

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

**IMPACT OF ELECTRIFICATION ON DIESEL EMISSIONS
FOR 13L LONG-HAUL TRUCKS**



M.Sc. THESIS

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**13L UZUN YOL TIRLARINDA ELEKTRİFİKASYONUN
DİZEL EMİSYONLAR ÜZERİNE ETKİSİ**



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To my wife, family, and friends,



FOREWORD

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Mustafa Caner BULUT
Mechanical Engineer



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ABBREVIATIONS

AGVES	: Advisory group on vehicle emission standards
ANPR	: Advanced notice of proposed rule
ASC	: Ammonia slip catalyst
BSFC	: Brake specific fuel consumption
CAA	: Clean Air Act
CARB	: California air resource board
CH₄	: Methane
CLOVE	: Consortium for ultra low emission vehicles
CO	: Carbon monoxide
CO₂	: Carbon dioxide
CTI	: Cleaner truck initiative
DOC	: Diesel oxidation catalyst
DPF	: Diesel particulate filter
EAS	: Engine aftertreatment system
EBV	: Engine brake valve
E-CAT	: Electrically heated catalyst
ECU	: Engine control unit
EGR	: Exhaust gas recirculation
E-TURBO	: Electric turbocharger
FMU	: Functional Mockup Unit
FTP	: Federal test procedure
GHG	: Greenhouse gas
H₂O	: Water
HC	: Hydrocarbons
HD	: Heavy-duty
HEV	: Hybrid electric vehicle
HHD	: Heavy heavy-duty
HiL	: Hardware-in-the-Loop
HP-EGR	: High-pressure exhaust gas recirculation
ICE	: Internal combustion engine

LEV	: Low-emission vehicle
LLC	: Low-load cycle
LP-EGR	: Low-pressure exhaust gas recirculation
MAW	: Mowing average window
MY	: Model year
N₂O	: Nitous oxide
NH₃	: Ammonia
NMHC	: Non-methane hydrocarbons
NMOG	: Non-methane organic gasses
NO_x	: Nitrogen oxides
NTE	: Not-to-exceed
PGM	: Precious metal group
PM	: Particulate matter
PN	: Particulate number
RMC-SET	: Ramped-Mode Cycle Supplemental Emission Test
SCR	: Selective catalytic reduction
THC	: Total hydrocarbons
TLEV	: Transitional low-emission vehicle
ULEV	: Ultra low-emission vehicle
USA	: United States of America
WHSC	: World harmonized steady cycle
WHTC	: World harmonized transient cycle
ZEV	: Zero emission vehicle

SYMBOLS

°C	: Celcius degree
bhp	: brake horsepower
bhp-hr	: brake horsepower hour
g	: Gram
g/bhp-hr	: Gram per brake horsepower hour
g/kWh	: Gram per kilowatt hour
h	: Hour
kg	: Kilogram
kW	: Kilowatt
kWh	: Kilowatt hour
l	: Liter
s	: Second
W	: Watt



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IMPACT OF ELECTRIFICATION ON DIESEL EMISSIONS FOR 13L LONG-HAUL TRUCKS

SUMMARY

Transportation is one of the basic needs of people. From a historical view, people supplied this need with animals up to the 20th century. Like many other topics, the shape of transportation changed by an invention just before the 20th century. For the traction of vehicles, animals were changed by internal combustion engines. The engine can be defined as the machine which converts the chemical energy in fuels to mechanical work by combustion. Traditionally, combustion engines consume petrol or diesel as fuel. The combustion products of diesel are called emissions. The main diesel emissions are hydrocarbons, carbon monoxide, nitrogen oxides, and particulate matter.

Emissions are harmful to people and the environment. However, they are not concerned until the mid of 20th century. The increasing vehicle number rises the danger of emissions. The legislative works have begun with the air pollution crisis in Los Angeles California in the 1940s. After that, vehicle emissions are limited by regulations, and those regulations become more stringent day by day. The upcoming regulations and more stringent limits become the driving force of the new emission control technologies. The current systems use exhaust gas recirculation, diesel oxidation catalyst, diesel particulate filter, selective catalyst reduction, and ammonia slip catalyst.

There are many works for new technologies to meet upcoming emission limits. Some of them are combustion improvement, heat loss gain for useful work, hybridization, and electrification. This thesis study investigates the effect of electrification on diesel emissions for 13l long-haul trucks. The 13l long-haul trucks are selected for investigation because they have a significant share in transportation and an important contribution to diesel emissions.

For electrified system design, three components are considered: electric turbocharger, exhaust gas recirculation pump, and electrically heated catalyst. The study is done in the simulation environment and no vehicle experiments are done. All models are created in the AVL Cruise-M which is a simulation environment specialized in the automotive industry. As the method of work, the electrified system layout results are compared with the conventional model to observe the impact of electrification on emissions. Also, they are compared with the upcoming emission limits to investigate whether they are successful to meet new regulations or not.

Firstly, the conventional system is modeled and simulated. When the cycle results are compared with current legislation it is seen that the model can be used as a benchmark 13l heavy-duty engine and aftertreatment system because they can satisfy both European and American current legislation.

Then, alone usage of three electrified components and their combinations are modeled. 7 different layouts are simulated according to Europe and USA's cold and hot drive cycles. The results indicate that some of the layouts have lower carbon monoxide, hydrocarbon, and particulate matter emissions than the conventional system. Also, some of the layouts can satisfy those upcoming limits.

