İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

EFFECTS OF VARIOUS DRIVE CYCLES ON EGR COOLER CONTAMINATION AND CONTAMINATION ON EGR VALVE POSITION

M.Sc. Thesis by
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Programme : Automotive

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JUNE 2010

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FARKLI SÜRÜŞ ÇEVRİMLERİNİN EGR SOĞUTUCUSU KİRLENMESİNE VE KİRLENMENİN EGR VALFİ KONUMUNA ETKİSİ

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FOREWORD

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ABBREVIATIONS

EGR	**:** Exhaust Gas Recirculation
ECU	**:** Electronic Control Unit
NO_x	**:** Nitrogen Oxides
PM	**:** Particulate Matter
HC	**:** Hydrocarbon
CO	**:** Carbon Monoxide
CO_2	**:** Carbon Dioxide
DPF	**:** Diesel Particulate Filter
SOF	**:** Soluble Organic Fraction
NEDC	**:** New European Driving Cycle

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LIST OF SYMBOLS

α	: Thermal Diffusivity
A_c	: Cold Side Heat Transfer Surface Area
A_h	: Hot Side Heat Transfer Surface Area
A_f	: Fin Surface Area
ΔP	: Pressure Drop
D_h	: Hydraulic Diameter
ε	: EGR Cooler Effectiveness
ξ	: Resistance Coefficient
h_c	: Cold Side Convection Heat Transfer Coefficient
h_h	: Hot Side Convection Heat Transfer Coefficient
k	: Fin Thermal Conductivity
η_{0c}	: Cold Side Overall Surface Efficiency
η_{0h}	: Hot Side Overall Surface Efficiency
η_f	: Single Fin Efficiency
Nu	: Nusselt Number
Pr	: Prandtl Number
R_{fc}	: Cold Side Fouling Factor
R_{fh}	: Hot Side Fouling Factor
R_w	: Wall Conduction Resistance
Q_{act}	: Actual Heat Transfer
$Q_{\max}$	: Maximum Possible Heat Transfer
ρ	: Density
Re	: Reynolds Number
Sc	: Schmidt Number
Sh	: Sherwood Number
t	: Fin Thickness
T_{Cin}	: EGR Coolant Inlet Temperature
T_{Gin}	: EGR Gas Inlet Temperature
T_{Gout}	: EGR Gas Outlet Temperature
ν	: Kinematic Viscosity
V	: Velocity

EFFECTS OF VARIOUS DRIVE CYCLES ON EGR COOLER CONTAMINATION AND CONTAMINATION ON EGR VALVE POSITION

SUMMARY

Diesel engines are commonly used throughout the world because of their high fuel economy and low maintenance cost although they are one of the main sources of air pollution. Stricter emission regulations are introduced in order to release less harmful gases to the nature. Exhaust gas recirculation (EGR) is a technology used in internal combustion engines to reduce the level of NO_x emissions by means of transferring a certain amount of gas from exhaust line of the engine to the intake line.

One of the components of an EGR system is the EGR cooler. This part is a heat exchanger, which is cooling the hot EGR gas taken from the exhaust line. The rationale behind cooling the hot gas is to reduce NO_x emissions and not to threaten intake system components with high gas temperatures. However, EGR coolers are subjected to fouling due to particulate build up on surfaces during engine operation, which in turn results in performance degradation of the cooler.

EGR coolers are contaminated in both cooler and bypass modes. In cooler mode, gas passing through the cooler is the source of contamination whereas leaking gas from the bypass flap is the reason in bypass mode. In this experimental study, eight-cylinder Eu5 diesel engine is tested to see the effect of different drive cycles on EGR cooler contamination. The point of interest is to evaluate if cooler mode or bypass mode is more significant source of fouling. Furthermore, the effect of EGR cooler degradation on EGR valve position is investigated in closed loop EGR control system.

Results showed that EGR cooler is subjected to more fouling in the drive cycle that is spending more time in bypass mode. The escaping low temperature gas through the cooler from the bypass flap is the main reason for this situation. EGR valve position changed by 3-4% on the average for the same operating point because of contamination after 110 hours running.

FARKLI SÜRÜŞ ÇEVRİMLERİNİN EGR SOĞUTUCUSU KİRLENMESİNE VE KİRLENMENİN EGR VALFİ KONUMUNA ETKİSİ

ÖZET

Dizel motorları, hava kirliliğinin ana kaynaklarından biri olmasına rağmen, yüksek yakıt ekonomisi ve düşük bakım maliyetleri nedeniyle dünya çapında yaygın olarak kullanılmaktadır. Doğaya daha az zararlı gazlar atmak amacıyla, emisyon regülasyonları giderek düşük seviyelere çekilmektedir. Egzoz Gazları Resirkülasyonu (EGR), bir miktar egzoz gazını emme kanalına göndererek içten yanmalı motorlarda NO_x emisyonlarını düşürmek için kullanılan bir teknolojidir.

EGR sisteminin parçalarından biri EGR soğutucusudur. Bu parça bir ısı dönüştürücüsü olup egzozdan alınan sıcak EGR gazını soğutur. Gazın soğutulmasındaki amaç NO_x emisyonlarını düşürmek ve emme sistemi parçalarını yüksek sıcaklıktan korumaktır. EGR soğutucuları, motorun çalışması esnasında yüzeylerinde partikül birikmesi nedeniyle kirlenmeye maruz kalırlar ve bunun sonucu olarak ısıl performansta bir düşüş olur.

EGR soğutucuları hem soğutma modunda hem de by-pass modunda kirlenebilir. Soğutma modunda kirlenmenin kaynağı soğutucunun içinden geçen gazken, by-pass modunda by-pass kanadındaki sızıntıdır. Yapılan deneysel çalışmada, sekiz silindirli Euro5 standartlarında bir dizel motoru test edilerek farklı sürüş çevrimlerinin EGR soğutucusunun kirlenmesine etkisi gözlemlenmiştir. Soğutma ve by-pass modlarından hangisinin kirlenmeye daha çok etkisinin olduğu incelenmiştir. Ayrıca, kapalı devre EGR kontrol sisteminde, EGR soğutucusundaki kirlenmenin EGR valfinin konumuna etkisi araştırılmıştır.

Elde edilen sonuçlar, by-pass modunda en fazla zaman geçiren sürüş çevriminde EGR soğutucusunun da en fazla kirlenmeye maruz kaldığını göstermektedir. Bu durumun ana nedeni by-pass kanadından soğutucuya kaçan düşük sıcaklıktaki gazdır. Ayrıca, 110 saatlik çalışmanın neden olduğu kirlenmeden dolayı, aynı çalışma noktasında EGR valfi açıklığının ortalama %3-4 arttığı görülmüştür.

1. INTRODUCTION

Modern diesel engines offer reasonably high power levels when compared to prior diesel engines. However, nitrogen oxide and particulate matter molecules, which are restricted to certain levels with emission regulations, are formed based on the high in-cylinder temperatures and diesel combustion nature respectively.

Exhaust gas recirculation (EGR) is a commonly used technology to decrease the level of NO_x emissions in internal combustion engines by replacing a portion of the fresh intake air with the exhaust gas from engine. This reduction is achieved by dilution, thermal, added-mass and chemical effects of EGR, which in turn leads to decreased oxygen availability and combustion temperatures within the cylinder [1].

EGR gas is directed to intake line through a set of components namely, EGR tubes, EGR valve and EGR cooler that are referred to as EGR system when assembled together. Function of EGR cooler is to decrease the temperature of the hot exhaust gas before feeding the gas to intake system since cooled EGR improves NO_x emissions for a wide range of operating conditions.

EGR coolers are subjected to fouling when in operation as the particles in the exhaust gas passing through the cooler, contaminate on the gas passage walls. Accumulating particles on the cooler surfaces build up an insulation layer that acts as an additional resistance to heat transfer and increases the pressure drop across the cooler. Assessment of EGR cooler performance deterioration is very important since it may adversely affect the NO_x emissions, as the in-cylinder temperatures will have relatively higher values because of inadequate cooling.

Experiments show that EGR cooler effectiveness does not have a continuously decreasing trend and contamination thickness stabilizes after some time although it is very hard to explain the complex behavior of fouling formation. Briefly, when the engine starts running with a clean cooler, mass deposition rate is dominant over mass removal rate, whereas mass removal rate becomes almost equal to the mass deposition rate leading to stabilization as time passes [2].

EGR coolers are contaminated in both cooler and bypass modes. In cooler mode, gas passing through the cooler is the source of contamination whereas leaking gas from the bypass flap is the reason in bypass mode.

Contamination occurs under various conditions and depends on numerous parameters simultaneously in addition to the stratified stages of fouling and cleaning mechanisms, which make it very hard to model or predict the behaviour. Hence, fouling is mostly investigated by experiments rather than theoritical calculations and models.

In order to compensate the performance deterioration in EGR system caused by fouling, closed loop controls have been introduced to electronic control units (ECU) of modern internal combustion engines. The principal is based on adjusting the EGR valve position according to the feedback from the intake line so that the desired EGR rate in engine EGR map for a specific operating point is maintained throughout the lifetime.

In this experimental study, effects of 3 different drive cycles on EGR cooler fouling were investigated by running each of the cycles with an unused cooler. The point of interest was to evaluate if cooler mode or bypass mode is more significant source of fouling. Furthermore, the influence of EGR cooler degradation on EGR valve position was monitored in closed loop EGR control system.

2. EGR SYSTEM

2.1 Definition, Effects, Advantages and Disadvantages

Exhaust gas recirculation is a commonly used technology to achieve reduced level of NO_x emission levels in today's diesel engines. The principal is to replace a portion of the fresh intake air with the exhaust gas from engine so that the specific heat capacity of the intake mixture is increased. By this way, N_2 and O_2 molecules in fresh air are substituted by H_2O and CO_2 molecules in exhaust gas and a lower peak temperature is obtained during combustion, which is beneficial in terms of lowering NO_x emissions. A schematic representation of a typical EGR system is shown in Figure 2.1.

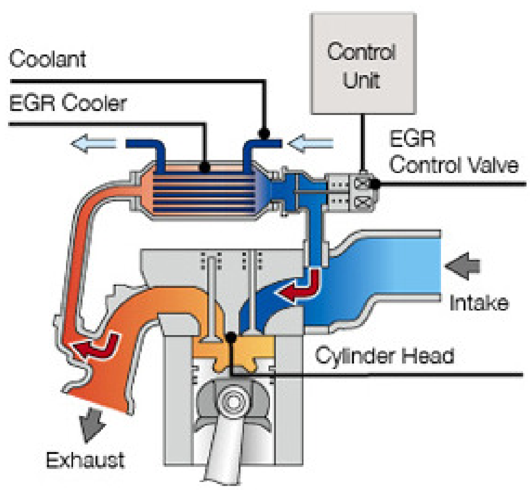

Figure 2.1 : Schematic representation of EGR system [3]

Generally, EGR rate is represented as percentage. EGR rate can be defined either on mass basis or on volume basis.

When mass basis is considered, EGR rate is the ratio of mass of recirculated gas in the total intake gas to the mass of total intake gas **(2.1)**. Mass percentages can go up to around 25-30% in application.

$$EGR(\%) = \frac{M_{EGR}}{M_{INTAKE}} x100 \qquad \textbf{(2.1)}$$

When volume basis is considered, EGR rate is the ratio of volume of recirculated gas in the total intake gas to the volume of total intake gas **(2.2)**. Volume percentages can go up to around 45-50% in application.

$$EGR(\%) = \frac{V_{EGR}}{V_{INTAKE}} x100 \qquad \textbf{(2.2)}$$

EGR systems reduce the NO_x emission levels by means of several effects, which are briefly explained below [1].

- Dilution Effect: Dilution effect is based on the reduction of O_2 concentration in the intake mixture because of non-reacting gas addition to the intake mixture. Reduced O_2 will in turn decrease the rate of NO_x formation.
- Thermal Effect: Heat capacity of the intake mixture is increased by addition of H_2O and CO_2 from exhaust gas. Increased heat capacity of the non-reacting gases in the intake air reduces NO_x formation.
- Added Mass Effect: Addition of diluting molecules to the intake mixture results in higher mass flow rates. This effect is different from thermal effect and introduces a higher heat capacity due to mass increase.
- Chemical Effect: Chemical effect is covering the combustion temperature reduction as certain amount of heat is absorbed by the endothermic dissociation reactions of H_2O and CO_2.

Main advantages of EGR application are summarized below.

- Specific heat capacity of intake mixture is increased so that peak combustion temperatures decrease. By this way, NO_x emission levels are reduced.
- Heat rejection and thermal energy loss decrease since the peak combustion temperature is lower.
- Chemical dissociation rate decreases since the peak combustion temperature is lower. This effect might not be very significant.
- Pumping losses are reduced especially in high pressure EGR systems since the EGR take off is before the turbocharger.

- EGR application improves knock tendency of the engine since lower peak pressures are obtained. Noise is also reduced based on the same reason.

On the other hand, EGR application has the following disadvantages.

- During power stroke, amount of power decreases since the specific heat ratio of combustion gases decreases by the addition of recirculated gases.
- Less amount of fuel is burned which in turn increases the PM emissions. Unburned fuel decreases the fuel efficiency resulting in energy loss.
- Engine wear and oil degradation have an increased rate since the carbon content is higher as a result of EGR application. These particles lead to a faster abrasion by absorbing the antiwear additives in the oil and deform the anti-wear films on critical surfaces.

2.2 Effect of EGR on Emissions

Satisfying the emission requirements is mandatory to manufacture saleable vehicle engines. EGR is a very common way of improving NO_x emissions in diesel engines. However, it has a negative effect on PM, HC and CO emissions as explained in the following sections.

2.2.1 NO_x emissions

EGR technology offers a great improvement in NO_x emissions. Among the four basic effects of EGR, which were explained in Section 2.1, dilution has the most significant impact [1]. The principal is based on the reduced oxygen concentration of the charge air resulting in lower flame and combustion product temperatures. EGR also has a negative effect on NO_x emissions since the inlet charge temperature is increased, which in turn increases the temperatures throughout the cycle. However, this effect has much less significant when compared to the improvement gained by the dilution effect.

Nitu et al. (2002) investigated the effects of EGR on engine emissions with an experimental study by running a direct injection, four-stroke cycle, electronically controlled high pressure fuel injection engine in a wide range of operating conditions and EGR ratios. Very sharp reduction in NO_x emissions was observed up to 40% of EGR rate as shown in Figure 2.2 [4].

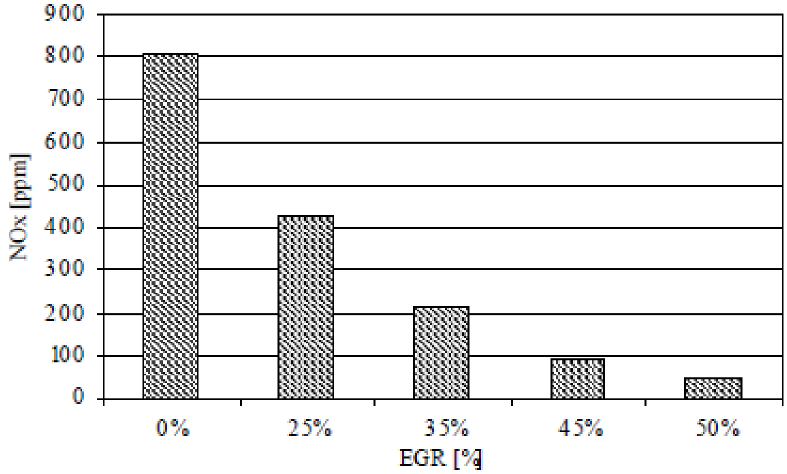

Figure 2.2 : Effect of EGR on NO_x emissions

When load is taken into account, NO_x emissions tend to increase with increasing load when EGR rate is kept constant as shown in Figure 2.3 since higher in cylinder temperatures are obtained [5]. This behavior makes EGR cooling a requirement in order to maintain the required air to fuel ratio.

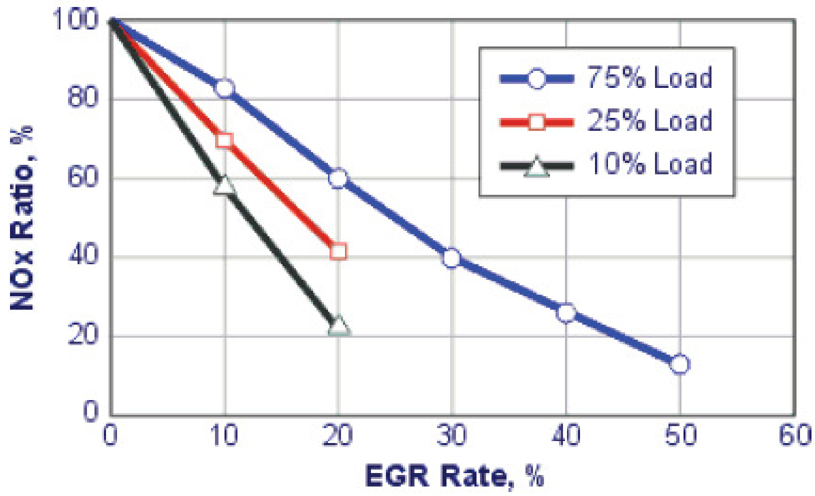

Figure 2.3 : Effect of load on NO_x formation

Herzog et al. (1992) carried out a detailed study about the effects of EGR cooling on NO_x emissions and intake manifold temperatures. At low loads, uncooled EGR attains improved NO_x characteristics when compared to cooled EGR as shown in Figure 2.4. The rationale here is the increased ignition delay, which leaves less time for NO_x formation. In order to take advantage of this phenomenon, EGR cooler bypass valves are introduced to modern EGR systems so that low NO_x emissions are achieved at low loads by routing the EGR gas through intake line without cooling.

Intake manifold temperature is also increasing with uncooled EGR as shown in Figure 2.4 [6].

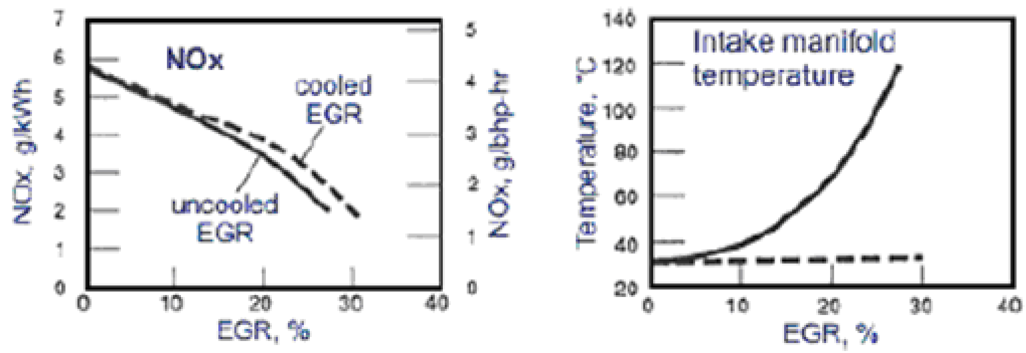

Figure 2.4 : Effect of uncooled EGR at low loads

2.2.2 PM emissions

EGR decreases the oxygen availability and hence the concentration in burning zone. Soot oxidation is disturbed and soot oxidation rate is reduced. As a result, PM emissions increase with increasing EGR rate as shown in Figure 2.5 [4].

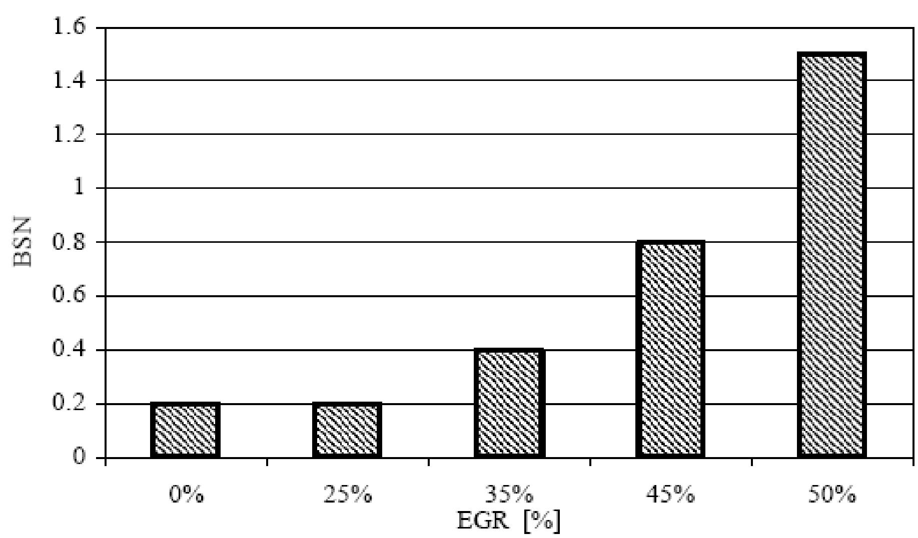

Figure 2.5 : Effect of EGR on PM emissions

Alriksson et al. (2005) investigated the effect excessive EGR on PM emissions. Up to 55% of EGR rate, soot emissions increase as result of decreased soot oxidation rate and increased equivalence ratio. However, when the EGR rate is above 55%, PM emissions drastically decrease as shown in Figure 2.6. This was explained by the effect of low temperature combustion due to low O_2 availability being dominant over the effect of high equivalence ratio [7].

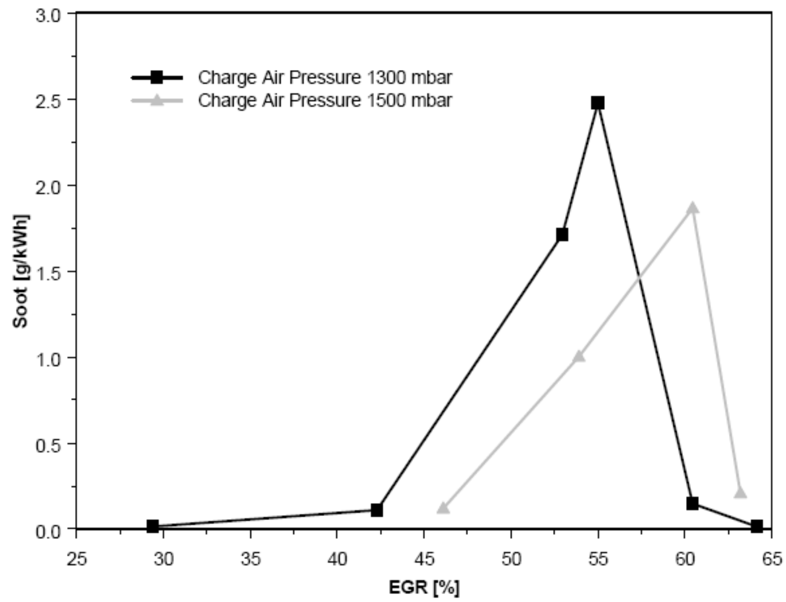

Figure 2.6 : Effect of excessive EGR on PM emissions

Ladommatos et al. (1996) investigated the effect of cooled EGR on PM and NO_x emissions. NO_x – PM trade-off improved with cooled EGR resulting in a decrease in both of these emissions as shown in Figure 2.7 [8].

