quality may therefore be hindering the ability of vehicles to conform to current Euro 5 and (if adopted) future Euro 6 standards in the real world.

In Japan and the USA there has been a similar alignment between fuels and emissions standards. Figure 19 shows that in Japan, fuel sulfur content was reduced to 10 ppm in 2005 and in the USA fuel sulfur content is being reduced to a 10 ppm maximum to accompany the introduction of the latest Tier 3 emission standard in 2017. In California, from 2012 petrol must have a maximum sulfur content of 20 ppm.
Regulated Durability of Emissions Systems

Emissions control technology must not only satisfy regulations when a vehicle is new but it must also be capable of providing acceptable performance after a defined vehicle life.

<table>
<thead>
<tr>
<th>DURABILITY REQUIREMENTS OF EMISSIONS STANDARDS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Standard</strong></td>
</tr>
<tr>
<td>Euro 2 to Euro 4</td>
</tr>
<tr>
<td>Euro 5 &amp; Euro 6</td>
</tr>
<tr>
<td>US Tier 2 &amp; LEV II</td>
</tr>
<tr>
<td>US Tier 3 &amp; LEV III</td>
</tr>
</tbody>
</table>

Sources: EPA & UE ECE

Table 18 – Durability Requirements of European and USA Emissions Standards

To demonstrate conformity to current Euro standards, a choice of one of the following three options is available to a vehicle manufacturer.

<table>
<thead>
<tr>
<th>OPTIONS TO DEMONSTRATE EURO 5 AND 6 DURABILITY</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Option</strong></td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
</tbody>
</table>

Source: UE ECE

Table 19 – Options to Demonstrate Euro 5 and Euro 6 Durability

In-service Conformity of Emissions Systems

In Europe, manufacturers must periodically test their vehicle emissions to ensure compliance with regulations throughout their service life. To aid this, the use of On-Board Diagnostics (OBD) is mandated to control and monitor the vehicle’s emission systems, informing the driver of any faults so that they can be rectified.

For vehicles conforming to Euro standards, those selected for in-service conformity must have been used for at least 6 months / 15,000 km but no more than 5 years / 100,000 km. Either market available fuel or reference fuel may be used during the checks.

On Board Diagnostics (OBD)

The vehicle’s OBD system must be capable of detecting issues with the operation of engine and exhaust aftertreatment systems, raising awareness to the driver by the illumination of the Malfunction Indicator Lamp (MIL) on the dashboard.

Upon returning the vehicle to the dealership, diagnostics equipment is connected to the vehicle’s Engine Control Unit (ECU) and any error codes can be determined. Error codes highlight specific occurrences of engine parameters falling outside of acceptable limits, or known events of a sensor malfunctioning.

The use of error codes by OBD systems enables fault identification and rectification, ensuring that the emissions and pollution control systems can function effectively throughout the vehicle’s life. OBD threshold limits for pollutants are set higher than the limits for vehicle type approval.
**CO₂ and Fuel Efficiency Regulations**

Japan, the USA, and Europe use CO₂ emission or fuel economy targets as part of their respective policies aimed at tackling climate change and conserving energy. It is difficult to compare these three standards on a like for like basis as each region uses different parameters, units, calculation methods, and drive cycles to determine fuel consumption &/or CO₂. Consequently, a high level overview of the key aspects of each region’s regulations are presented in order to understand how vehicle design has been influenced by the legislation in their home market.

At present Australia has no regulation of CO₂ emission or minimum fuel economy targets for petrol engine light duty vehicles.

**Japanese ‘Top Runner’ Fuel Economy Standard**

In Japan a minimum limit for fuel economy is used as part of their conservation of energy regulations, with no direct limits for CO₂ production (although it is indirectly linked by the fuel consumed by the vehicle). For the following vehicle categories this standard applies: passenger car of less than 10 seat capacity, passenger cars of 11 seat or more capacity but with mass less than 3500 kg and light duty freight vehicles with mass less than 3500 kg.

Table 21 shows the 16 vehicle mass categories and their respective fuel economy for the 2015 Target. The “Top Runner” standard encourages manufacturers to improve vehicle fuel economy by determining the best fuel economy attained by vehicles in each category and using this figure as the top runner to which all vehicles must aspire.

The fuel economy is measured in km travelled per Litre of fuel used; km/L.