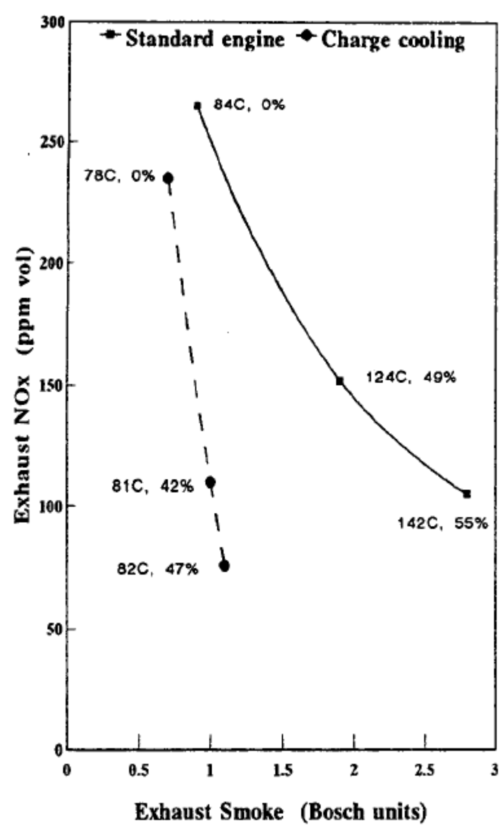

Figure 2.7 : Effect of cooled EGR on PM and NO_x emissions

2.2.3 CO and HC emissions

EGR application decreases the oxygen concentration in combustion chamber and causes an increase in incomplete combustion products. Lack of oxygen prevents the oxidation of CO to CO_2 and hence results in higher-level CO emissions as shown in Figure 2.8 [4].

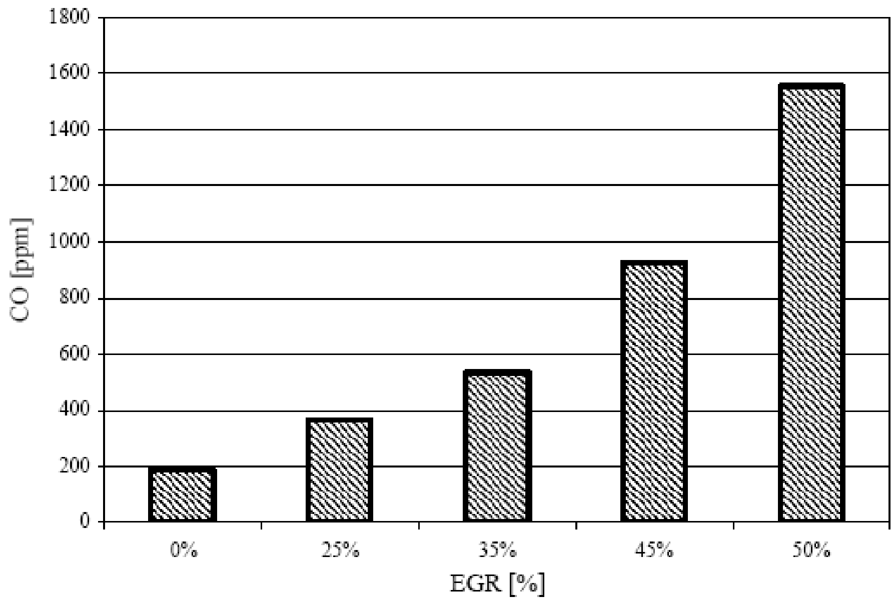

Figure 2.8 : Effect of EGR on CO emissions

HC emissions show a very similar behavior to CO emissions with increasing EGR rates due to the dilution effect of EGR as shown in Figure 2.9 [4].

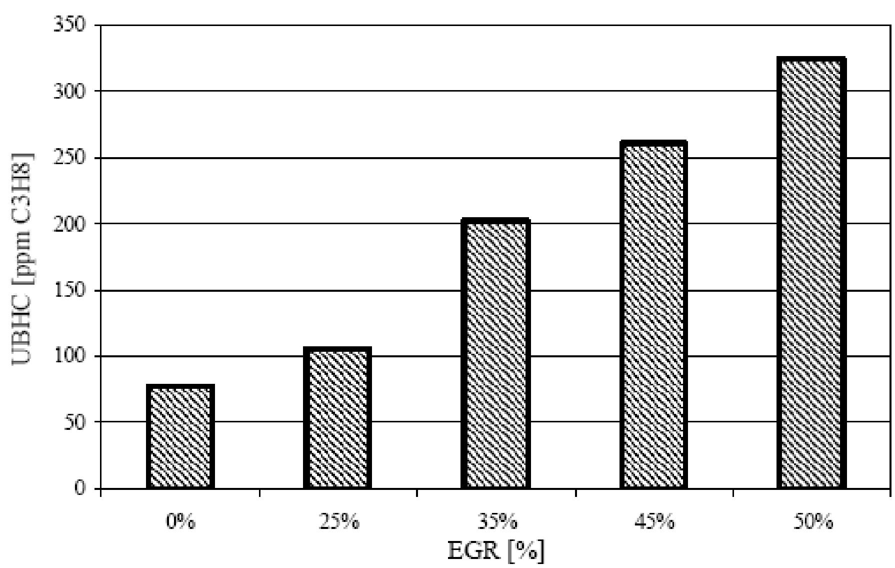

Figure 2.9 : Effect of EGR on HC emissions

Low level of oxygen concentration increases the equivalence ratio and rich mixtures are formed. This phenomenon is then followed by improper combustion. As a result, CO and HC emissions increase with increasing EGR rates as shown in Figure 2.10 [7].

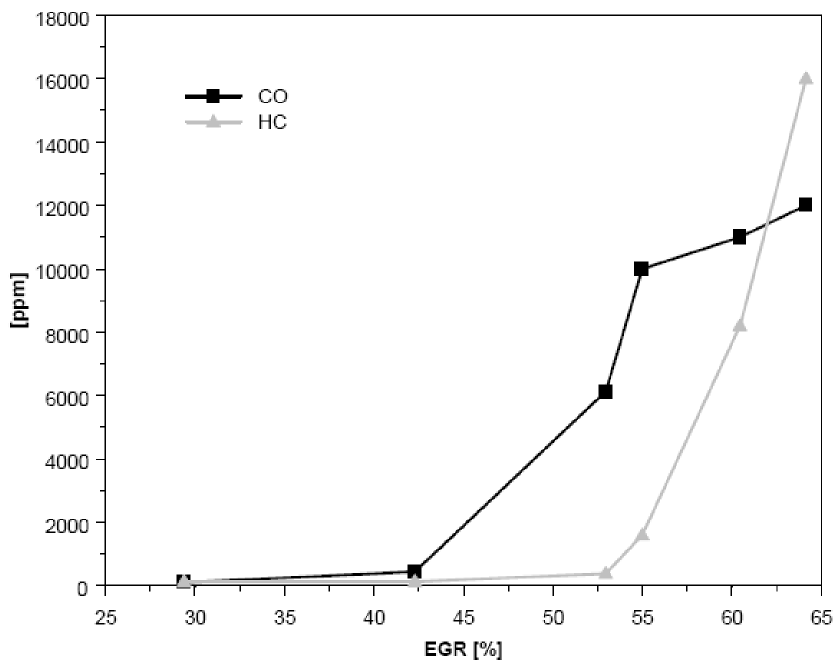

Figure 2.10 : Effect of EGR on CO and HC emissions

HC and CO emissions can be filtered by introducing after treatment systems although these systems bring an add-on cost to the overall system. However, they are of great importance to satisfy today's emission regulations.

2.3 EGR System Components

Components of a typical EGR system are EGR tubes, EGR valve, EGR cooler bypass valve and EGR cooler. These components are explained further in detail in the upcoming sections. In addition to these, there are also joint elements such as bolts and/or clamps to form the EGR system as an assembly and gaskets in between the mating components.

2.3.1 EGR tubes

Commonly, there are two EGR tubes on a diesel engine namely, EGR inlet and EGR outlet tubes. EGR inlet tube is feeding the gas from the engine exhaust line to EGR system. Similarly, EGR outlet tube is routing the gas from EGR system to intake manifold. These pipes are generally made up of stainless steel in order to withstand the high temperatures of the exhaust gas. Figure 2.11 shows different EGR tubes.

Figure 2.11 : EGR tubes [9]

As seen in Figure 2.11, EGR tubes generally have a corrugation profile in order to compensate the thermal expansion when in contact with the hot exhaust gas. These corrugations are also beneficial from assembly point of view because of the additional flexibility they provide. However, corrugations have great effect on the vibration durability of the tube and hence they must be located on the right portion of the tube according to the vibration characteristics of the engine and distance from the joint.

EGR pipes usually have flange and bolt type joints with increased sealing area for the gasket. They are generally covered by a thermal heat sock to reduce the amount of radiated heat towards adjacent components. An example of a heat sock is given in Figure 2.12.

Figure 2.12 : EGR tube with a heat sock [10]

Following list of items should be considered during design stage of EGR tubes.

- *Thermal Fatigue*: Temperature of the gas passing through the pipe is continuously varying which might lead to thermal fatigue failures.
- *Pressure Fatigue*: Pressure of the gas passing through the pipe is continuously varying which might lead to pressure fatigue failures.
- *Vibrational Durability*: Pipes should be durable to engine vibration since they are used in a high pressure and high temperature region.
- *Pressure Drop*: The geometry of the pipe should be well designed in order not to affect the required flow characteristics through EGR system.
- *Corrosion*: Material composition should be selected appropriately to prevent corrosion as the EGR tubes are subjected to high temperatures.

2.3.2 EGR valve

EGR valve is the component to adjust the amount of EGR gas that will be directed to intake manifold. EGR valves need to be actuated precisely to satisfy emission regulations. Most common types are pneumatically actuated and electrically actuated EGR valves, which are briefly explained below.

Pneumatically actuated EGR valves have a diaphragm, which is controlled by applying vacuum. There is a preloaded spring in the vacuum actuator. Applying more vacuum results in a higher force so that the spring force is exceeded and the stem starts moving. By this way, position of valve stem is adjusted as required. Figure 2.13 shows a pneumatically actuated EGR valve.

Figure 2.13 : Pneumatically actuated EGR valve [11]

Advantages of pneumatically actuated EGR valves are their flexibility to different packaging requirements, lower energy consumption, low weight and low cost as well as high durability. On the other hand, they cannot be controlled very precisely in low lift conditions, which can be considered as the main disadvantage.

Electrically actuated EGR valves are generally operated by a DC motor. A certain amount of voltage is applied to the DC motor according to the operating point so that the valve position is adjusted. By this way, valve position can be precisely controlled. An electrically actuated EGR valve is shown in Figure 2.14.

Figure 2.14 : Electrically actuated EGR valve [11]

Sealing characteristics of an EGR valve is of great importance to provide secure operation in cases of exhaust back pressure and charge air pressure. EGR valves should also close rapidly in sudden load increase to prevent increased smoke and particulate matter. From this point of view, electrically actuated EGR valves are advantageous as they can respond very quickly to sudden changes.

Following list of items should be evaluated during design stage of EGR valves in addition to basic design considerations.

- *Seat Leakage*: There will be a certain amount of leakage through the valve even the valve is in closed position since there is no gasket between the valve poppet and its seat. This leakage should be kept at very low levels in order not to affect emission characteristics of the engine when the EGR valve is closed.

- *Response Time*: Sudden changes in operating conditions require fast response of EGR valve. Response time of the valve should be kept as low as possible to keep up with transient engine operation.
- *Cycling*: EGR valve should be durable to cycling since its position is always changing throughout its lifetime during engine start, engine stop and transient operation.

2.3.3 EGR cooler and EGR cooler bypass valve

Cooling EGR gas is essential to reduce NO_x emissions as the charge air density can be increased by higher EGR ratios. EGR cooler is a heat exchanger used to cool the hot exhaust gas prior to intake line by using engine coolant. Gas flow and coolant flow take place in separate circuits within the component. It is important to note that cooler performance is degraded within time due to the deposit accumulation on heat transfer surfaces.

Internal geometry of an EGR cooler, which is commonly made up of stainless steel, needs to be well designed to satisfy the required heat transfer performance while minimizing the fouling on surfaces. Various EGR coolers are shown in Figure 2.15.

Figure 2.15 : EGR coolers [12]

EGR cooler bypass valve is a component used to reduce CO and HC emissions at cold start, low loads and low speeds. It eliminates the low temperature gas passing through the cooler at specific operating conditions to prevent excessive fouling of the cooler and helps the engine to warm up in cold start by means of not cooling the EGR gas.

There is not a perfect sealing between the bypass flap and the cooler, which means that there is always some amount of gas escaping from the bypass flap to the cooler. This leads to low temperature cooler fouling even the EGR system is operating in bypass mode. Figure 2.16 shows a schematic of an EGR system with an EGR cooler bypass valve. If the exhaust gas temperatures become above the limiting values, then EGR cooler bypass flap allows the hot gas to get into the cooler.

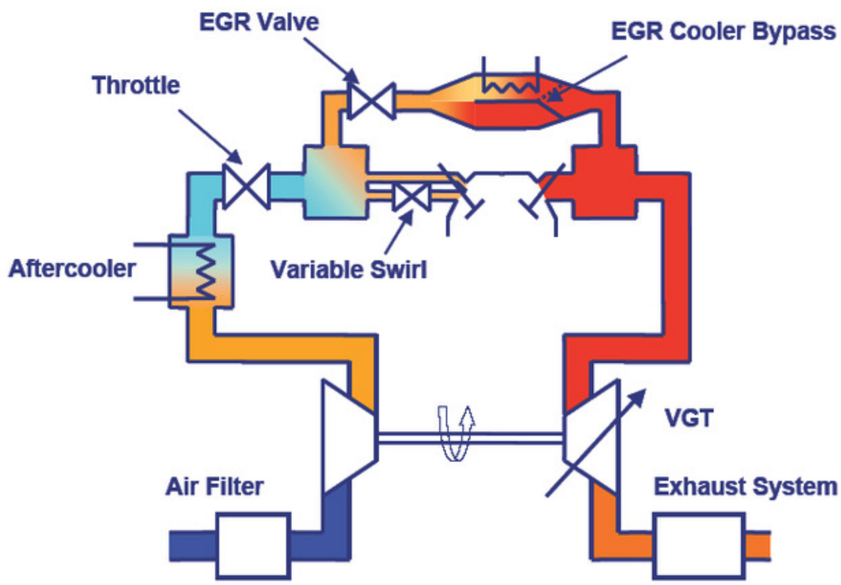

Figure 2.16 : Schematic of an EGR system with an EGR cooler bypass valve [13]

Following list of items should be evaluated during the design stage of EGR coolers in addition to basic design considerations.

- *Heat transfer performance*: EGR cooler must fulfill the necessary heat transfer performance while meeting packaging requirements.
- *Coolant and gas circuits leak tests*: Cooler and gas need to be leak tested in order to prevent mixing during operation. Otherwise, engine coolant, which is of vital importance for engine cooling, might be contaminated with the exhaust gas.
- *Coolant side and gas side pressure drops*: The internal geometry of the EGR cooler should not to disturb the required flow characteristics of the gas or coolant when pressure drops are increased as a result of fouling.

- *Thermal fatigue*: EGR cooler must be durable to cyclic thermal loads since the flow rate and temperature of the exhaust gas is continuously varying during operation.
- *Pressure fatigue*: EGR cooler must be durable to cyclic pressure loads since the flow rate and pressure of the exhaust gas is continuously varying during operation.

2.4 EGR System Configurations

EGR system configurations can be briefly classified as high pressure EGR system, low pressure EGR system and Internal EGR. These configurations are further explained in the following sections.

2.4.1 High pressure EGR system

Exhaust recirculation gas is taken from upstream of turbocharger turbine to mix it with compressed intake air at the turbocharger compressor outlet, which actually means EGR is operating at around boost pressure. Figure 2.17 shows a schematic of commonly used high pressure EGR system. EGR cooler is taking the high pressure gas from the exhaust manifold and the gas is mixed with charge air after intercooler.

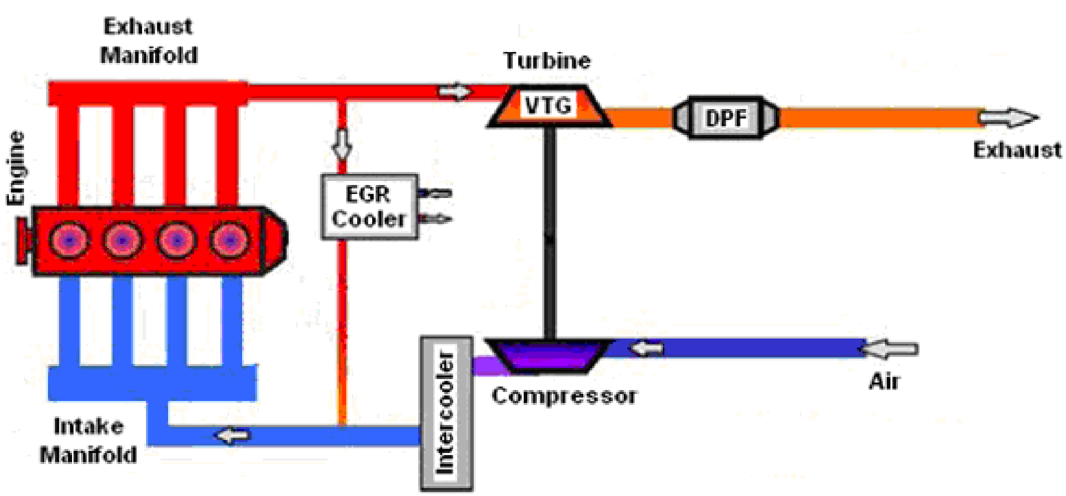

Figure 2.17 : Schematic representation of high pressure EGR [14]

2.4.2 Low pressure EGR system

Exhaust recirculation gas is taken after the particulate filter from downstream of turbocharger turbine to mix it with intake air between the turbocharger compressor inlet and air filter as shown in Figure 2.18, which actually means EGR is operating at around atmospheric pressure.

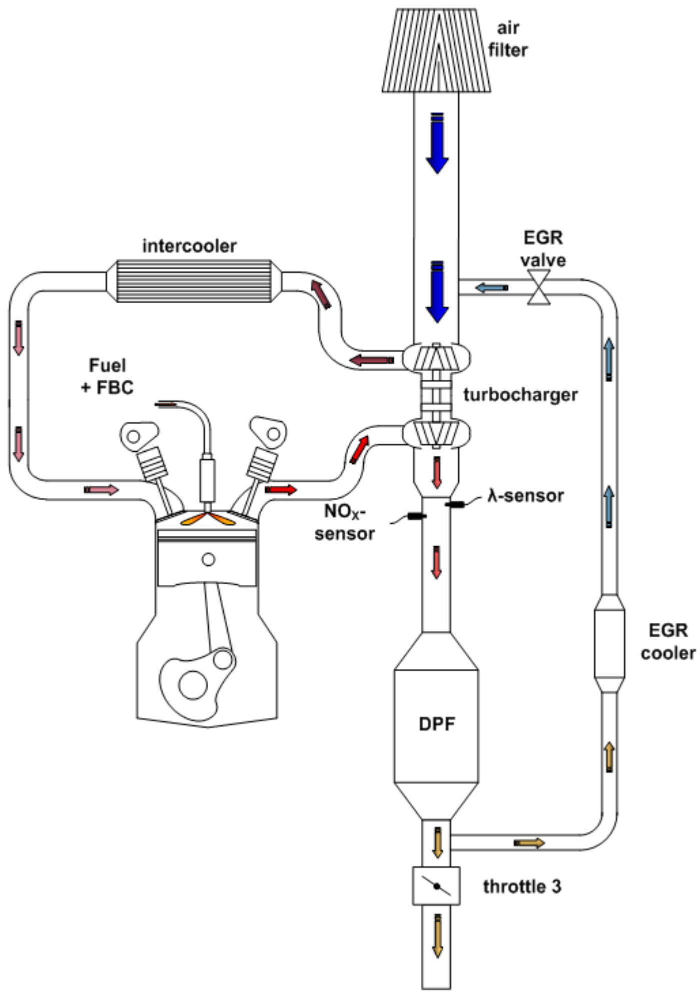

Figure 2.18 : Schematic representation of low pressure EGR [15]

Exhaust gas is cooled using the engine coolant. It is not desired to have very low coolant temperatures in EGR cooler as it may lead to condensation before compressor.

The engine shown in Figure 2.19 has two turbochargers together with an intercooler. In order to eliminate the risk of condensation in low pressure charge air cooler, low pressure charge air cooler is cooled with engine coolant. On the other hand, low temperature coolant is used in high pressure charge air cooler. EGR is routed through the charge air cooler with charge air. By this way, low intake manifold temperatures are obtained. However, acid condensation is formed in the charge air cooler. Special aluminum alloys are used to overcome this problem.

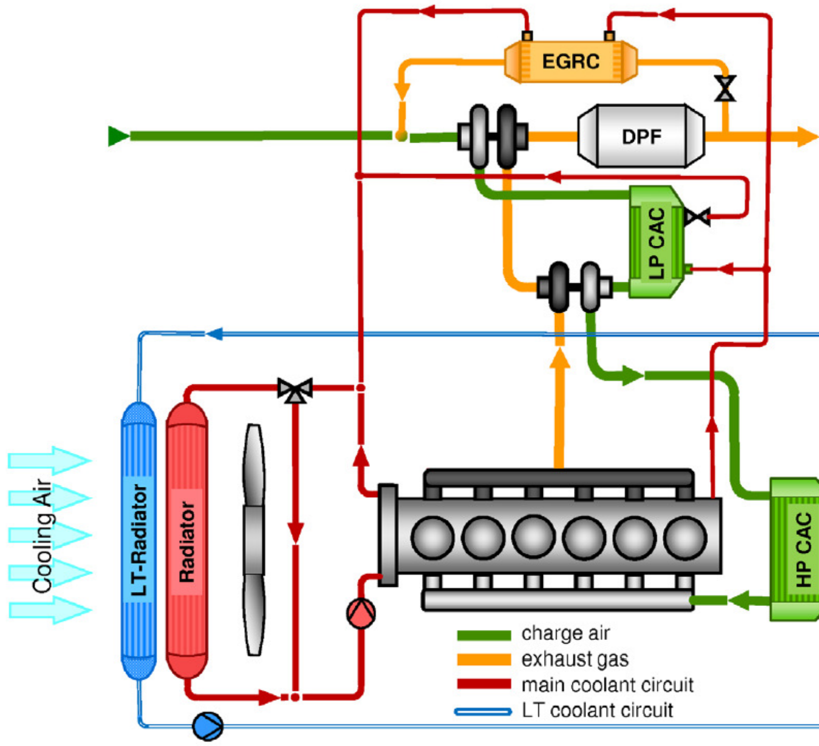

Figure 2.19 : Schematic of low pressure EGR with cooling system [16]

Figure 2.20 shows a schematic of double cooled low-pressure EGR application. As seen in the figure, EGR is taken after the Diesel Particulate Filter (DPF). Recirculated gas is initially cooled in EGR cooler and then mixed with charge air before the turbocharger compressor. Charge air and the re-circulated gas are further cooled in intercooler before they are sent to intake manifold.

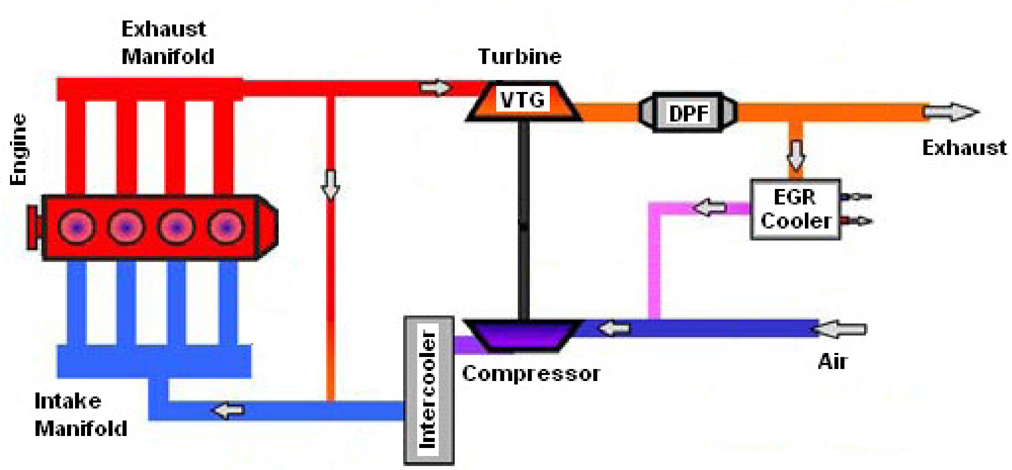

Figure 2.20 : Schematic of double cooled low pressure EGR [14]

As seen in Figures 2.19 and 2.20, it is applicable to take EGR from downstream of aftertreatment system even after DPF. This application obviosuly results in a cleaner cooler as the EGR is free of particulates and unburned HCs. However, most of the car manufacturers prefer to have a high-pressure EGR system as having a high-pressure EGR system increases fuel efficiency.

Main advantages of low pressure EGR are listed below.

- There is almost no soot in intake line as the recirculated gas is filtered.
- Low pressure EGR gas temperatures are lower when compared to the temperatures in high pressure EGR gas temperatures, as the loop is longer. A smaller cooler is sufficient.
- Low pressure EGR is easier to be assembled on an existing engine, as this process does not need great modifications.

On the other hand, response time to EGR variations is longer in low pressure EGR systems during transient operations, which can be considered as the main disadvantage.

2.4.3 Internal EGR system

Internal EGR can be simply defined as using residual gas for NO_x emissions reduction. Uncooled EGR can be retained in the cylinder by proper engine valve actuation strategy with the addition of a secondary lobe on the exhaust valve cam. The principal is to open the exhaust valve again during intake stroke so that high pressure exhaust gas is able to return to cylinder. [5]

Timing and lift distance of the secondary lobe is of great importance in terms of adjusting the rate of EGR flow. In addition, pressure pulsations from other cylinders need to be considered in design stage as they will directly affect the pressure differential across the exhaust valve.

Main advantages of internal EGR are summarized below.

- Cost and complexity are significantly reduced since there is no piping, EGR cooler and EGR valve. This application is also useful in terms of engine packaging.

- Pumping work and variable geometry turbine adjustment are not required to maintain the flow from exhaust line to intake line.
- Difficulties and problems of conventional EGR system during transient operation (lags, precision, and contamination) are avoided.

On the other hand, internal EGR has the following disadvantages.

- Less reduction can be achieved in NO_x emissions when compared to cooled EGR.
- For a specific NO_x emissions level, fuel consumption is increased when compared to cooled EGR.
- Uncooled EGR would result in a reduced intake charge density and hence higher PM emissions as well as power loss at high loads.

Schematic of an internal EGR system is shown in Figure 2.21.

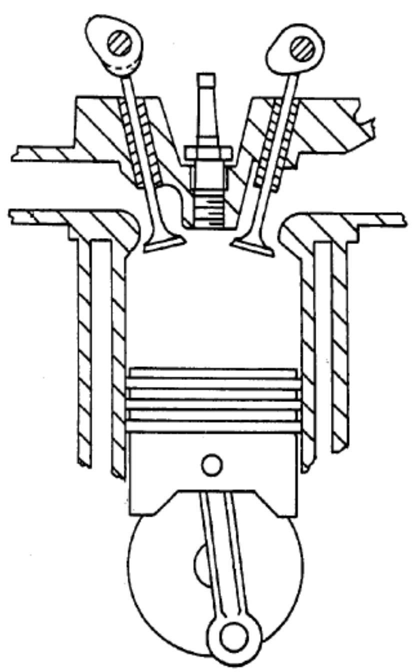

Figure 2.21 : Internal EGR system [17]

2.5 EGR System Control

Precise adjustment of EGR rate, which is regulated by EGR valve, is required to maintain the desired NO_x and PM emissions. EGR flow is a function of EGR valve position and pressure differential across the exhaust and intake line. Typically, EGR rate is reduced at high loads and EGR valve is closed when air to fuel ratio is low or sudden performance (high level of acceleration) is demanded.

Two types of EGR control are available based on the control strategy. These are open loop EGR control and closed loop EGR control.

In open loop control, ECU reads the desired EGR rate from the EGR maps (look up table) according to the engine speed and load. EGR valve is directed to the desired position. A schematic of open loop EGR system control is given in Figure 2.22 [5].

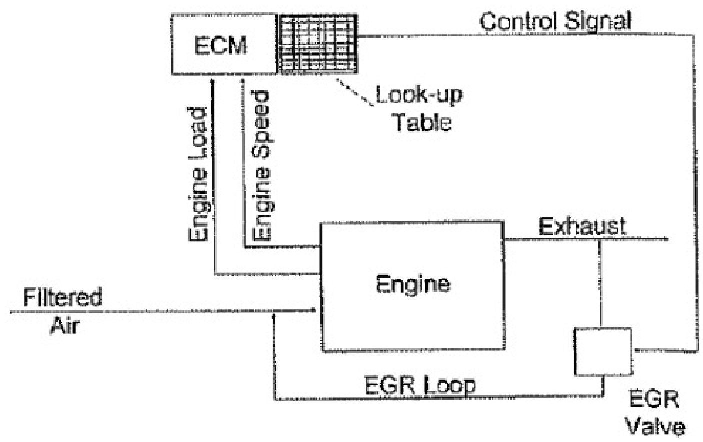

Figure 2.22 : Open loop EGR system control

In closed loop control, the principal is similar to open loop control but mass airflow is used as a feedback. By this way, actual and desired (specified in the EGR maps) EGR flows are compared and the EGR valve position is adjusted accordingly. A schematic of closed loop EGR system control is shown in Figure 2.23 [5].

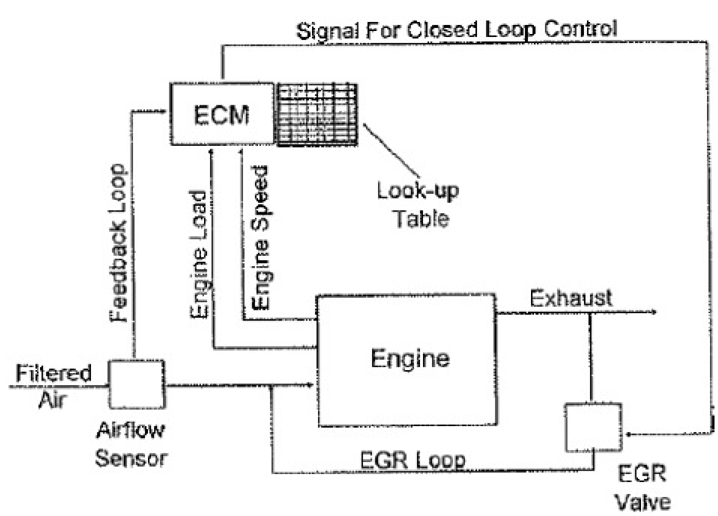

Figure 2.23 : Closed loop EGR system control

EGR cooler bypass valve (if present) also has a control strategy aiming to avoid overcooling of EGR gas at low speeds and loads. The rationale is to reduce the NO_x emissions at low loads and to prevent excessive contamination of EGR cooler. Bypass mode also helps engine warm-up after cold start.

3. EGR COOLERS

EGR coolers are the components used to cool EGR gas in order to decrease emission levels. Various studies have been performed to see the effect of cooled EGR on emissions. Results show that cooled EGR reduces NO_x emissions (not necessarily at low loads) significantly and improves particulate emissions slightly [6].

Most of today's engines have a single EGR cooler which uses engine coolant to cool the recirculated exhaust gas. There are also engines with multi coolers which are used when extra cooling is required (generally in vee engines) or when packaging requirements do not allow using a single cooler.

Nowadays, addition of a second cooling system to engine is under consideration during design phases to have more compact and effective coolers by keeping the coolant temperature around 50^{o}C. However, this application increases the overall cost of EGR system as well as leading to packaging related problems.

EGR coolers are described further in detail through this section in terms of basic design parameters, types and fouling.

3.1 EGR Cooler Basics

EGR coolers are effective heat exchangers to cool the EGR gas within a small volume allowed by the engine packaging requirements. They should meet required heat transfer performance without leading to higher-than-allowed pressure drop. Basic design parameters namely, overall heat transfer coefficient, effectiveness and pressure drop are explained in the following sections.

3.1.1 Overall heat transfer coefficient

Overall heat transfer coefficient can be defined as the ability to heat transfer for a set of elements, which may be either conductive or convective. This parameter is very important in determination of EGR system performance since cooling level has a significant impact on emissions.

Calculation of overall heat transfer coefficient is based on the conduction and convection resistance between the fluids passing through the cooler as shown in Equation 3.1 [18].

$$\frac{1}{UA} = \frac{1}{\eta_{0c} h_c A_c} + \frac{R_{fc}}{\eta_{0c} A_c} + R_w + \frac{R_{fh}}{\eta_{0h} A_h} + \frac{1}{\eta_{0h} h_h A_h} \qquad \textbf{(3.1)}$$

Overall efficiency of a finned surface can be calculated using Equation 3.2.

$$\eta_0 = 1 - \frac{A_f}{A}\left(1 - \eta_f\right) \qquad \textbf{(3.2)}$$

Single fin efficiency is given in Equation 3.3, where m is defined as in Equation 3.4.

$$\eta_f = \frac{\tanh(mL)}{mL} \qquad \textbf{(3.3)}$$

$$m = \left(\frac{2h}{kt}\right)^{1/2} \qquad \textbf{(3.4)}$$

Nusselt Number is the heat transfer coefficient in non-dimensional form and can simply be defined as the ratio of convective heat transfer perpendicular to the boundary to conductive heat transfer perpendicular to the boundary. It is dependent on Reynolds Number and Prandtl number as seen in Function 3.5.

$$Nu = f\left(\mathrm{Re}, \mathrm{Pr}\right) \qquad \textbf{(3.5)}$$

Reynolds number is the ratio of inertial forces to viscous forces and non-dimensionally expressed in Equation 3.6. A characteristic length is required to find the Reynolds number, which is the hydraulic diameter in the case of heat exchangers.

$$\mathrm{Re} = \frac{VD_h}{\nu} \qquad \textbf{(3.6)}$$

Prandtl number is a non-dimensional number and defined as the ratio of kinematic viscosity to thermal diffusivity as given in Equation 3.7.

$$\mathrm{Pr} = \frac{\nu}{\alpha} \qquad \textbf{(3.7)}$$

In case of mass transfer, Sherwood number is used. It is the ratio of convective mass flux in the boundary layer to pure diffusional flux and depends on Reynolds and

Schmidt numbers as shown in Function 3.8 where Schmidt number is defined as in Equation 3.9 [19].

$$Sh = f(\mathrm{Re}, Sc) \tag{3.8}$$

$$Sc = \frac{\nu}{D} \tag{3.9}$$

Mass transfer is usually out of scope in EGR coolers since there is no path for mass transfer between the gas and coolant circuits.

3.1.2 Effectiveness

Effectiveness is considered as the most common performance measure for EGR coolers and can be defined as the ratio of actual heat transfer to the maximum possible heat transfer, which would be when the EGR gas outlet temperature is equal to the EGR coolant inlet temperature. It can simply be calculated by measuring the coolant and gas temperatures as shown in Equation 3.10.

$$\varepsilon = \frac{Q_{act}}{Q_{\max}} = \frac{T_{Gin} - T_{Gout}}{T_{Gin} - T_{Cin}} \tag{3.10}$$

Effectiveness shows an asymptotic behavior based on the asymptotic deposit thickness formed on the heat transfer surfaces of the EGR cooler. This phenomena is further explained in section 3.3.5.

3.1.3 Pressure drop

Pressure drop is the pressure difference of EGR cooler inlet gas and EGR cooler outlet gas. Pressure drop is affected from the fouling of the heat exchange surfaces as well as the erosion of these surfaces throughout the lifetime. Among all of the EGR system parts, the biggest contributor to pressure drop is the EGR cooler.

Bernoulli's equation, which is given in equation 3.11, might be used to calculate the pressure drop across the EGR cooler. The equation is based on the exhaust gas density, local velocity of the exhaust gas and the resistance coefficient.

$$\Delta P = \xi \frac{\rho V^2}{2} \tag{3.11}$$

Resistance coefficient is increasing with the increased fouling of the cooler. Zhang and Nieuwstadt (2008) studied the change in resistance coefficient by investigating the pressure drop of an EGR cooler at different completed working hours.

The results show that, for an EGR cooler which is at a certain number of completed working hours, pressure drop is directly proportional to the velocity pressure of the fluid. It is also noted that a significant pressure drop increase is obtained because of the fouling formed within the cooler. The plot in Figure 3.1 shows the pressure drop with respect to velocity pressure for unused (new) cooler and for a cooler that has completed 234 working hours [20].

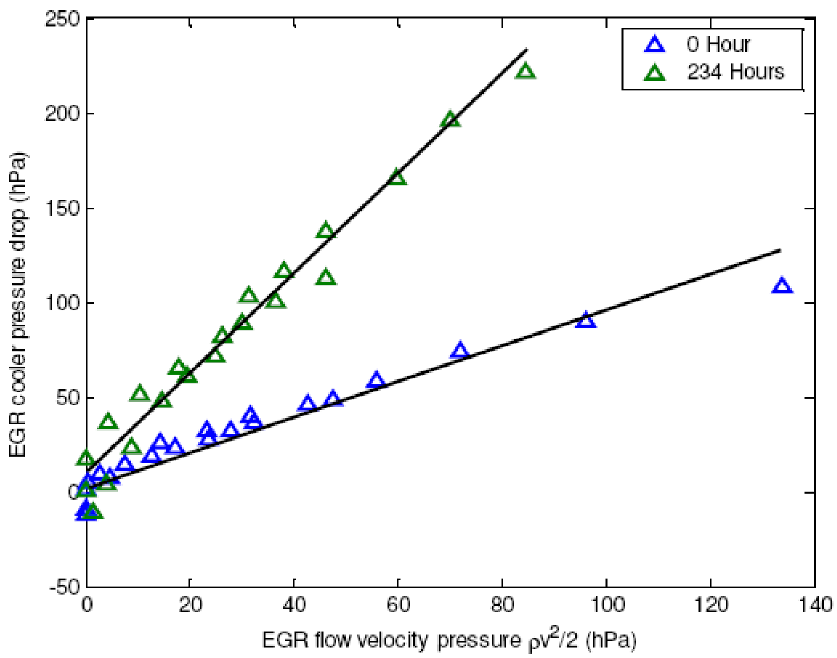

Figure 3.1 : EGR cooler pressure drop change with flow velocity pressure

3.2 EGR Cooler Types

Design of an EGR cooler includes optimization of heat transfer performance, pressure drop and resistance to contamination build-up while meeting the packaging requirements. Most common EGR cooler types are shell-and-tube EGR coolers and plate-and-fin EGR coolers, which are briefly explained in the following sections.

3.2.1 Shell-and-tube coolers

Shell-and-tube coolers are widely used for various engineering applications due to their possible low cost constructions. The structure consists of round tubes embedded in a cylindrical shell such that the tube axes are parallel to shell axis. Hot gas is driven through the round tubes. Coolant flowing through the shell cools the EGR gas. Configuration of a shell-and-tube cooler is shown in Figure 3.2.

Selection of tube material is critical since the tube is in contact with both the gas and the coolant. The tube should withstand the thermal stresses (since hot gas is passing through) and thermal expansion of the tube needs to be kept at certain levels in order not to threaten the durability of the cooler. Tubes should be made up of a material that has a high thermal conductivity so that satisfactory heat transfer is achieved. Finally, tubes should be corrosion-resistant in order to avoid unexpected failures.

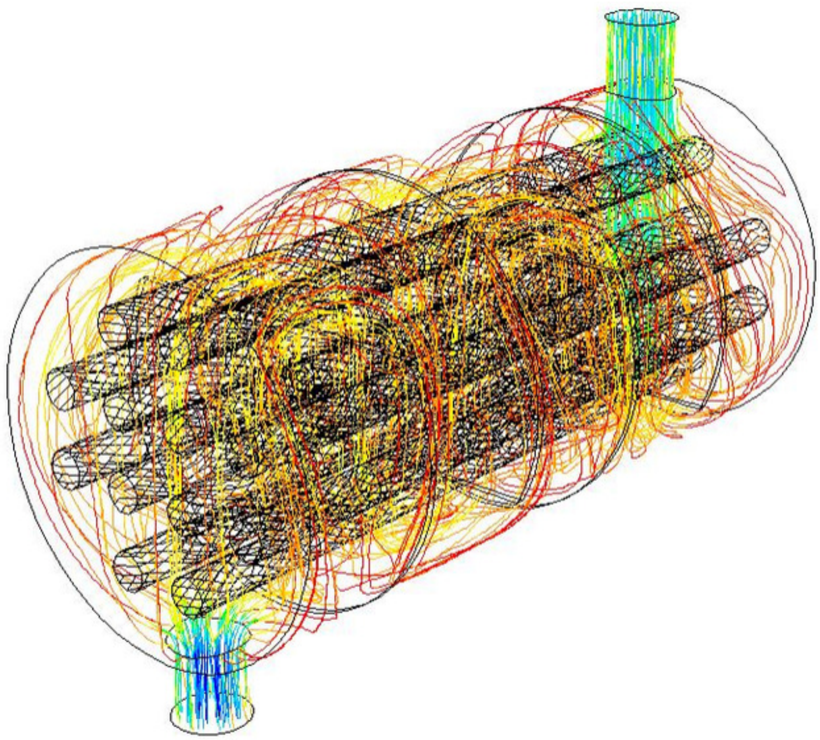

Figure 3.2 : Configuration of a shell-and-tube cooler [21]

3.2.2 Plate-and-fin coolers

Plate-and-fin coolers are commonly used in automotive and aerospace applications due the significant mass and volume reduction they provide. Flat plates separate gas and coolant flow and the flow channels include fins. The plate thickness is usually varying between 0.5mm and 1mm whereas; fin thickness has a range between 0.15mm and 0.75mm. Components are generally brazed to form the cooler structure. Basic structure of a plate-and-fin cooler is shown Figure 3.3.

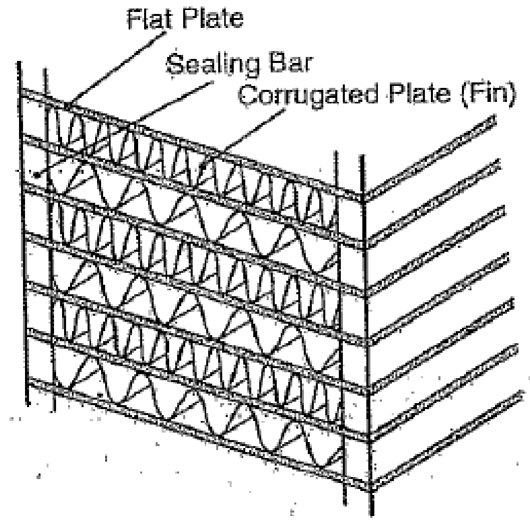

Figure 3.3 : Structure of a plate-and-fin cooler

Corrugated sheets supply an extended heat transfer area as well as providing structural support and they have several types. Plain fin, serrated fin and wavy fin are few of these types. Fins improve the heat transfer performance of a cooler since higher heat transfer coefficients are obtained. However, they lead to a higher pressure drop. In order to avoid excessive pressure drop, small flow channels are used in plate-and-fin coolers so that the mass velocity is kept at low values (10-300 kg/m^2s) [22].

3.3 EGR Cooler Fouling

Main goal of cooling EGR is to decrease the intake charge air temperature and hence the combustion temperatures while keeping the air to fuel ratio as required since NO_x and PM emissions can be reduced by low temperature combustion.

Hoard et al. (2008) studied diesel EGR cooler fouling in detail and revealed a comprehensive summary of fouling phenomena. Over the years, EGR coolers were used with low EGR rates and EGR cooler outlet gas temperatures around 125^{o}C depending on the emission regulations. With emission regulations getting stricter, EGR rates are increasing with reduced gas temperatures and low exhaust gas temperatures are very likely to form soot deposits, hydrocarbon deposits and acid deposits on the EGR cooler wall. EGR cooler heat transfer performance is degraded through life time due to deposit buildup on the walls of the cooler. This reduction might get values up to 20-30%. In addition to degraded heat transfer performance, pressure drop across the cooler is also increasing which can effect engine efficiency in some operating conditions. Some harmful effects of the deposits can be summarized as following.

- Contamination decreases the heat transfer performance of the cooler and intake charge air temperature increases.
- Contamination results in higher pressure drop which in turn leads to an increased pumping work and hence an increase in fuel consumption.
- Acidic deposits can easily lead to corrosion.

EGR cooler deposits can not be prevented since soot and HC are formed as a result of combustion process. Cooled surfaces tend to have thermophoretic soot deposition as well as HC and acids condensation. Oxidation catalysts can be used to remove unburnt hydrocarbons and hence reduce the fouling in some applications. An oxidation catalyst together with a wall-flow filter have a better performance in reduction of fouling.

Deposit materials can also be reduced by adjustment of engine calibration because cooled EGR gas is of great importance for emission control. Increasing gas velocities is another possibility to decrease the level of fouling. However, this leads to higher pressure drop across the cooler.

Different EGR cooler types have distinct deposit formation charactersitics. Common thinking is that fin type coolers are less subjected to contamination when compared to shell and tube type coolers because they have a larger surface area. However, experiments and investigations show that both type of coolers can be significantly contaminated. In modern engines, type of the cooler is generally chosen by considering the package requirements rather than only deposit performance.

After some operating time, deposits in the cooler tend to stabilize. This operating time has a range between 50 and 200 hours as per experiment results [18]. There is no clear understanding of stabilization mechanism in coolers but common ideas suggest that this case may be due to the deposit removal mechanisms or decrease in deposition rate with contamination build up.

Deposition composition in diesel engines is summarized with a pie chart in Figure 3.4 and is almost equally shared by soluble organic fraction (SOF) and soot. Soot is made up of carbon and ash where carbon is the top contributor among all the deposits and forms 80% of the soot; that is 40% of total contamination. SOF, which is composed of unburnt fuel, unburnt oil, sulphate and water forms the other half of fouling. Unburnt fuel is dominant over the other SOF components and forms more than half of the SOF. Unburnt oil is the least significant ingredient.

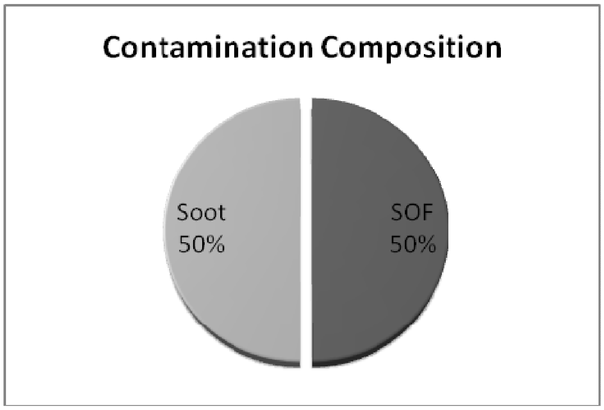

Figure 3.4 : Diesel engine contamination composition

Participants of deposition are briefly summarized below.

- Water: Formed as a combustion product.
- Soot: Solid carbon particles.
- HC: Carbon chains of different lengths, originating from diesel and oil.
- NO_x: From atmospheric Nitrogen (79% of Air)
- SO_x: From sulphur present in diesel.
- Fluorides: From aluminum brazed components and polymers
- Chlorides: From diesel and oil
- Ash: Due to inorganic salts present in diesel

Presence of sulphuric, nitric, and acetic acids is also common in diesel engines throughout the operation.

3.3.1 Deposition occurance conditions

Deposition can occur under the following conditions.

- Exhaust gas passing through EGR system results in contamination deposition under both steady-state and transient operating conditions.

- EGR valve is shut down in specific engine operating conditions especially when high performance is demanded, that is when throttle is wide open. In such a circumstance, recirculating gases are trapped within the EGR system with gas velocities of almost zero. “Super cooling” will take place which is actually the worst case for contamination.
- At engine start up, coolant temperatures are very low when compared to the coolant temperatures after warm-up. This results in additional cooling of recirculating gases. Low temperature EGR gas will form deposits.
- If the engine is operating in a cold climate region, coolant temperatures are lower and this leads to additional cooling resulting in deposits.
- At engine shut down, EGR valve is closed so that recirculating gases are trapped within EGR system. Condensation of particles and gases will form deposits.