Source: ECE 692/2008

**EURO 5 AND 6c OBD THRESHOLD LIMITS FOR POLLUTANTS**

<table>
<thead>
<tr>
<th>Pollutant Emissions (g/km)</th>
<th>CO</th>
<th>NMHC</th>
<th>NOₓ</th>
<th>PM*</th>
<th>PN*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Euro 5</td>
<td>1900</td>
<td>250</td>
<td>300</td>
<td>50</td>
<td>-</td>
</tr>
<tr>
<td>Euro 6c</td>
<td>1900</td>
<td>170</td>
<td>90</td>
<td>12</td>
<td>**</td>
</tr>
</tbody>
</table>

*PM and PN limits apply to Direct Injection Petrol vehicles only
** A limit for the Number of Particulates emitted in-service has not yet been established.

Source: ECE 692/2008

**Table 20 – Euro 5 and Euro 6c OBD threshold limits for pollutants**

**JAPANESE “TOP RUNNER” PASSENGER CAR FUEL EFFICIENCY STANDARD (2015 TARGET)**

<table>
<thead>
<tr>
<th>Category</th>
<th>Vehicle Mass Range (kg)</th>
<th>Target Fuel Economy (km/L)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>≤ 600</td>
<td>22.5</td>
</tr>
<tr>
<td>2</td>
<td>601 – 740</td>
<td>21.8</td>
</tr>
<tr>
<td>3</td>
<td>741 – 855</td>
<td>21</td>
</tr>
<tr>
<td>4</td>
<td>856 – 970</td>
<td>20.8</td>
</tr>
<tr>
<td>5</td>
<td>971 – 1080</td>
<td>20.5</td>
</tr>
<tr>
<td>6</td>
<td>1081 – 1195</td>
<td>18.7</td>
</tr>
<tr>
<td>7</td>
<td>1196 – 1310</td>
<td>17.2</td>
</tr>
<tr>
<td>8</td>
<td>1311 – 1420</td>
<td>15.8</td>
</tr>
<tr>
<td>9</td>
<td>1421 – 1530</td>
<td>14.4</td>
</tr>
<tr>
<td>10</td>
<td>1531 – 1650</td>
<td>13.2</td>
</tr>
<tr>
<td>11</td>
<td>1651 – 1760</td>
<td>12.2</td>
</tr>
<tr>
<td>12</td>
<td>1761 - 1870</td>
<td>11.1</td>
</tr>
<tr>
<td>13</td>
<td>1871 – 1990</td>
<td>10.2</td>
</tr>
<tr>
<td>14</td>
<td>1991 – 2100</td>
<td>9.4</td>
</tr>
<tr>
<td>15</td>
<td>2101 – 2270</td>
<td>8.7</td>
</tr>
<tr>
<td>16</td>
<td>≥ 2271</td>
<td>7.4</td>
</tr>
</tbody>
</table>

Source: http://www.eccj.or.jp/

Table 21 - Japanese 2015 “Top Runner” Fuel Economy Target
For each mass category, a manufacturer’s sales-weighted average fuel economy must meet this minimum standard by the target date. The fuel economy of a vehicle is determined by testing the vehicle in a laboratory according to the same drive cycles as used for pollutant emissions. For the Japanese standard, this consists of two JC08 drive cycles; the first from cold start of the engine and the second from a hot start. The fuel economy is calculated as the weighted average from the cold and hot drive cycles, with a weighting of 0.25:0.75 respectively. The JC08 drive cycle represents the conditions experienced by light vehicles driven in Japan.

If the sales-weighted fuel economy of vehicles in a category is vastly better than the minimum target, it may be used to offset that of another category. This encourages manufacturers to promote sales of their more fuel efficient vehicles which produce less CO₂.

The current 2020 fuel economy standard places more stringent limits on fuel economy. Chart 12 shows the increased fuel economy required at each of the vehicle mass categories by the new 2020 target. This will require manufacturers to develop more fuel efficient vehicles.

The 2020 fuel economy standard introduces the use of a Corporate Average Fuel Economy (CAFE) method for determining the overall fuel economy. This method allows manufacturers to offset high sales of fuel efficient cars that exceed the minimum economy target for a given category against low sales of less fuel efficient cars in another category. So long as the overall CAFE rating of fuel economy is greater than or equal to that determined by calculating sales-weighted average fuel economy from using the minimum fuel economy at each vehicle category, a manufacturer can satisfy the fuel economy standard.

The top runner fuel economy standard classifies diesel and petrol vehicles within the same category. A translation factor is used to convert diesel fuel economy into an equivalent petrol economy for comparison against the standard. The same process is used for LPG vehicles.

USA fuel economy and CO₂ regulations

There is a long history of fuel economy regulations in the USA, with Corporate Average Fuel Economy regulations first enacted in 1975. In 2007 CO₂ was recognised as a pollutant emission under the USA Clear Air Act, the emission of which is considered as part of the Greenhouse Gas (GHG) regulations. These regulations consider the impact that other gases in addition to CO₂ have on global warming, with limits also placed on the emission of hydrofluorocarbons from air conditioning systems, nitrous oxide (N₂O) and methane (CH₄). Consequently, the USA has separate but co-ordinated regulations for both fuel economy and CO₂ emission.

The CAFE is measured in miles per US gallon, mpgUS, and is determined by driving according to various driving cycles that are representative of the conditions experienced on road in the USA, accounting for hot and cold engine starts and the use of air conditioning. Like the Japanese standard, the consumption of fuel is not measured directly but by use of a carbon balance method. This uses exhaust gas analysis equipment to measure the emission of CO₂ and other carbon-based compounds from the vehicle exhaust tailpipe, which is then back calculated to obtain a figure for fuel consumption using a known carbon content of the fuel used during the test. This allows accurate determination of the fuel consumption, particularly at low fuel consumption rates.
Unlike the Japanese regulations, the USA CAFE regulation categorises vehicles based on their footprint rather than mass. The footprint is defined as the area enclosed by the vehicle's wheelbase between front and rear axles and the width of track between the centre lines of the wheels, and is measured in square feet. Figure 21 explains the calculation of the vehicle footprint.

Vehicles with larger footprint are permitted to have higher fuel consumption than those with a smaller footprint. For each manufacturer their sales weighted average fuel economy is calculated from the actual sales and fuel economy of vehicles in each footprint category. Limits are placed on the overall Corporate Average Fuel Economy that must be attained, with the current 2016 target set at 34.1 mpg US and 2025 target of 49.6 mpg US.

The CAFE light duty vehicle standard applies to passenger cars with Gross Vehicle Weight (GVW) up to 8500 lb (3864 kg). Medium duty Sports Utility Vehicles (SUVs) with GVW up to 10000lb (4545 kg) are included in a separate light truck standard, making direct comparison with Japanese or European regulations complex.

The USA GHG regulations measure emission of other gases in addition to CO₂, but there is not a strict limit for CO₂ emission per se. Instead, the other GHG emissions are expressed in term of equivalence to CO₂. As an example, in 2013 the fraction of CO₂ as a proportion of the total Greenhouse gases was determined to be 0.986.

**European CO₂ regulations**

The European commission proposed in 2007 that the EU should set an objective of 30 % reduction in greenhouse gas emission by 2020 (comparing with 1990 levels). As passenger cars produce around 12 % of the total EU emissions of CO₂, this resulted in strict targets placed on the production of CO₂ from new passenger car vehicles.

The 2015 target was an average of no greater than 130 g CO₂ emitted per km travelled (g CO₂/km) for new passenger car vehicles registered in the EU. This emission is determined by measuring CO₂ emissions of a vehicle whilst driving the New European Drive Cycle (NEDC) in a laboratory. In future the Worldwide Harmonised Light Vehicle Test Procedure (WLTP) will be used to determine vehicle CO₂ production in a laboratory, and will provide a much more realistic simulation of the driving conditions experienced in the real world.

For the European regulation, vehicles are classified by mass with a reference mass of 1372 kg used for the 130 g CO₂/km target. This means that lighter mass vehicles must emit less than 130 g CO₂/km, and heavier mass vehicles are permitted to emit more than this target so long as a manufacturer’s sales-weighted fleet average emission meets the overall target.

A new target for 2021 requires the fleet average CO₂ emissions of cars to be only 95 g CO₂/km, with a phase-in period allowing 95 % of a manufacturer’s vehicles to comply with this target from 2020 until the 2021 target applied to 100% of the fleet average.

The CO₂ targets apply to passenger cars of any fuel type, and are partly responsible for the trend in Europe for Diesel vehicles sales to increase over recent years. In order to incentivise the adoption of engine technologies that reduce CO₂, manufacturers may claim CO₂ savings of up to 7 g/km per year for their fleet average if they employ innovative vehicle technologies that are independently verified. Also, manufacturers are allowed to pool their average CO₂ emissions with other manufacturers in order to meet the target. Strict penalties apply for every gram per kilometre CO₂ produced in excess of the fleet weighted average, applying to the total sales volumes of vehicles. Currently a consultation is open on the revision of CO₂ regulation to set a target for 2025 or beyond.
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