3.3.2 Forces acting on the particles

Particles in EGR gas is continuously under the effect of several forces which causes these particles to deviate from the main flow and leads to deposition on EGR cooler walls.

Forces acting on the particles are significantly dependant on the particle size and can be classified in two main groups namely, deposition forces and removal forces. Deposition forces are further explained below.

- *Thermophoretic force*: Particles being close to a hot source are subjected to a force in the direction away from the source since the air molecules near to hot side of the source are hotter and more energetic. This behaviour has the most significant effect on fouling and can be explained by the temperature gradient, thermophoretic force and drag force as shown in Figure 3.5.

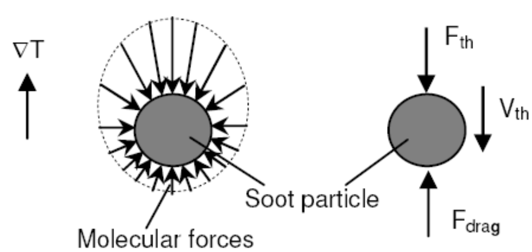

Figure 3.5 : Thermophoretic force on a particle

- *Gravitational force*: EGR gas is composed of particles with different densities and gravitational settling forces are acting on the particles as a result of density variation.
- *Electrostatic force*: Polar molecules available in the exhaust gas initiates a static charge forming an electrostatic field as a result of the friction between these molecules and the EGR cooler wall. This phenomena, however, is considered to have a minor effect on contamination when compared to other significant effects.
- *Brownian force*: Random movements of the adjacent particles affects the overall motion of the particles [23].
- *Diffusiophoretic force*: A particle is highly likely to be impacted by water molecules if it is near to an evaporating surface, especially on the surface side of the particle. Deposition velocity of a particle is slightly increased as there is a net force towards the surface since average molecular weight of air is greater than the molecular weight of water.

3.3.3 Parameters affecting fouling

Parameters that affect fouling are briefly summarized below and their effects on fouling are presented in Table 3.1.

- Temperature of exhaust gas: Fouling severity increases with decreasing exhaust gas temperature.
- Temperature of coolant: Fouling severity increases with decreasing coolant temperature.
- Concentration of PM: Fouling severity decreases with decreasing PM concentration.
- Concentration of HC: Fouling severity decreases with decreasing HC concentration.
- Reynolds number of exhaust gas: Fouling severity increases with decreasing Reynolds number of exhaust gas.
- Heat transfer surface area: Fouling severity increases with decreasing heat transfer surface area.

Table 3.1: Parameters affecting fouling

Parameter	Action	Fouling Severity
Temperature of exhaust gas	↓	Increase
Temperature of coolant	↓	Increase
Concentration of HC	↓	Decrease
Concentration of PM	↓	Decrease
Exhaust gas Reynolds number	↓	Increase
Heat transfer surface area	↓	Increase

3.3.4 Fouling mechanism

Fouling is a complicated combination of various mechanisms. Mulenga et al. (2009) covered these mechanisms under the following four items [24].

- Thermophoretic particle deposition: Thermal gradients are formed within the gas channels of EGR cooler as a result of internal flow temperature distribution which in turn leads to deposition of HCs and ash particles on the cooler wall.
- Condensation: Condensed acids and HCs on cooler surface triggers the adhesion of more particles to the surface since they form a glue-like film.
- Turbulence: Ash particles and soot deposits are formed as they hit the cooler wall during turbulent flow.
- Diffusion: Condensates on the cooler wall forms a low concentration region and initiates a concentration gradient. This is followed by the diffusion of particles towards the cooler wall.

Teng and Regner (2009) briefly explained the fouling in three stages. Deposit formation starts with nano particles landing on the cooler wall as a result of thermophoresis. These particles are held together by van der Waals forces and forms a coating on the surface. This layer is defined as base layer and has a high density with high thermal conductivity. Then, intermediate layer starts to develop which is composed of molecules held together by random packing and has moderate density and thermal conductivity. Particles close to base layer are experiencing van der Waals forces as well. Uppermost layer is referred to as surface layer where the molecules are kept together by mechanical interlock. This is a highly porous layer with low density and thermal conductivity.

Deposit structure, which is composed of three layers, is shown in Figure 3.6. Base layer has a high density and low porosity (smaller than 10nm). Intermediate layer has medium sized porosities ranging between 10nm and 50nm whereas surface layer has pores with sizes greater than 50nm. It is important to note that special treatment is necessary to remove the base layer while EGR flow can remove partices from intermediate and surface layers with shear force based on the flow velocity.

Heat transfer resistance depends on the thicknesses of the three layers as shown with a schematic in Figure 3.7 [23].

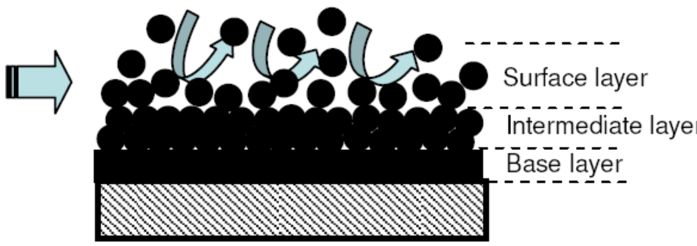

Figure 3.6 : Deposit structure

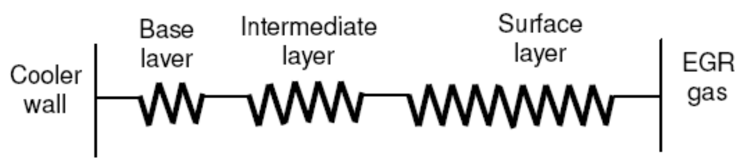

Figure 3.7 : Deposit resistance to heat transfer

Condensation depends significantly on flow conditions and can be studied in the following three cases according to the magnitude of pressure drop. Table 3.2 is a summary of condensation characteristics under different conditions.

- *Low Wall Side Pressure Drop and Low Gas Pressure Drop*: This case occurs when the engine is in warm up phase and results in condensate accumulation in the whole cooler.
- *Low Wall Side Pressure Drop and High Gas Pressure Drop*: This case occurs when the engine is warm and results in a moist surface on cold end of the cooler.
- *High Wall Side Pressure Drop and High Gas Pressure Drop*: This case also occurs when the engine is warm and results in a dry wall on hot end of the cooler.

Table 3.2: Different condensation conditions

Wall Side Pressure Drop	Gas Side Pressure Drop	Effect on Fouling
↓	↓	Condensate accumulation
↓	↑	Wet contamination
↑	↑	Dry contamination

3.3.5 Asymptotic fouling

Fouling shows an asymptotic behaviour rather than an always increasing trend throughout the life time. Initially, when the cooler is clean, contamination mass deposition rate ($\dot{M}_d$) is greater than contamination mass removal rate ($\dot{M}_r$). However, fouling settles around a certain value after some time which in fact means that mass deposition rate is becoming equal to mass removal rate. Asymptotic fouling is shown with a graph in Figure 3.8.

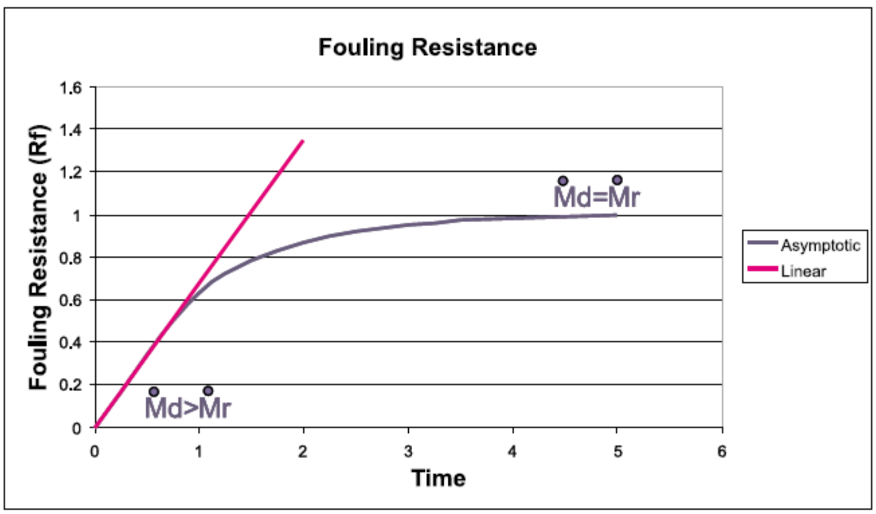

Figure 3.8 : Asymptotic fouling in coolers [2]

Local flow near the wall will result in a wall shear stress. A schematic is given in Figure 3.9 to represent the gas flow, mass deposition rate and mass removal rate.

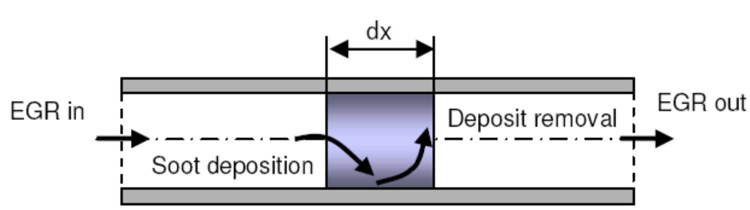

Figure 3.9 : Schematic of gas flow, mass deposition and removal rates [23]

Speed near the wall depends highly on tube geometry. Flow distribution and obstacles in the flow need to be considered to evaluate their effects on the flow and speed.

Velocity distributions differ with different tube geometries. Some geometries tend to form stagnation points which results in a lower speed and hence worse fouling characteristics. Figure 3.10 shows the fluid velocity distribution in a tube. Colors from green to red stand for increasing speeds.

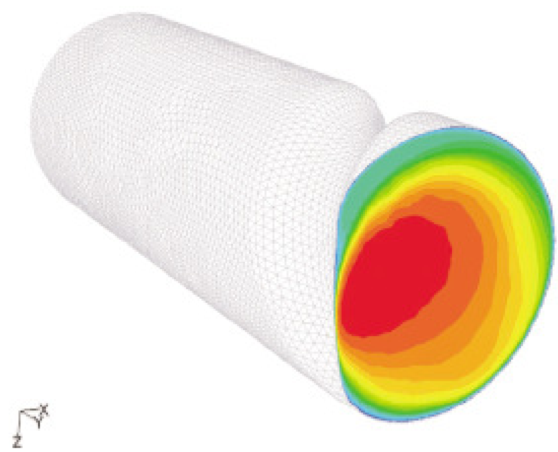

Figure 3.10 : Velocity distribution of a fluid in a tube [2]

Obstacles in the flow is another point of consideration. The boundary layer is broken whenever an obstacle is present and as a result low speed and low wall shear stress are obtained which leads to worse fouling. The effect becomes more significant with increasing obstacle depth. Square tubes and notched tubes are generally sources of obstacles as shown in Figure 3.11 and 3.12 respectively. Notched tubes are commonly used to meet packaging requirements.

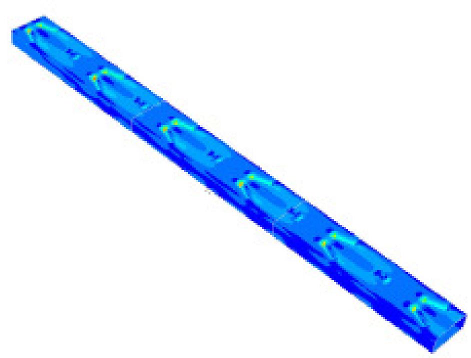

Figure 3.11 : Square tube

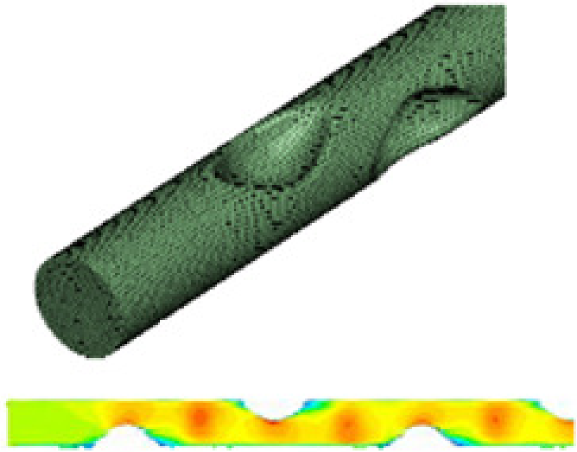

Figure 3.12 : Notched tube

Wall shear stress is in fact a measure of friction between the gas and the tube. Wall shear stress for spiral tubes deviate throughout the length of the tube. Wall shear stress distribution of a spiral tube is given in Figure 3.13. Colors from blue to red stand for increasing shear stresses. Top of the ridges is the location where maximum shear stress is obtained whereas minimum wall shear stress locations are before and after the corrugations.

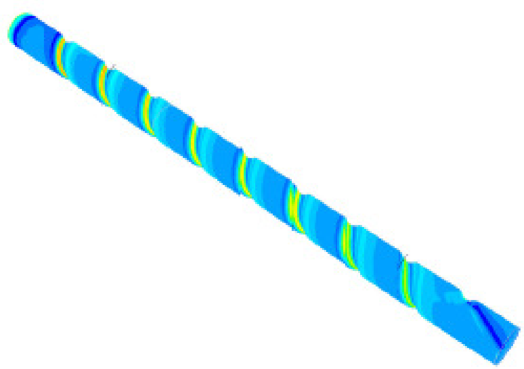

Figure 3.13 : Wall shear stress distribution of a spiral tube

Corrugations are generally added to cooler tubes in order to increase the heat transfer area and to compensate the thermal expansion during operation. Randomly added corrugations may result in detachment of the flow from the tube. Hence, pitch to corrugation depth ratio needs to be determined in a way which ensures the flow is recovered after passing through the corrugations. Average wall shear stress and pressure drop increase with increasing depth of the corrugation. Pressure drop and efficiency relation with increasing corrugation depth is shown in Figure 3.14.

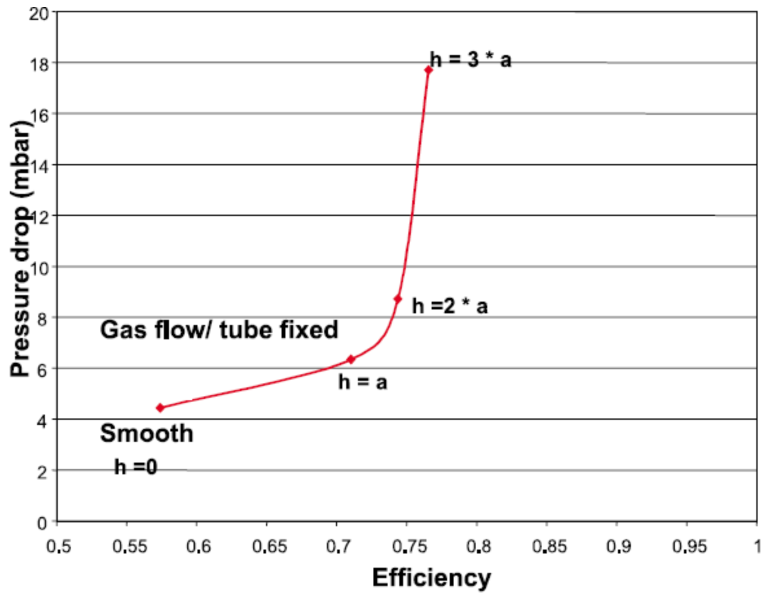

Figure 3.14 : Effect of corrugation depth on pressure drop and efficiency [2]

As seen in Figure 3.14, having a corrugation increases the efficiency. However, after a certain corrugation depth, efficiency does not tend to increase much whereas the pressure drop increases significantly. This figure also supports that corrugation depth should be selected by considering the efficiency and pressure drop.

Following remarks can be listed based on the previously explained sections.

- Engine calibration and working conditions have great effect on soot emissions.
- Lower performance reduction is obtained with higher average speed gas flows.
- Velocity distribution is of great importance, especially near the wall.
- Corrugation parameters need to be determined to get the maximum performance without detaching the flow from the tube.

3.3.6 Cleaning mechanisms

Cleaning mechanisms can be broadly classified in two groups, namely physical and chemical cleaning mechanisms.

Most significant chemical cleaning mechanism is combustion which is the ignition of deposited HCs at high gas temperatures.

Physical cleaning mechanisms can be summarized as following.

- Blowing: Blowing is the breaking of non-stable deposits from deposit layer.
- Washing: Condensation washes the deposits.
- Cracking: Deposit layer is cracked due to temperature and pressure cycling.
- Evaporation: If EGR system operating temperature is higher than the contaminants' dew point temperature, this results in evaporation.

Dew point temperature is the temperature at which the first droplet of liquid is formed within a vapor. Dew point temperatures for sulphuric acid and nitric acid are given for various H_2O compositions in Figures 3.15 and 3.16 respectively.

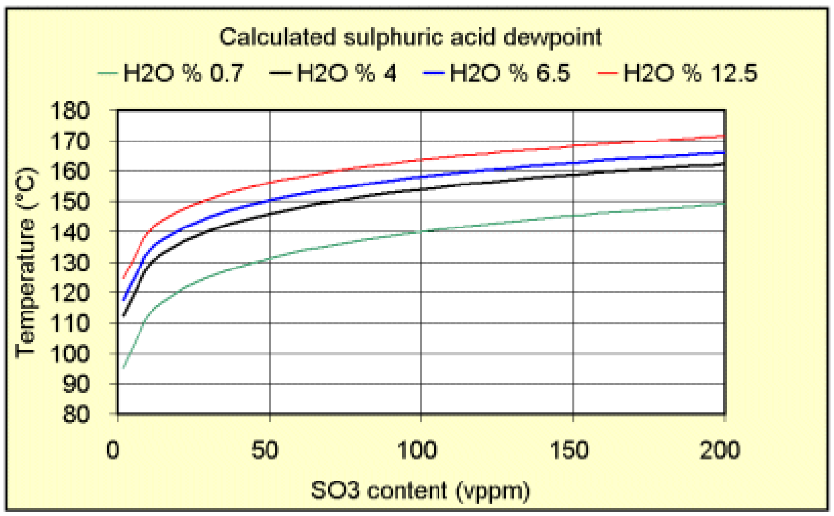

Figure 3.15 : Dew point temperature of sulphuric acid [25]

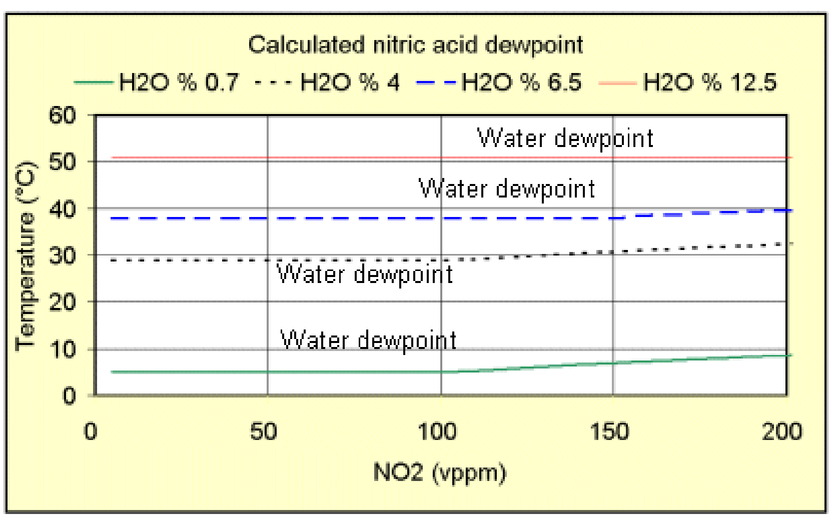

Figure 3.16 : Dew point temperature of nitric acid [26]

3.3.7 Fouling reduction strategies

Few of most common fouling reduction strategies are listed below.

- Allowing high pressure drop within EGR cooler.
- EGR valves can be sequentially adjusted rather than having a non-single EGR system.
- Application of EGR cooler bypass mode under a certain gas temperature.
- Minimizing the leak through bypass valve so that the speed is maximized.

In addition to above listed recommendations, a fouling cycle needs to be determined to set the specifications for EGR system components in fouled state.

4. THE EXPERIMENTS

4.1 Objective

The objective of this experimental study is to determine the effect of different drive cycles on EGR cooler contamination and to assess the effect of EGR cooler contamination on EGR valve position in closed loop EGR control system.

4.2 Test Engine

Test engine is a 4.4L V8 Euro5 direct injection diesel engine with a common rail fuel injection system of up to 2000 bar injection pressure. EGR system is composed of EGR tubes, a hot side water-cooled EGR valve and a cold side EGR cooler with EGR cooler bypass valve as shown with a schematic in Figure 4.1

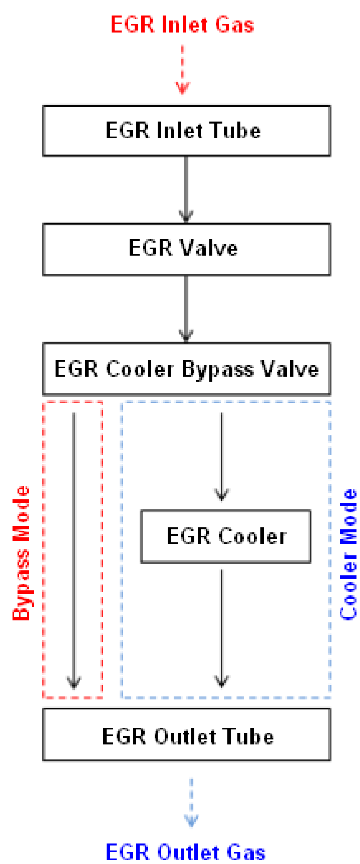

Figure 4.1 : Test engine EGR system schematic

4.2.1 Test engine specification

Test engine specification is given in Table 4.1.

Table 4.1 : Test engine specification

4.4L Common Rail Diesel Engine	
Displacement	4367 cc
Number of cylinders	8
Valves per cylinder	4
Bore x stroke	84 mm x 98.5 mm
Compression ratio	16:1
Maximum power	225 kW @ 4000 rpm
Maximum torque	700 Nm @ 1500-3000 rpm
Maximum engine speed	4500 rpm

4.2.2 EGR system cooler and bypass modes

Engine calibration activates EGR system when engine torque is lower than 400Nm and engine speed is lower than 2000rpm as shown with the blue boundary in Figure 4.2.

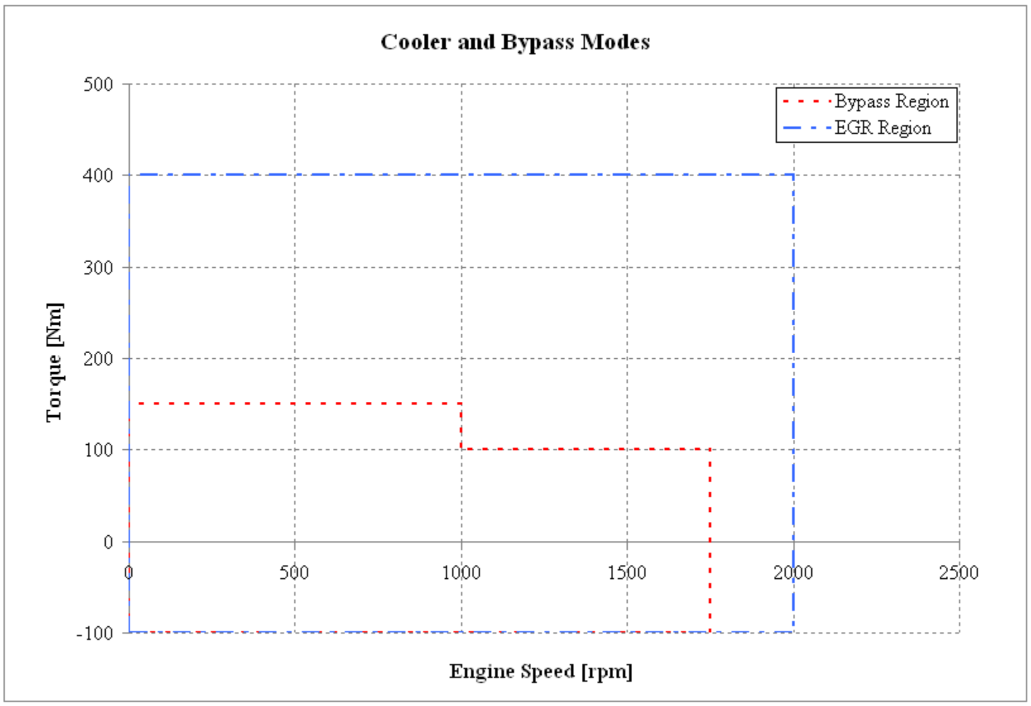

Figure 4.2 : Cooler and bypass modes

Exhaust recirculation gas is bypassed the cooler in some conditions based on the following rationales.

- To reduce the NO_x emissions at low loads.

- To prevent excessive fouling of the EGR cooler.
- To support engine warm-up in cold start conditions.

Bypass mode is utilized for torque values lower than 150Nm between engine idle speed and 1000rpm plus torque values lower than 100Nm between 1000rpm and 1750rpm. Bypass mode operating range is shown with the red boundary in Figure 4.2. The region remaining between the blue and red boundaries is the cooler mode operating range.

Transition within cooler and bypass modes might have slight variations although they are strictly separated in Figure 4.2, which is a generic overview. Engine calibration has two different maps for bypass and cooler modes to determine the transition conditions.

If EGR system is working in bypass mode at a boundary point (very close to cooler mode), bypass mode map is considered as explained below.

- For a specific operating point, if the engine temperature is higher than the defined temperature in bypass mode map, cooler mode is activated.
- For a specific engine speed, if the engine temperature is lower than the defined temperature in bypass mode map, cooler mode is activated at a slightly higher torque than specified in Figure 4.2.

If EGR system is working in cooler at a boundary point (very close to bypass mode), cooler mode map is considered as explained below.

- For a specific operating point, if the engine temperature is lower than the defined temperature in cooler mode map, bypass mode is activated.
- For a specific engine speed, if the engine temperature is higher than the defined temperature in cooler mode map, bypass mode is activated at a slightly lower torque than specified in Figure 4.2.

It is important to note that EGR system is active in bypass mode in motoring conditions. This is the region where negative torque is obtained as can be seen in Figure 4.2. This condition is representing clutch engaged case with no load and hence no fuel injection.

4.3 Drive Cycles

Three different drive cycles, with different engine speed and torque characteristics as well as different bypass mode and cooler mode distributions, were run to compare the level of EGR cooler fouling.

Among these cycles, cycle 1 represents low load driving conditions. It has the lowest speed, torque and hence power averages forming an appropriate environment for high level of contamination. Engine speed and torque plot with respect to time for cycle 1 is shown in Figure A.1. EGR is active almost all of the time and greater time is spent in bypass mode. Distribution of cycle 1 is shown with a scatter plot in Figure A.2.

Cycle 2 represents expressway driving conditions with relatively high speed and torque averages. Engine speed and torque plot with respect to time for cycle 2 is shown in Figure A.3. EGR active period is slightly less than the two other cycles and greater time is spent in cooler mode since higher exhaust gas temperatures are obtained. Distribution of cycle 2 is shown with a scatter plot in Figure A.4.

Cycle 3 stands for countryside driving conditions with average speed, torque and power values being in between cycles 1 and 2. Engine speed and torque plot with respect to time for cycle 3 is shown in Figure A.5. EGR is active almost all the time and slightly more time is spent in bypass mode when compared to the time spent in cooler mode. Distribution of cycle 3 is shown with a scatter plot in Figure A.6.

Table 4.2 is a summary of EGR active, cooler mode and bypass mode percentages of the three drive cycles whereas Table 4.3 shows the average speed, average torque and average power of the cycles.

Table 4.2 : EGR active, cooler mode & bypass mode percentages of drive cycles

Cycle	EGR Active [%]	Cooler Mode [%]	Bypass Mode [%]
Cycle 1	99,50	20,33	79,17
Cycle 2	97,72	67,86	29,86
Cycle 3	99,17	43,86	55,31

Table 4.3 : Average speed, average torque & average power of drive cycles

Cycle	Av. Speed [rpm]	Av. Torque [Nm]	Av. Power [kW]
Cycle 1	1177	62	8
Cycle 2	1430	161	26
Cycle 3	1367	96	15

4.4 Test Points

Performance parameters of the EGR system were recorded at certain operating points in specific time intervals to monitor the degradation within time. Once the running period of the driving cycle is over, engine was run at these points and parameters were recorded after steady state is reached. Cooler mode points were considered since the cooler contamination is the main point of interest.

Seven EGR active cooler mode operating points were used to collect the steady state data. Among these seven points, three points are selected to be presented as test points. These points are 1750rpm/300Nm (test point 1), 2000rpm/300Nm (test point 2) and 2000rpm/347Nm (test point 3). Test points are located on the EGR active region in Figure 4.3.

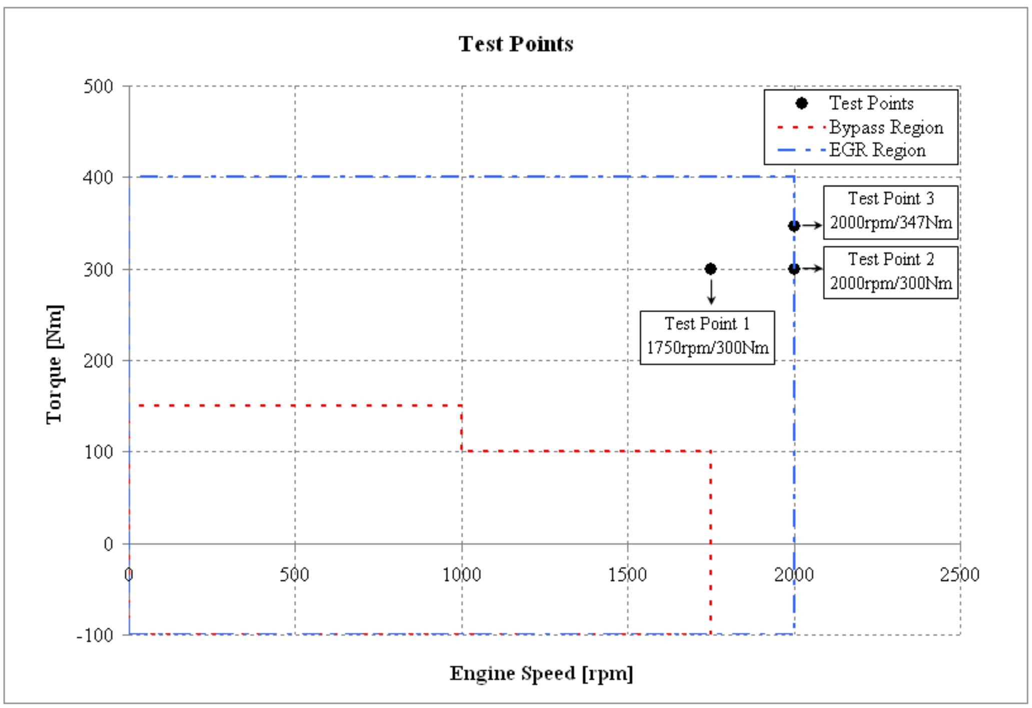

Figure 4.3 : Test points

4.5 Test Procedure

Test procedure is illustrated below.

1. Fit an unused EGR cooler to the engine.
2. Record EGR gas inlet temperature, EGR gas outlet temperature, EGR coolant inlet temperature, EGR gas inlet pressure, EGR gas outlet pressure, EGR

valve position, CO_2 percentage in feedgas and CO_2 percentage in intake manifold at the beginning of the test.

3. Run the cycle for 1 hour.
4. Shut down the engine while it is hot for 10 minutes.
5. Repeat steps 3 and 4 nine more times to complete 10 hours run.
6. Record EGR gas inlet temperature, EGR gas outlet temperature, EGR coolant inlet temperature, EGR gas inlet pressure, EGR gas outlet pressure, EGR valve position, CO_2 percentage in feedgas and CO_2 percentage in intake manifold at the end of 10 hours running.
7. Shut down the engine for 5hours to cool.
8. Repeat steps 3 to 7 till 110 running hours are completed.
9. Repeat steps 1 to 8 for the second and the third drive cycles.

4.6 Results and Discussion

Throughout the test, degradation or behavior of several parameters were monitored to evaluate the effect of different drive cycles. These include the EGR cooler effectiveness, EGR valve position, EGR rate and EGR system pressure drop whose results are summarized in the following sections. It is important to note that the test engine has a closed loop control for EGR system and adjustments are made by the system to compensate the deterioration caused by fouling during operation.

4.6.1 Effects of various drive cycles on EGR cooler contamination

EGR cooler effectiveness was calculated in certain time intervals with measured EGR gas inlet temperature, EGR gas outlet temperature and EGR coolant inlet temperature by using Equation 3.10. Because of contamination build up, effectiveness values were found to be decreasing.

Effectiveness curves for test point 1, test point 2 and test point 3 are shown in Figures 4.4, 4.5 and 4.6 respectively for all drive cycles. Investigation of these plots yields that the highest level of contamination was observed in drive cycle 1 resulting in the highest effectiveness drop (approximately 5%).

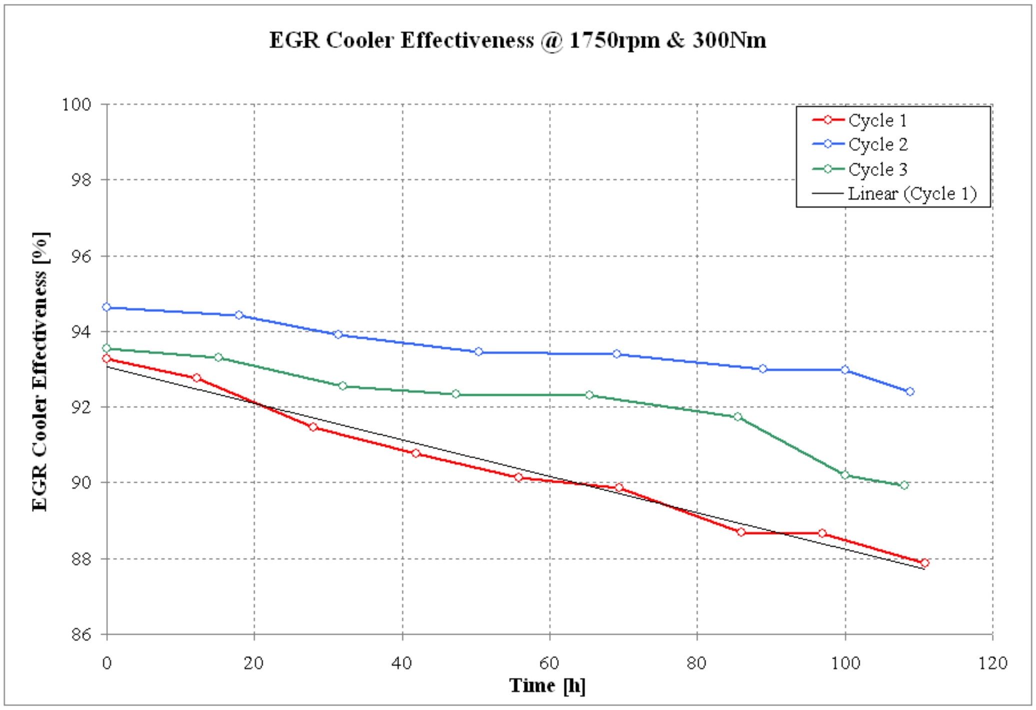

Figure 4.4 : EGR cooler effectiveness @ test point 1

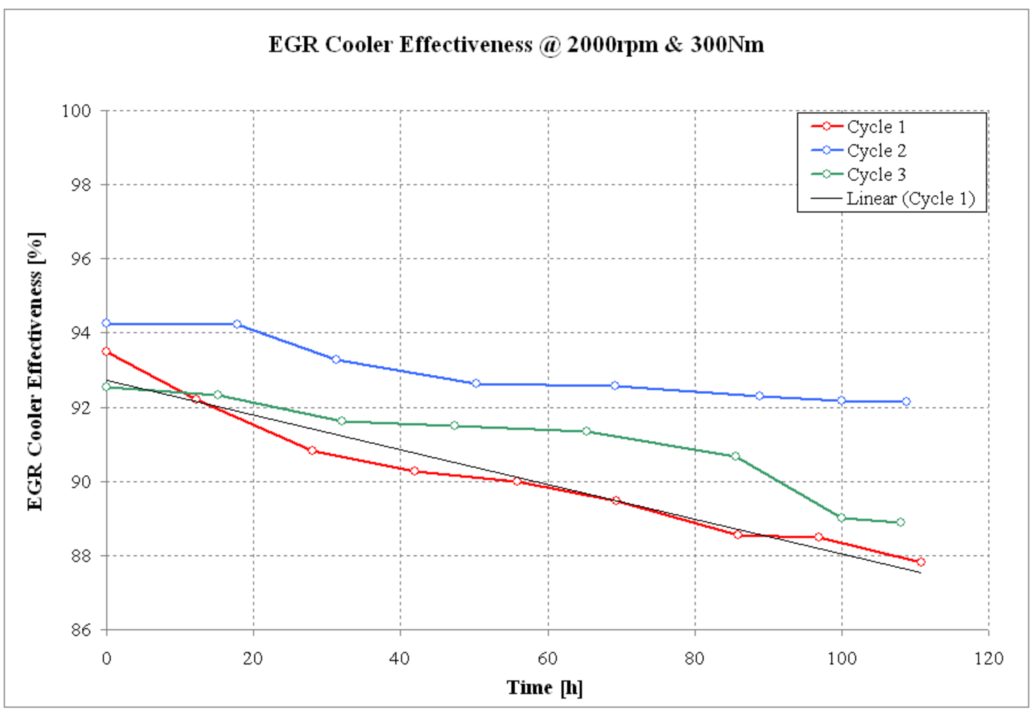

Figure 4.5 : EGR cooler effectiveness @ test point 2

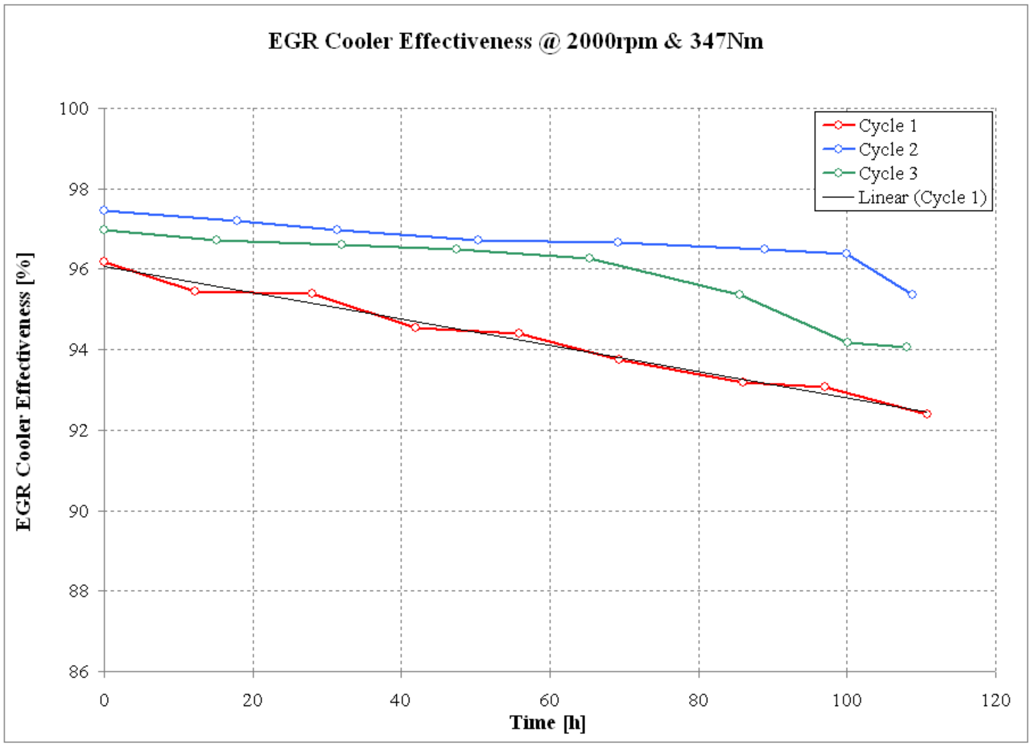

Figure 4.6 : EGR cooler effectiveness @ test point 3

Cycle 1 has the lowest average load, lowest average speed and hence the lowest average power. This would result in a slow low temperature flow through EGR system and form an appropriate environment for contamination. However, EGR cooler mode is only active for 20.33% during this cycle, which would mean that the gas is bypassing the cooler most of the time. High level of contamination in cycle 1 can be explained by the leakage across the bypass flap through the cooler because there is not a sealing available between the flap and its seat. Even the system is operating in bypass mode; bypass flap is not fully closed in order to prevent sticking and approximately 20% of the overall flow is passing across the cooler. When combined with the suitable fouling environment, particles getting inside the cooler, build up the most significant fouling layer among the three different drive cycles.

EGR cooler from cycle 2 has the least level of contamination although it is spending the greatest amount of time in cooler mode (67.86%). Average load and average speed of this cycle are greater than those of other two cycles. This would result in a high temperature gas flow with high Reynolds number (high turbulence) which makes the EGR cooler less prone to fouling.

Cycle 3 has medium loads, medium speeds and at the end had mid-level of fouling. The time spent in bypass mode is between that of cycle 1 and 2. Obtained results are supporting each other and lead to a general comment that the fouling is more severe with low loads, low speeds while spending more time in bypass mode.

Mulenga et al. (2009) carried out an experimental study about EGR cooler fouling at freeway cruise with various types of EGR coolers. The engine was run at a single operating condition to monitor the degradation in EGR cooler effectiveness and results are shown in Figure 4.7 [24]. EGR cooler effectiveness settled at around 30hrs in Mulenga's study whereas coolers that have completed 110hrs did not stabilize in this study. This behavior can be explained by the flow characteristics as the drive cycles have a transient attitude. Nevertheless, the trends of the obtained curves are very similar to the curves in Figure 4.7 for the first few hours.

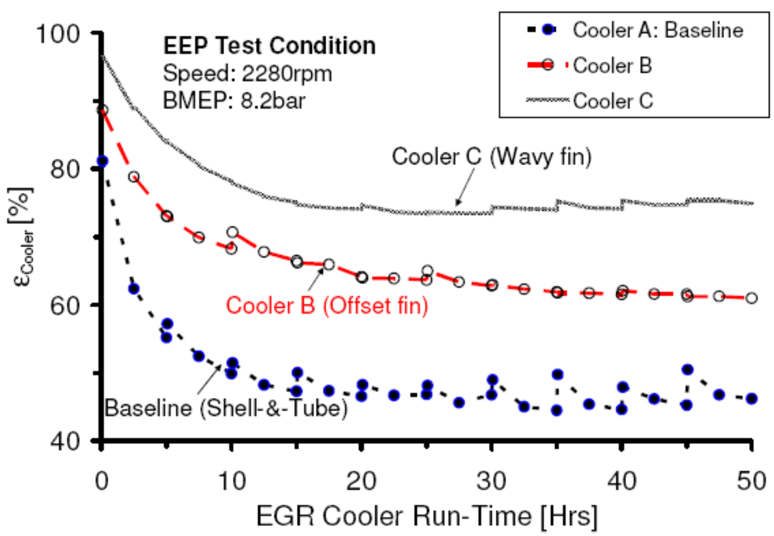

Figure 4.7 : EGR cooler effectiveness degradation

EGR cooler contamination is inevitable when the nature of the ingredients of the exhaust gas is considered. Keeping in mind that the contamination thickness and resistance stabilize after some time rather than showing an always-increasing trend, EGR coolers are designed a bit oversized so that they will continue to meet operation requirements after subjected to fouling.

Introducing an oxidation catalyst in the EGR cooler upstream was another option studied by Hoard et al. (2008) to reduce the HC content passing through the cooler. By this way, less fouling was observed with a higher stabilized cooler effectiveness [18].

4.6.2 Effects of contamination on EGR valve position

EGR valve position is continuously adjusted with closed loop control to maintain the desired EGR rate defined in EGR map for an operating point. As the cooler gets contaminated, EGR valve starts to open more to keep the required level of flow. Measured EGR valve positions for test point 1, test point 2 and test point 3 are shown in Figures 4.8, 4.9 and 4.10 respectively for all drive cycles.

Greatest valve position was recorded in cycle 1 for all of the three test points. This is consistent with the results of cooler contamination since the highest level of cooler contamination was also observed in cycle 1.

A relation was developed for EGR valve position depending on the EGR cooler effectiveness by fitting the best lines to the measured points for test point 1, test point 2 and test point 3 as shown in Figures 4.11, 4.12 and 4.13 respectively for all drive cycles. Line equations are also embedded to these figures where "y" stands for the EGR valve position in percentage whereas "x" stands for the EGR cooler effectiveness in percentage. It is important to note that the slopes of the lines are negative since the valve opening increases with decreasing cooler effectiveness.

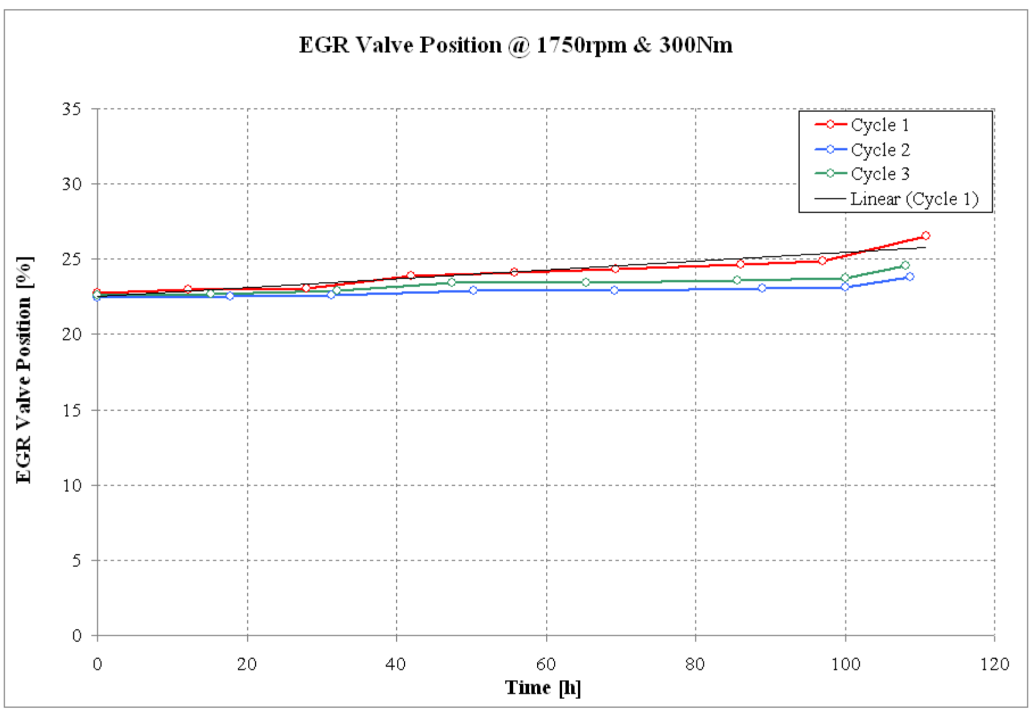

Figure 4.8 : EGR valve position @ test point 1

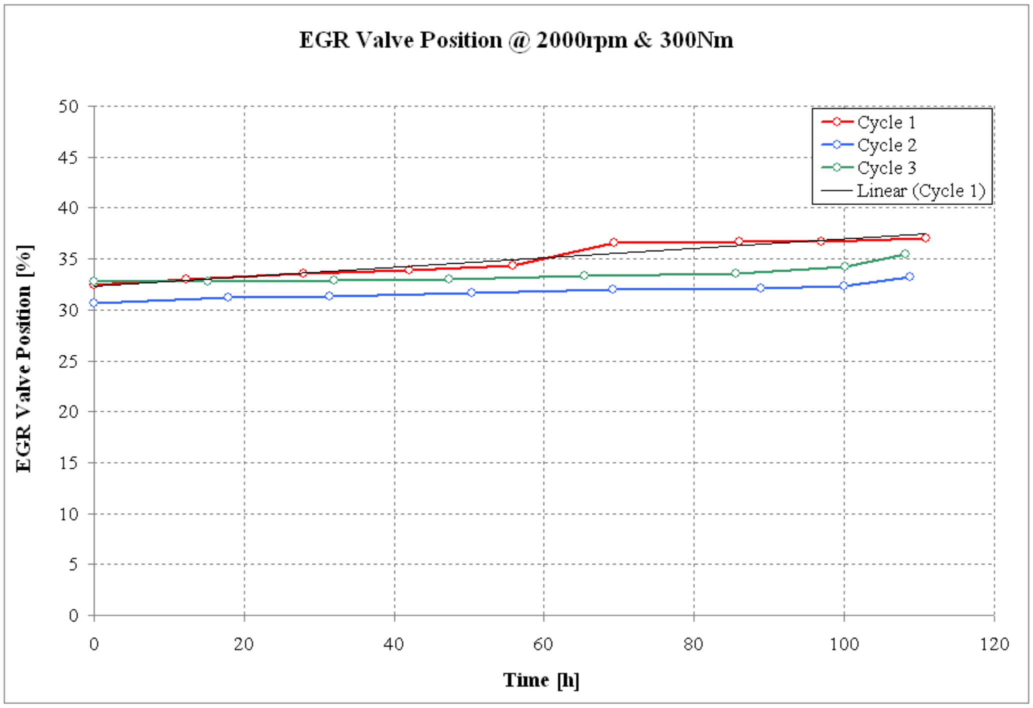

Figure 4.9 : EGR valve position @ test point 2

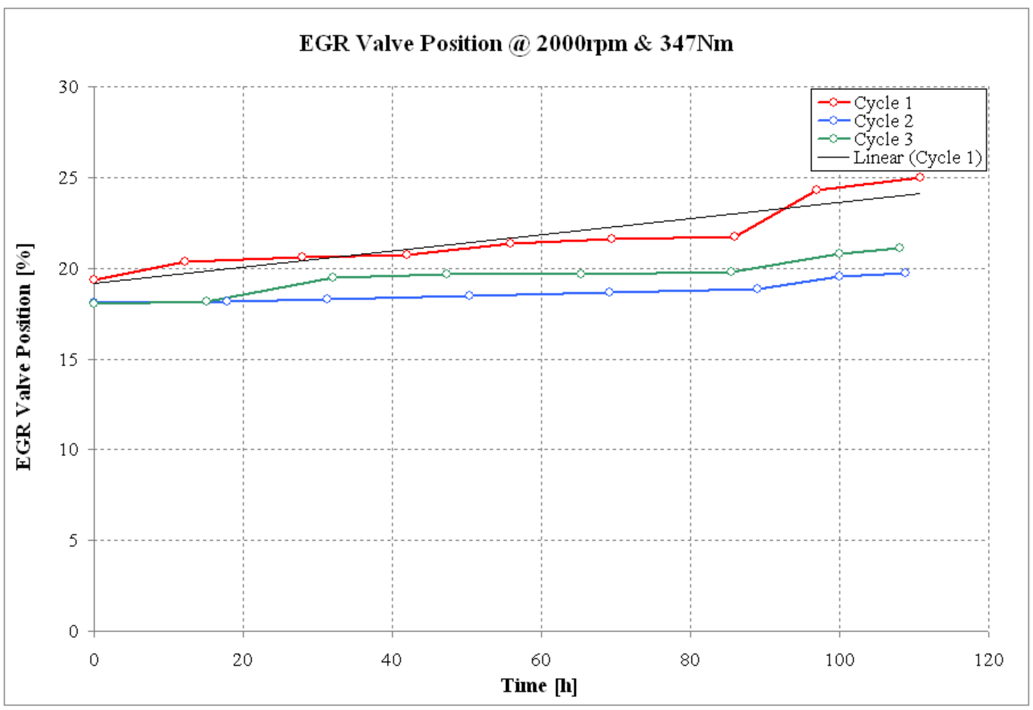

Figure 4.10 : EGR valve position @ test point 3

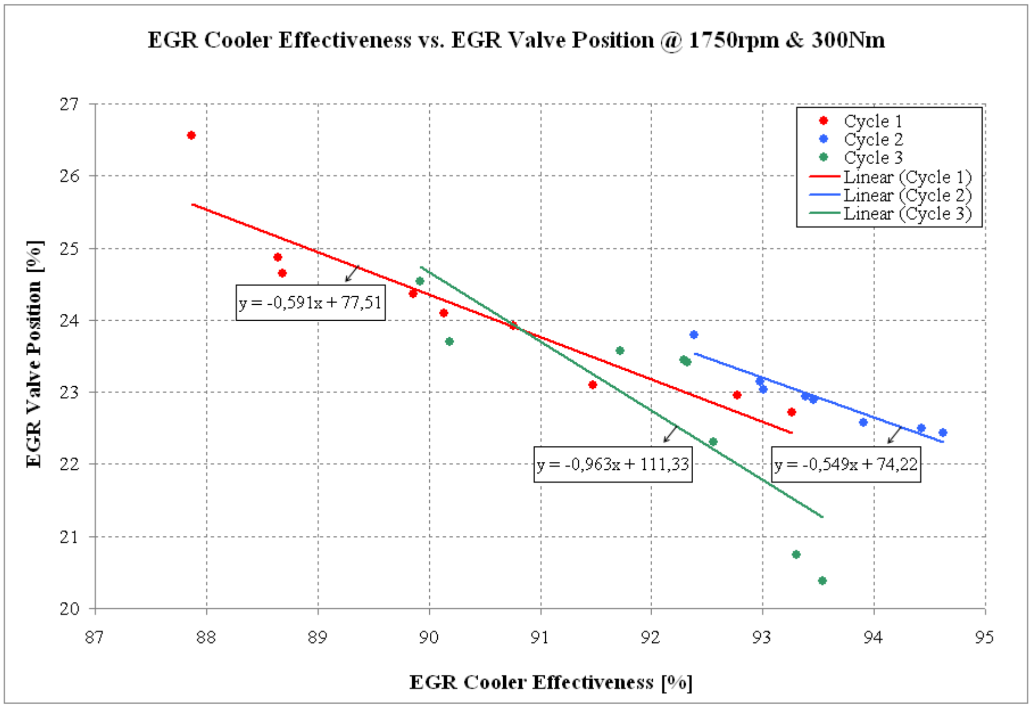

Figure 4.11 : EGR cooler effectiveness vs. EGR valve position @ test point 1

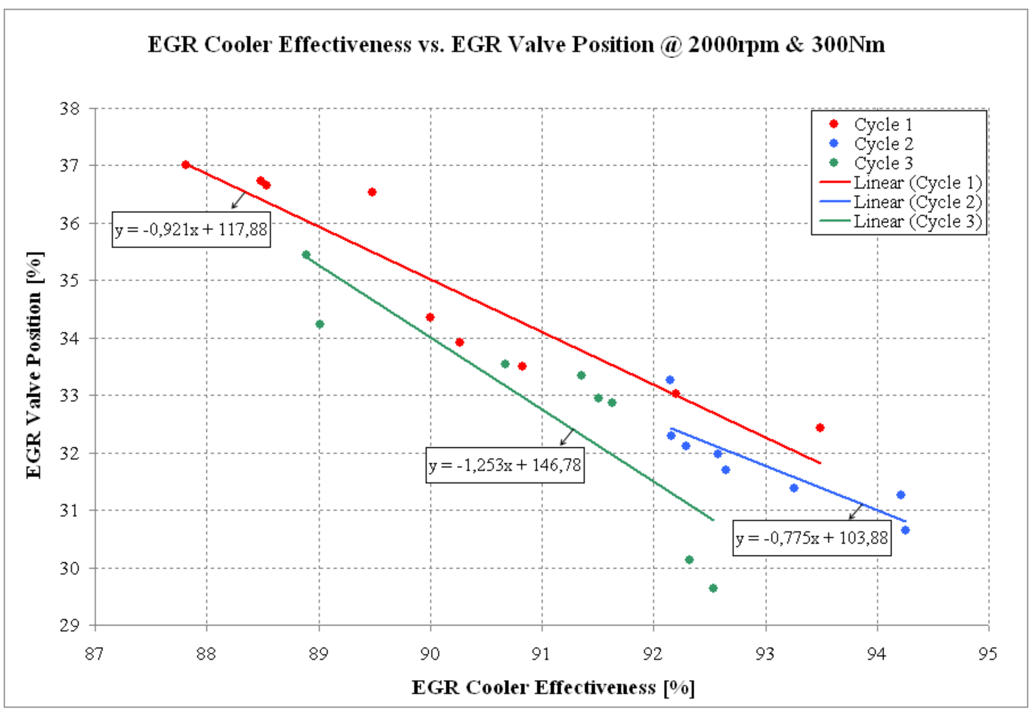

Figure 4.12 : EGR cooler effectiveness vs. EGR valve position @ test point 2

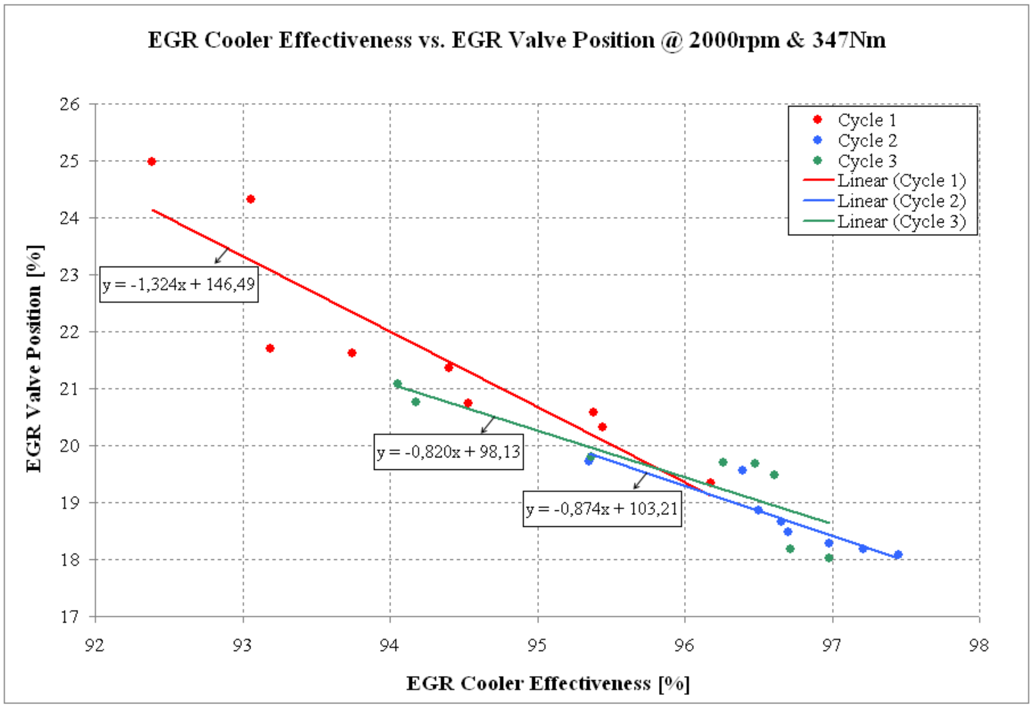

Figure 4.13 : EGR cooler effectiveness vs. EGR valve position @ test point 3

For test point 1, Equations 4.1, 4.2 and 4.3 were obtained for drive cycles 1, 2 and 3 respectively.

y = -0,541x + 77,51 for t≤110 hrs **(4.1)**

y = -0,549x + 74,22 for t≤110 hrs **(4.2)**

y = -0,963x + 111.33 for t≤110 hrs **(4.3)**

For test point 2, Equations 4.4, 4.5 and 4.6 were obtained for drive cycles 1, 2 and 3 respectively.

y = -0,921x + 117,88 for t≤110 hrs **(4.4)**

y = -0,775x + 103,88 for t≤110 hrs **(4.5)**

y = -1,253x + 146,78 for t≤110 hrs **(4.6)**

For test point 2, Equations 4.7, 4.8 and 4.9 were obtained for drive cycles 1, 2 and 3 respectively.

y = -1,324x + 146,49 for t≤110 hrs **(4.7)**

y = -0,874x + 103,21 for t≤110 hrs **(4.8)**

y = -0,820x + 98,13 for t≤110 hrs **(4.9)**

Pressure drop of the overall EGR system was also monitored to assess the trend during the experiment and the results from all drive cycles are shown in Figures 4.14, 4.15 and 4.16 for test point 1, test point 2 and test point 3 respectively. The curves have a fluctuating behavior because of the pressure drop increase due to contamination build up in the cooler and pressure drop decrease due to the increasing EGR valve lift.

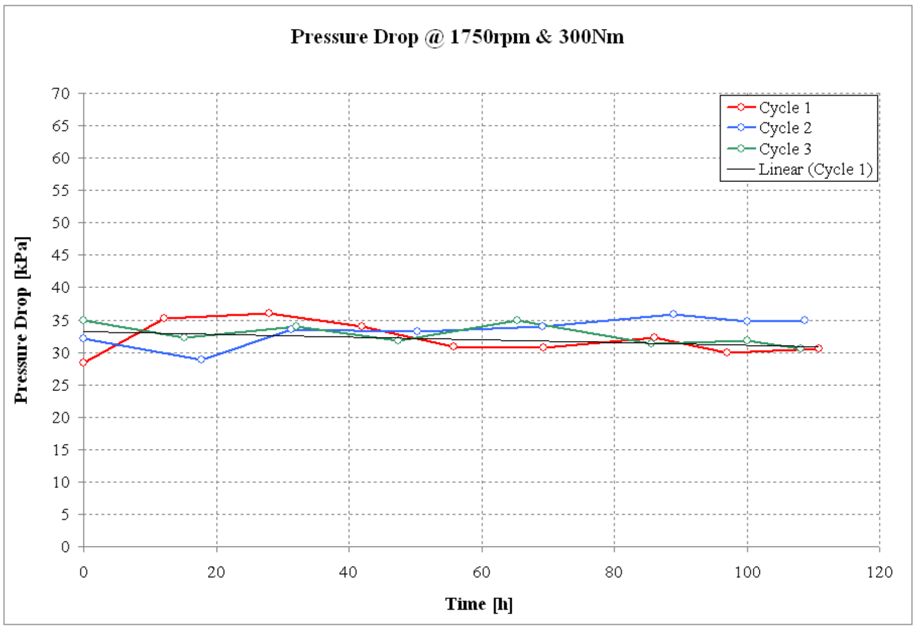

Figure 4.14 : EGR system pressure drop @ test point 1

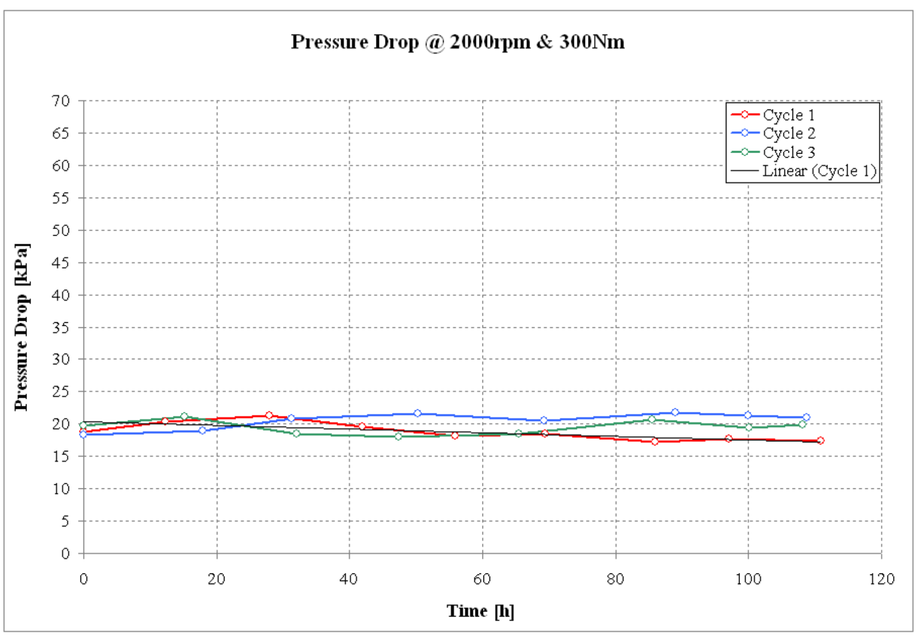

Figure 4.15 : EGR system pressure drop @ test point 2

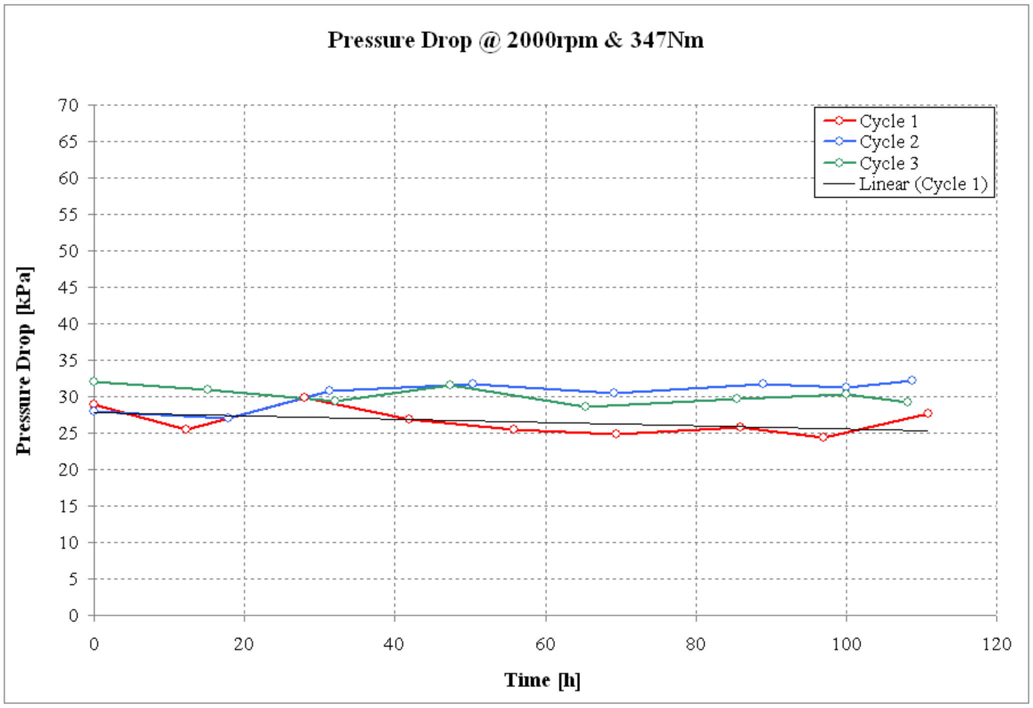

Figure 4.16 : EGR system pressure drop @ test point 3

4.6.3 EGR rate in closed loop control & comparison with fixed EGR position

EGR rate was calculated with measured CO_2 concentrations in feed gas and intake manifold. EGR rates for test point 1, test point 2 and test point 3 are shown in Figures 4.17, 4.18 and 4.19 respectively for all drive cycles.

As seen in these figures, EGR rate is fluctuating around a value, which is defined in the EGR map for that specific operating point. EGR rate for test point 1 is ~39% while it is ~35% and ~25% for test point 2 and test point 3 respectively. It is important to note that the EGR rate is decreasing with increasing load due to performance demand.

Closed loop EGR control aims to maintain the desired EGR rate by adjusting EGR valve position appropriately to compensate the deterioration in EGR cooler performance and keep the level of emissions same. By this way, engine will continue to satisfy emission regulations throughout its lifetime as seen in Figures 4.17, 4.18 and 4.19.

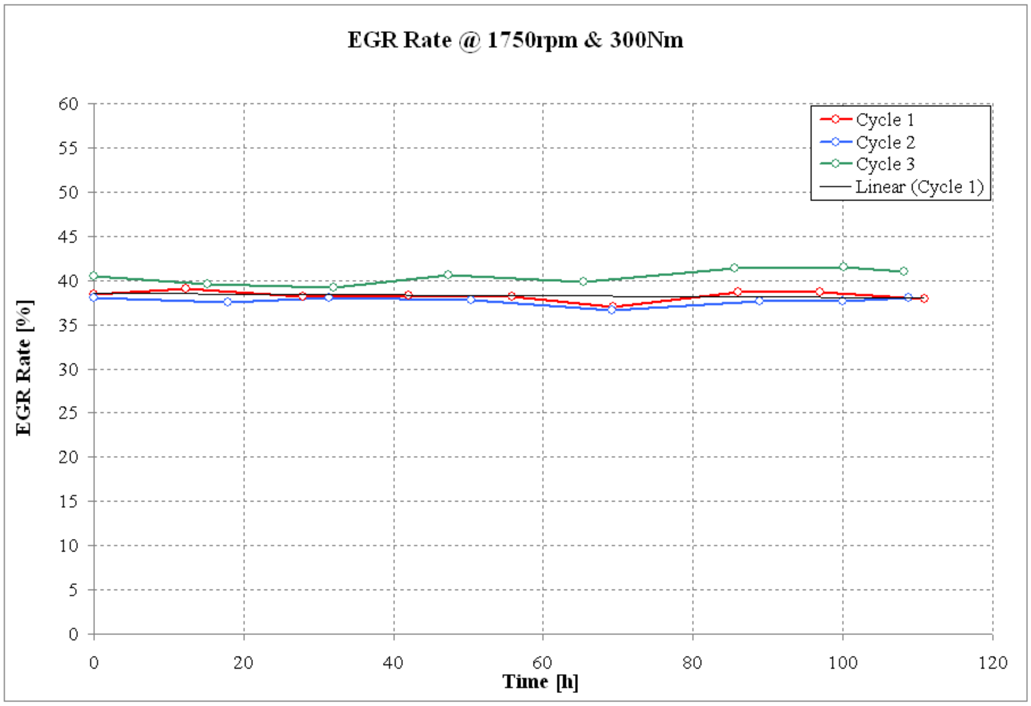

Figure 4.17 : EGR rate @ test point 1

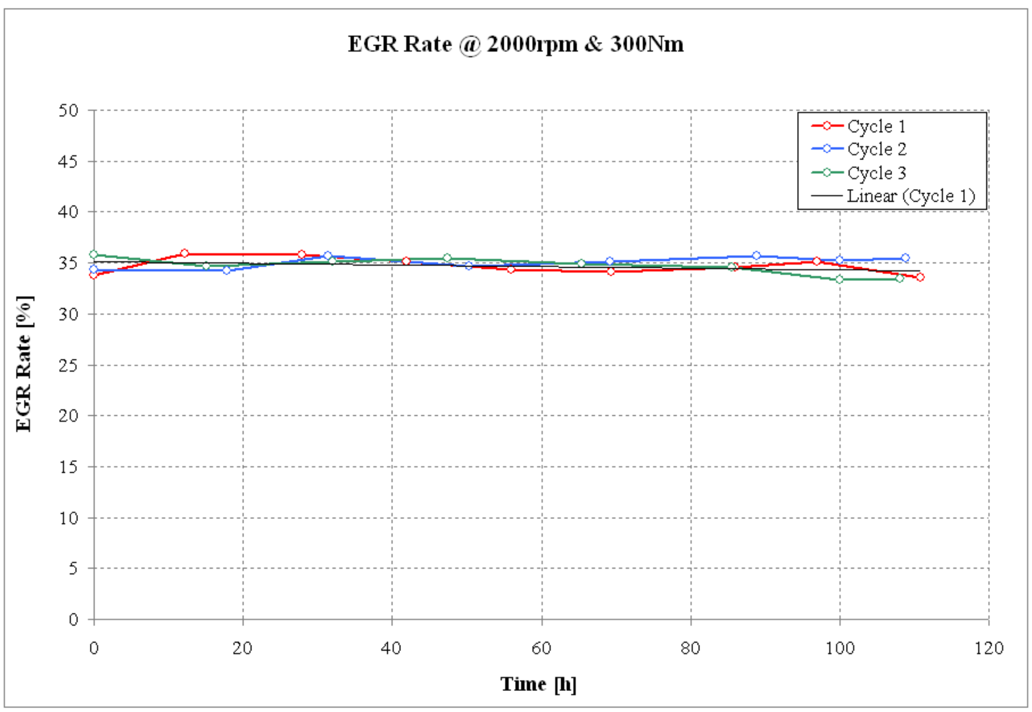

Figure 4.18 : EGR rate @ test point 2

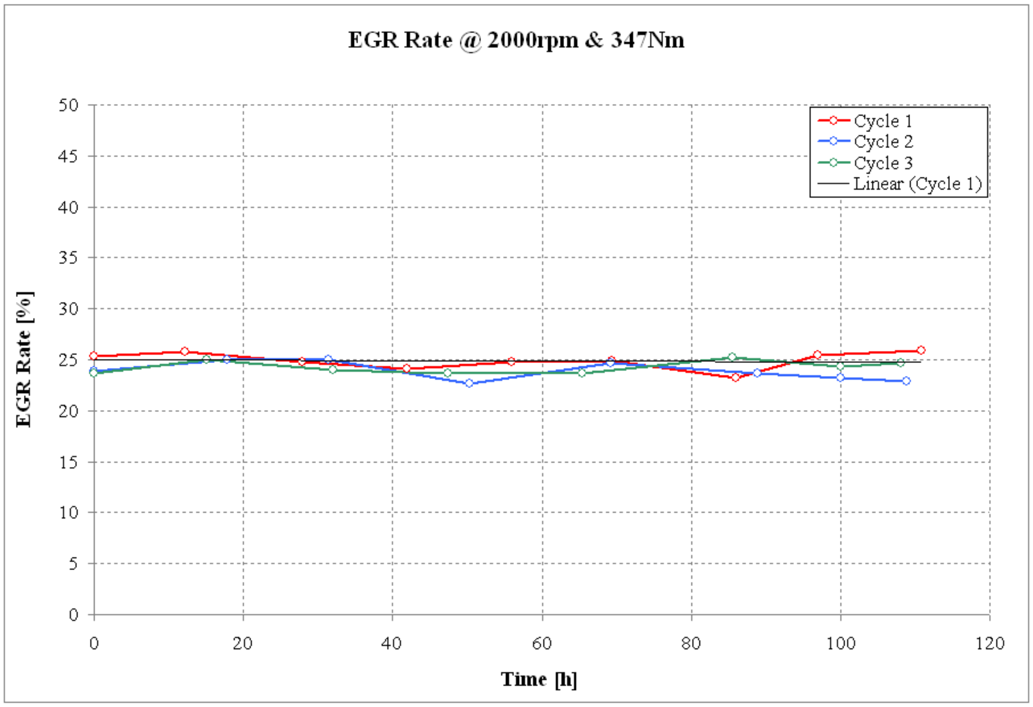

Figure 4.19 : EGR rate @ test point 3

At this point, it is important to highlight the effects of contamination on emissions without closed loop control to have an idea about the significant impact of fixed EGR position on EGR flow and compare the results with the explained effects of EGR on emissions in Section 2.2.

Mulenga et al. (2009) studied the effects of contamination on EGR parameters and emissions with fixed EGR valve position (without closed loop control). In other words, the valve has a certain defined position for an operating point and it goes to that position regardless of the contamination build-up level. As the cooler is fouled, EGR mass flow is decreased as shown in Figure 4.20. This will in turn lead to a decrease in EGR rate and effect the emissions [24].

As explained in the prior sections, main purpose of having an EGR application in an internal combustion engine is to decrease the level of NO_x emissions. Figure 4.21 shows the increase in NO_x emissions with contaminated EGR cooler and fixed EGR valve position. The increase is around 40%, the minimum. Keeping the valve position same against decreasing cooler performance deteriorates the NO_x emissions significantly.

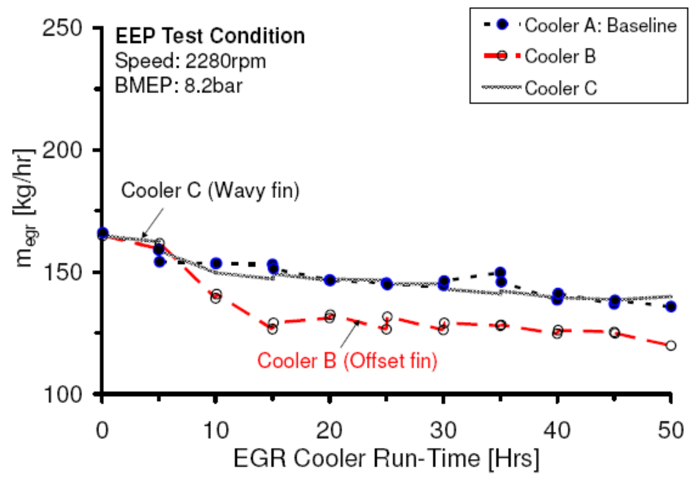

Figure 4.20 : Decreasing EGR mass flow with fixed EGR position [24]

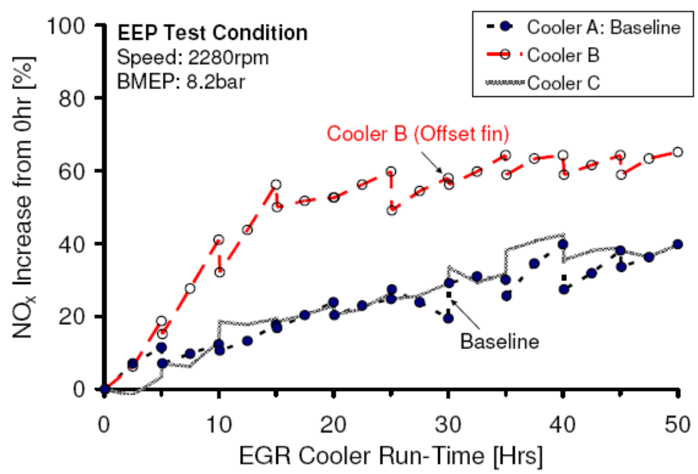

Figure 4.21 : Increasing NO_x emissions with fixed EGR position [24]

As explained in Section 2.2.2, PM emissions increase with increasing EGR rates due to reduced soot oxidation rates. When the system is in a fixed position operation, EGR rates reduce in time because of the reduced EGR flow rate and FSN decreases as shown in Figure 4.22 since oxygen concentration is getting higher and higher when compared to the initial oxygen concentration attained with unused EGR cooler for a specific operating point.

There will be an increase in oxygen availability with EGR rate reduction so that the oxidation of CO molecules to CO_2 would be easier resulting in decreased CO emissions as shown in Figure 4.23. Similarly, HC emissions would decrease due to the relatively less dilution effect of EGR when the cooler is subjected to fouling in fixed valve position. Figure 4.24 shows the reduction in HC emissions as the EGR cooler gets fouled with fixed EGR valve position.

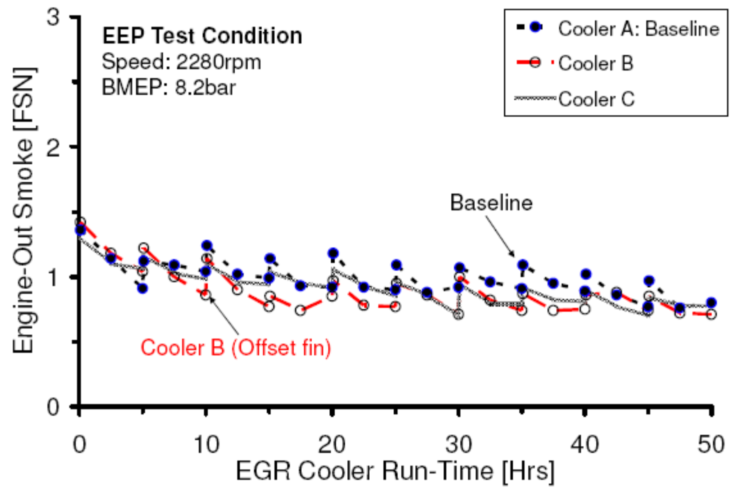

Figure 4.22 : Decreasing FSN with fixed EGR position [24]

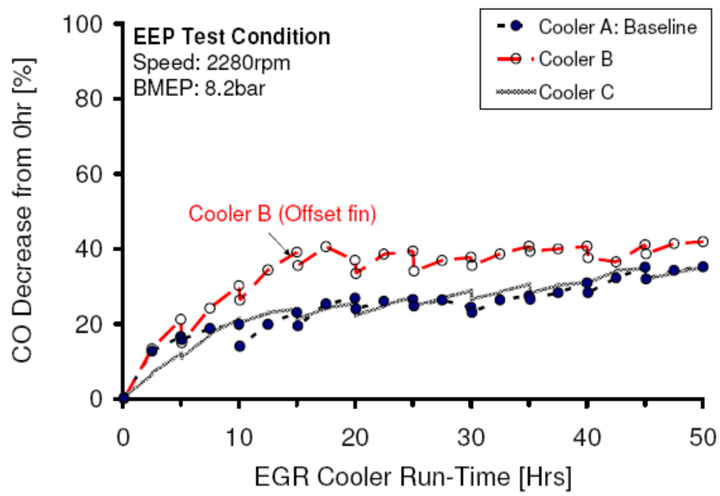

Figure 4.23 : Decreasing CO emissions with fixed EGR position [24]

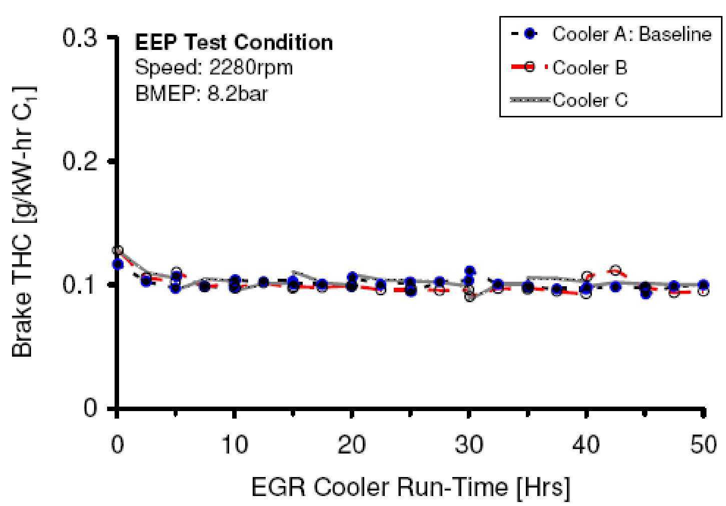

Figure 4.24 : Decreasing HC emissions with fixed EGR position [24]

By comparing the results obtained in this study and Mulenga's study with fixed EGR position, it can be concluded that EGR system closed loop control is of great importance to maintain the nitrogen oxide emissions within limits defined by governmental regulations throughout the lifetime of the engine.

4.6.4 EGR cooler contamination estimation for NEDC

Governments make it mandatory to verify emission regulations in order to make a vehicle saleable. Vehicles to be for sale in Europe are tested on a chassis dynamometer based on New European Driving Cycle (NEDC) after being conditioned for 6 hours in an environment of 20-30^{o}C temperature. Emission samples collection starts simultaneously with the engine start. Samples are then diluted and analyzed to quantify the emissions in grams per kilometer.

NEDC is composed of four successive ECE (also referred to as Urban Driving Cycle) segments representing city drive as shown in Figure A.7, followed by one EUDC (Extra Urban Drive Cycle) segment representing high-speed drive as shown in Figure A.8 [27]. Overall vehicle speed vs. time cycle is shown in Figure A.9 and cycle parameters are summarized in Table 4.4 [28].

Table 4.4 : Summary of parameters in NEDC

Characteristics	Unit	ECE	EUDC
Distance	km	4x1,013=4,052	6,955
Duration	s	4x195=780	400
Average Speed	km/h	18,7 (with idling)	62,6
Maximum Speed	km/h	50	120

Table 4.5 is a summary of European emission regulations for passenger cars with compression ignition engines. Regulations are continuously becoming stricter as shown on the table and given the names from Euro 1 to 6.

Euro 5 requirement was put in progress in September 2009 and is currently ongoing. It is important to note that the most significant impact was on PM emissions where it dropped to 20% of its Euro 4 value with Euro 5 implementation. This drastic reduction in PM emissions brought the introduction of diesel particulate filters (DPF) in vehicles although it brings an add-on cost to the overall system, as 0,005 g/km is a very tight specification to satisfy without an after treatment system.

Upcoming European emission regulation is Euro 6 and is planned to be introduced in September 2014. There will be a remarkable reduction in NO_x emissions, which is achievable by means of dual EGR systems (combination of low-pressure EGR system and high-pressure system functioning simultaneously).

Table 4.5 : EU emission standards for passenger cars [g/km]

Tier	Date	CO	HC	HC+NO_x	NO_x	PM
Euro 1	1992.07	2,72	-	0,97	-	0,14
Euro 2	1996.01	1,00	-	0,70	-	0,08
Euro 3	2000.01	0,64	-	0,56	0,50	0,05
Euro 4	2005.01	0,50	-	0,30	0,25	0,025
Euro 5	2009.09	0,50	-	0,23	0,18	0,005
Euro 6	2014.09	0,50	-	0,17	0,08	0,005

During this experimental study, NEDC was not run. However, by considering the final drive ratios of the gearbox, vehicle speeds in NEDC was transformed to engine speed and the distribution is shown in Figure A.10.

For each test point, durations of cycle 1 and cycle 3 to reach the final effectiveness value in cycle 2 (least contaminated cycle) were calculated. Then, by linearly interpolating the bypass mode percentage of NEDC (shown in Table 4.6) and average power of NEDC (shown in Table 4.7), duration to reach the final effectiveness value in cycle 2 was estimated for NEDC. Effect of bypass mode percentage and effect of average power were equally weighed during this estimation.

Table 4.6 : EGR active, cooler mode & bypass mode percentages of NEDC

Cycle	EGR Active Region [%]	Cooler Mode [%]	Bypass Mode [%]
Cycle 1	99,50	20,33	79,17
Cycle 3	99,17	43,86	55,31
NEDC	99,83	35,87	63,96

Table 4.7 : Average speed, average torque & average power of NEDC

Cycle	Av. Speed [rpm]	Av. Torque [Nm]	Av. Power [kW]
Cycle 1	1177	62	8
Cycle 3	1367	96	15
NEDC	1145	74	11

EGR cooler effectiveness drop estimations for NEDC are shown in Figures 4.25, 4.26 and 4.27 respectively for all test points. Effectiveness values were found to reach the final value in 65hrs, 57hrs and 78hrs for test point 1, test point 2 and test point 3 respectively.

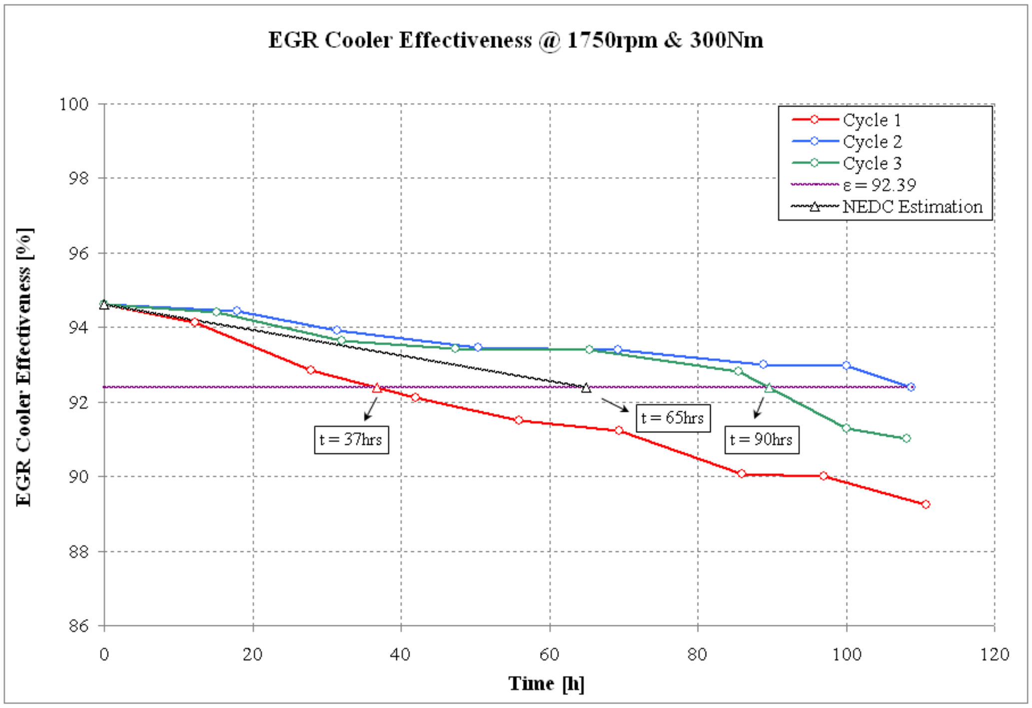

Figure 4.25 : EGR cooler contamination estimation for NEDC @ test point 1

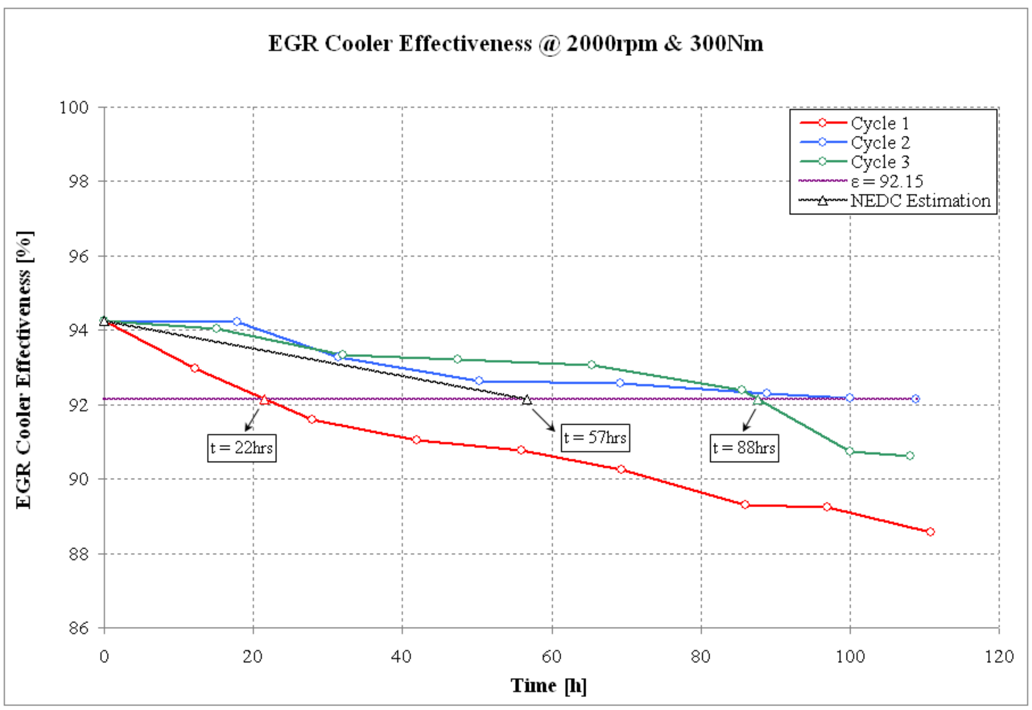

Figure 4.26 : EGR cooler contamination estimation for NEDC @ test point 2

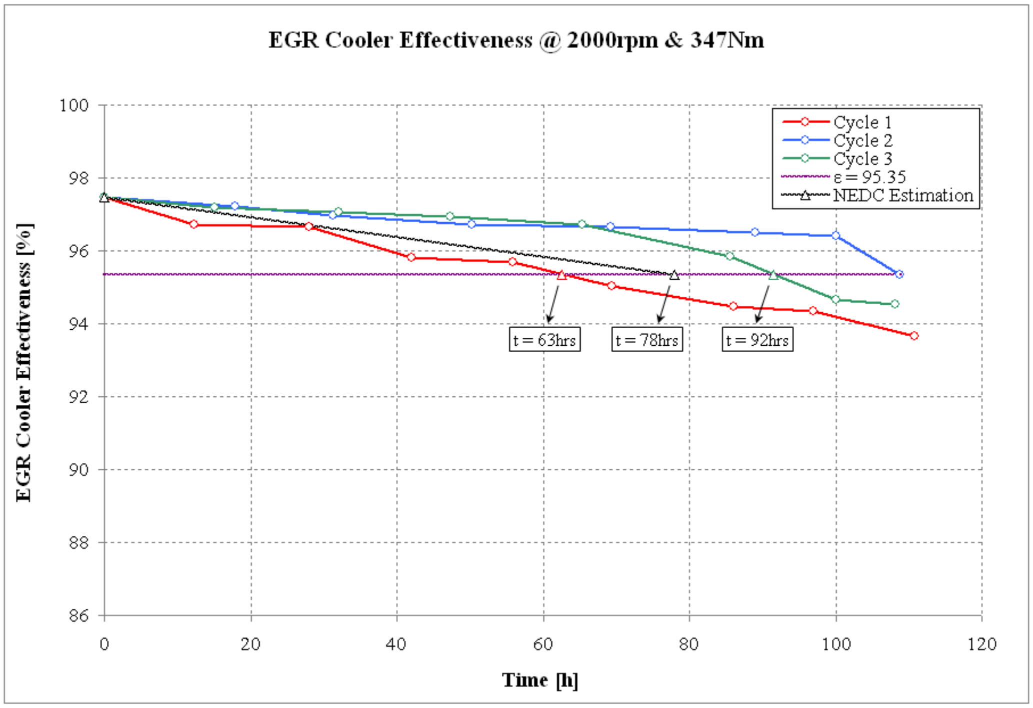

Figure 4.27 : EGR cooler contamination estimation for NEDC @ test point 3

When tested drive cycles and NEDC are compared with actual driving conditions, it can be concluded that NEDC is quite representative for a wide range of drivers as it mostly stands for urban drive while including high speed drive partly. Low speed drive with several stop-and-go segments in the first 800 seconds forms a very suitable environment for EGR cooler fouling. EGR is activated also in the EUDC segment, where high speed drive is represented, but this stage generally does not lead to severe fouling when compared to the UDC segments, as supported by the test results.

Minority of the drivers, who prefer to maintain less or more engine speeds and accelerations than specified in NEDC, may have a closer overall behavior to cycle 1 resulting in higher EGR cooler fouling with lower fuel consumption or cycle 2 resulting in less EGR cooler fouling with worse fuel economy respectively.

5. CONCLUSION AND RECOMMENDATIONS

In this experimental study, effects of various drive cycles on EGR cooler contamination and contamination on EGR valve position with closed loop EGR control were investigated. Results of the experiments are summarized with the following concluding remarks.

- Most severe EGR cooler fouling was observed in the drive cycle with the lowest average torque and lowest average speed although it spends most of the EGR active time in bypass mode. The main reason for this is the slow low-temperature gas (suitable environment for fouling) leaking through the EGR cooler bypass valve flap (~20% of the overall flow) even though the system is operating in bypass mode. Leakage from bypass flap may be reduced with improved designs to overcome excessive fouling of EGR cooler in case target values can not be attained.
- Results highlight that EGR cooler bypass mode is extremely important to prevent excessive fouling of EGR cooler. Cooler is significantly contaminated even the system is operating in bypass mode due to the leaks through bypass flap. If EGR system was always operating in cooler mode, then fouling would be much worse since entire slow low-temperature flow was going to pass through the cooler.
- Greatest EGR valve position change was recorded in the cycle where most severe fouling was observed. EGR valve lift is increased by closed loop EGR control to maintain the desired EGR flow for a specific operating point as EGR cooler contaminates.
- Cooler fouling did not stabilize after 110 hours of engine running. Stabilization time is typically ranging between 50 and 200 hours. Cycles could be run further to find out the effectiveness stabilization time.
- Pressure drop of the overall EGR system was found to be fluctuating. This situation can be explained by the pressure drop increase due to contamination

build up in the cooler and pressure drop decrease due to the increasing EGR valve lift.

- Closed loop EGR control is of great importance to maintain the desired EGR rate by adjusting EGR valve position appropriately to compensate the deterioration in EGR cooler performance and keep the level of NO_x emissions same. By this way, engine will continue to satisfy NO_x emission regulations throughout its lifetime.

- NEDC was not run on the test engine as a drive cycle but vehicle speeds in NEDC was transformed to engine speed and torque so that NEDC cooler contamination was estimated for a comparison. Cycle 1 was found to result in a higher effectiveness drop than NEDC.

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APPENDIX

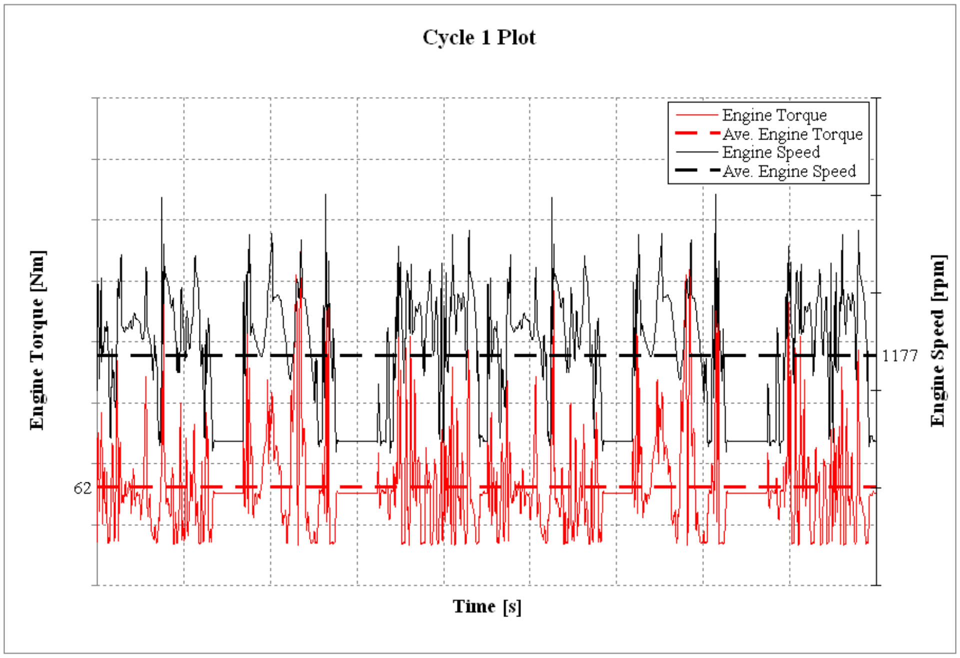


Figure A.1 : Cycle 1 plot

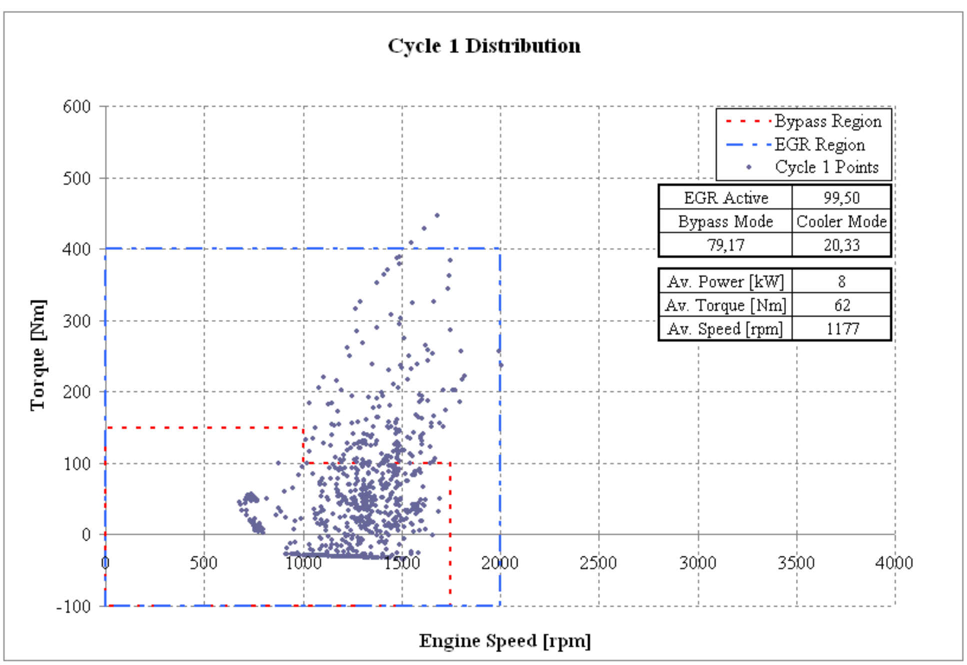


Figure A.2 : Cycle 1 distribution

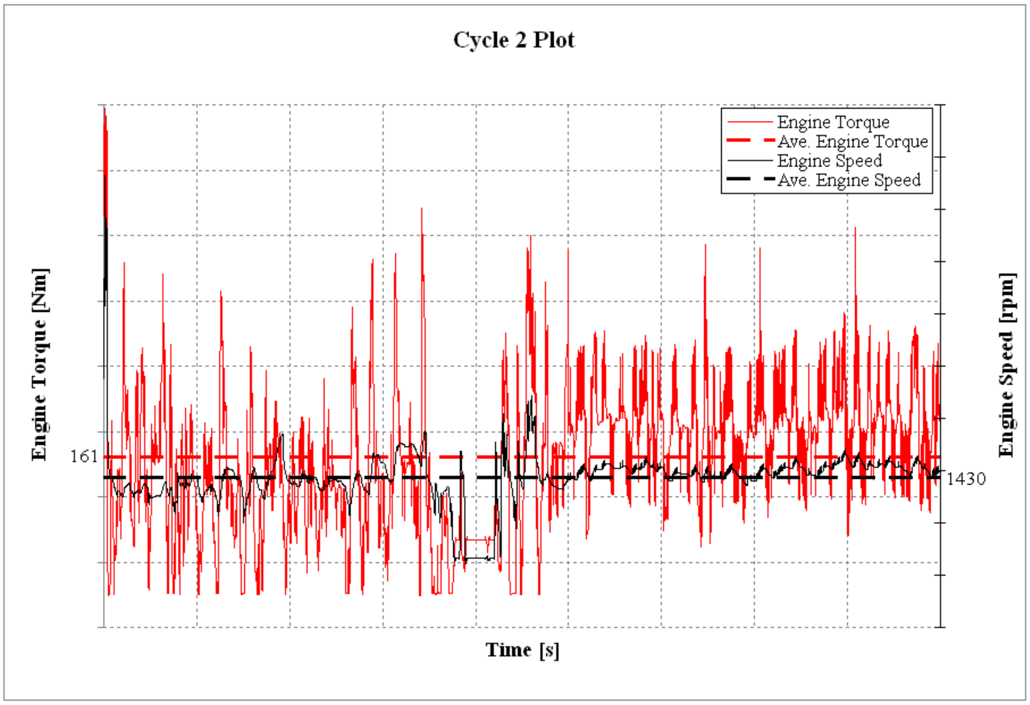


Figure A.3 : Cycle 2 plot

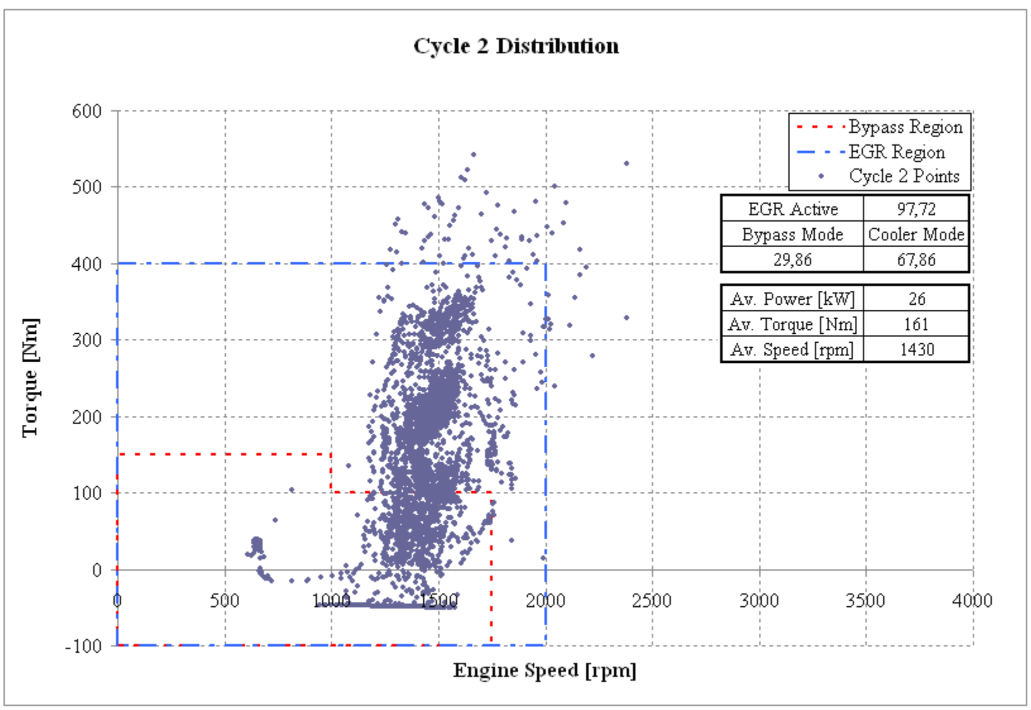
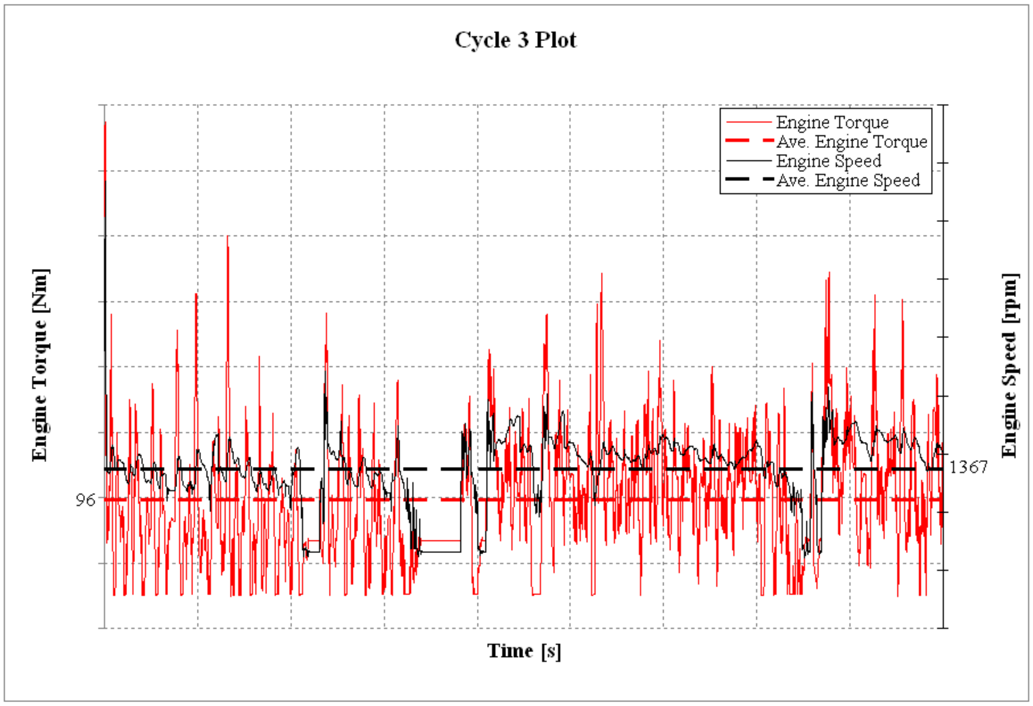


Figure A.4 : Cycle 2 distribution



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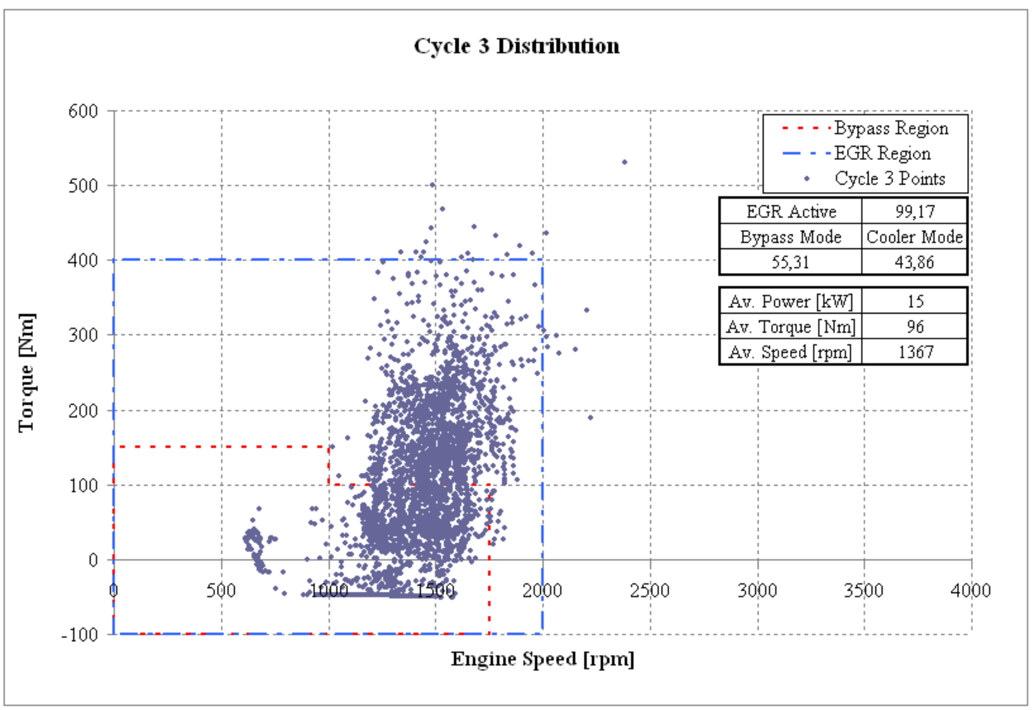

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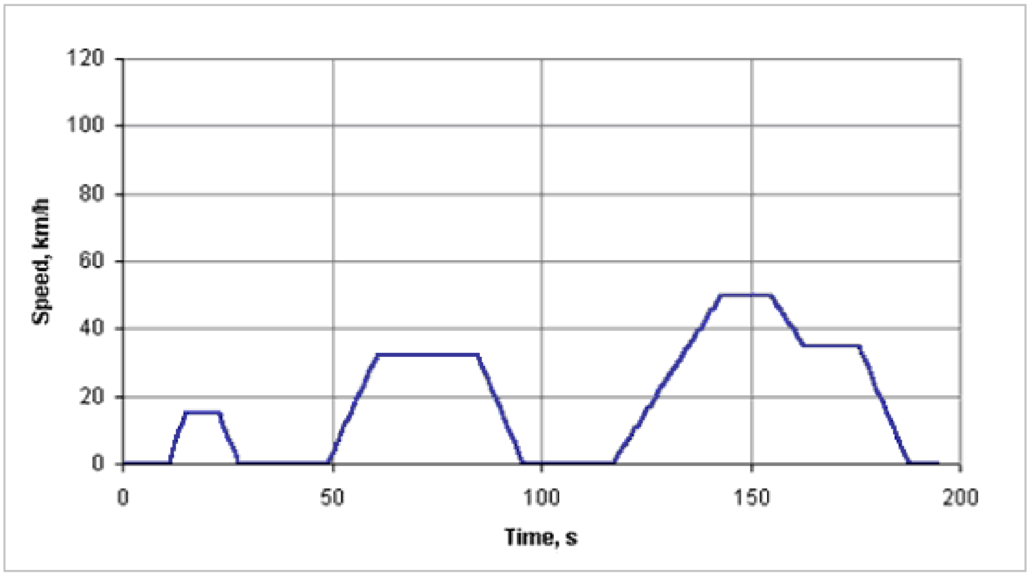

Figure A.7 : ECE Segment

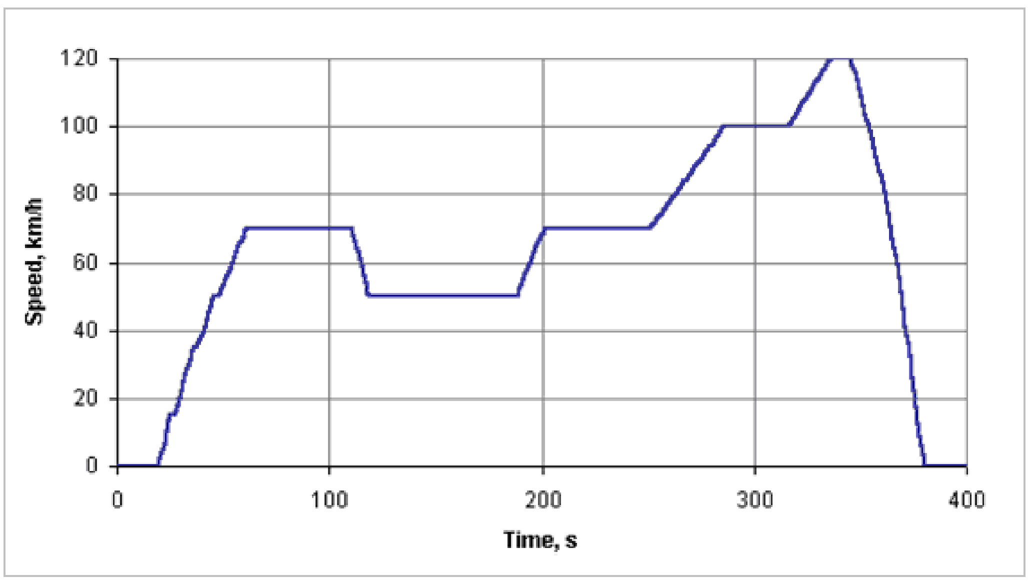

Figure A.8 : EUDC Segment

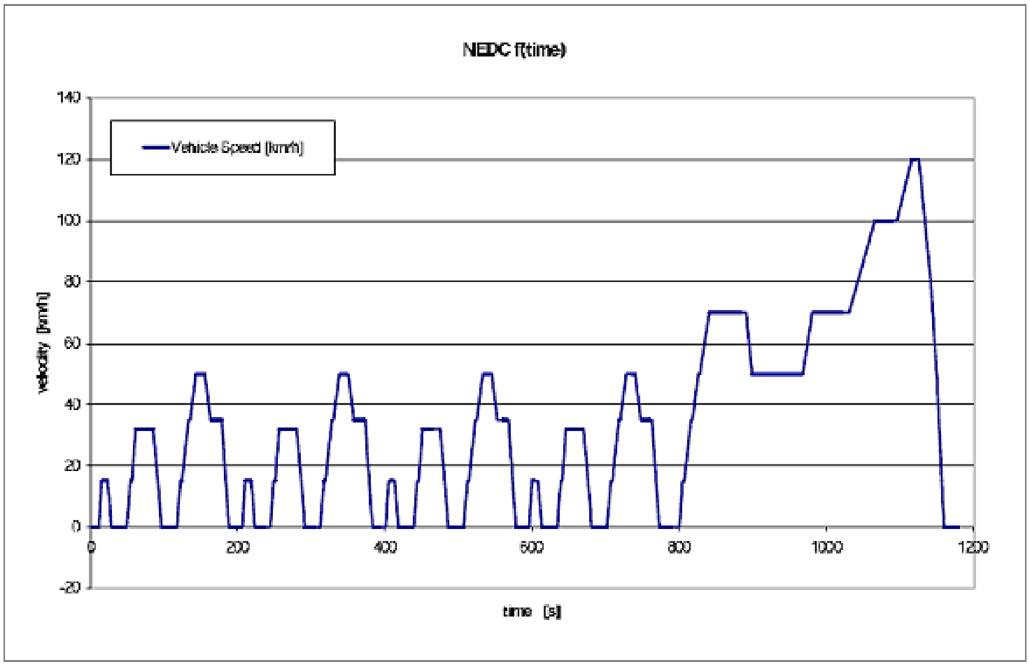

Figure A.9 : NEDC

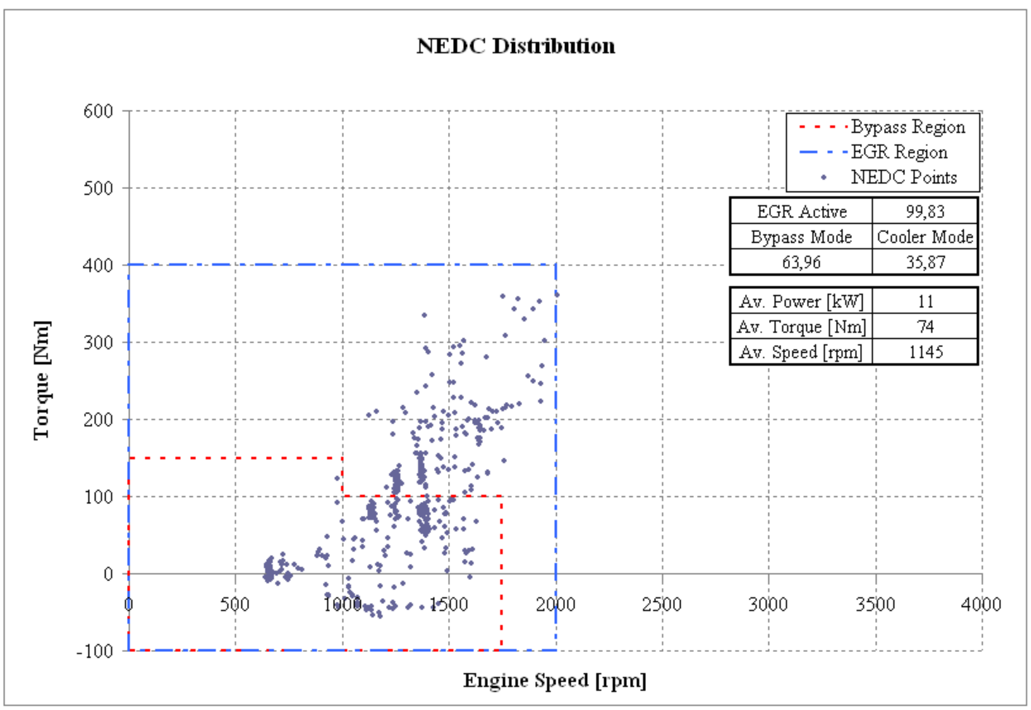

Figure A.10 : NEDC distribution

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