The optimum layout decision is made according to the best performance of nitrogen oxide and carbon dioxide reduction together since there will be a significant reduction of limits of those emissions. According to the results of both Europe and the USA's drive cycles, using the electric turbocharger and electrically heated catalyst provides the best carbon dioxide and nitrogen oxide reduction. Also, this system is self-sufficient and does not need any external power source according to power generation over the turbine, and power consumption of electrically heated catalyst. When the system is compared with the upcoming limits, it is concluded that none of the layouts can satisfy the new US regulation of both nitrogen oxides and carbon dioxides. However, the optimum system is successful to meet the new European legislation.

Finally, the research topics related to this study are given as future work. Although there is an increasing trend for full-electric vehicles and alternative fuels, more effort to develop more efficient and clean diesel systems will probably be required because the heavy-duty trucks will probably keep their importance in transportation and the share of diesel for fuels of heavy-duty trucks will probably not decrease suddenly in the near future.

13 L UZUN YOL TIRLARINDA ELEKTRİFİKASYONUN DİZEL EMİSYONLAR ÜZERİNE ETKİSİ

ÖZET

Tarih boyunca ulaşım insanların en temel ihtiyaçlarından biri olmuştur. Tarihsel açıdan bakıldığında bu ihtiyaç 20. yüzyılın başlarına kadar hayvan gücü yardımıyla sağlanmıştır. Pek çok alanda olduğu gibi 20. yüzyılın başlarındaki teknolojik atılımlar ulaşımın şeklini de değiştirmiştir. Ulaşımdaki bu teknolojik değişim, otomobillerin kullanıma girmesiyle olmuştur. Araçların hareketi daha öncesinde hayvan gücü ile sağlanırken, içten yanmalı motorun icadı, buradaki hayvan gücü ihtiyacını ortadan kaldırmıştır.

Bir yakıtta depolanan kimyasal enerjiyi yanma sonucunda mekanik işe çeviren makineye içten yanmalı motor denir. Motorun içinde kapalı ortamda yakıtın yanması sonucu ortaya çıkan ısı, silindir içindeki basıncı artırarak pistonların hareket etmesini sağlar. Pistonların bu doğrusal hareketi bağlı oldukları krank adı verilen bir mil sayesinde döner harekete çevrilir. Buradan elde edilen güç ve dönme hareketi çeşitli elemanlar ile tekerleklerle iletilerek araçların hareket etmesi sağlanır. Günümüzde elektrikli araçlar ve alternatif yakıtlarda yükselen ilgiye rağmen, içten yanmalı motorlarda yaygın olarak petrol bazlı iki tip yakıt kullanılır: benzin ve dizel. Özellikle ulaşım ve taşımacılık dikkate alındığında, burada kullanılan ağır vasıta araçlarda en büyük payı dizel yakıtlı araçlar oluşturmaktadır.

Teorik olarak, organik bir maddenin yanma tepkimesi sonucu karbon dioksit ve su açığa çıkar. Dizel de organik bir madde, karbon ve hidrojen elementlerinden oluşan, olduğu için yanma tepkimesinin ürünleri karbon dioksit ve sudur. Ancak, motor içerisinde teorik denklemdeki gibi düzgün bir yanma gerçekleşmediğinden, ayrıca yakıtlara eklenebilen başka kimyasallardan ötürü, yakıtın yanması sonucu istenmeyen başka maddeler de açığa çıkar. Yanma sonucu açığa çıkan bu istenmeyen maddelere yakıt emisyonları, emisyon ya da dizel özelinde dizel emisyonları denir. Dizel emisyonlarını başlıca hidrokarbonlar, karbon monoksit, nitrojen oksitler ve katı partiküller oluşturmaktadır. Hidrokarbonlar yanmamış yakıt zincirleridir. Karbon monoksit yetersiz oksijen ile yanma sonucu oluşur. Silindir içerisindeki yüksek sıcaklık, ortamdaki azot ve oksijen moleküllerinin birleşmesine neden olur ve bunun sonucunda nitrojen oksitler açığa çıkar. Burada oluşan nitrojen oksitler azot oksit ve azot dioksittir. Emisyonlar açısından azot bileşiklerin toplamı değerlendirilir. Son olarak yetersiz yanma sonucu oksitlenmeden kalan karbon atomları katı partikülleri oluşturur.

Emisyonların insan sağlığına ve çevreye pek çok zararları bulunmaktadır. Ancak 20. yüzyılın ortalarına kadar bu konuya önem verilmemiştir. Zamanla artan otomobil sayısı emisyonların verdiği zararı gözle görünür hale getirmiştir. 1940'lara gelindiğinde Amerika Birleşik Devletleri'nin Kaliforniya eyaletinde emisyon kaynaklı hava kirliliği o kadar artmıştı ki Los Angeles şehrinin üzerini bir sis kaplamıştı. Hava kirliliğindeki bu artış gözlerde kaşıntı, ciğerlerde yanma ve burun akıntısı gibi

şikayetlerin hızlıca artmasına neden olmuştur. Bu olaydan sonra emisyonların yarattığı hava kirliliği ve insan sağlığına zararı ele alınmaya başlamıştır. Emisyonların verdiği zararı en aza indirmek için, kural koyucular araçların salabilecekleri emisyon miktarları üzerine sınırlar koymaya başlamışlardır. Oluşan bu durumun sonucunda 1970'lere gelindiğinde emisyonlar üzerindeki ilk sınırlandırıcı kuralları oluşmaya başlamış ve 1990'lara gelindiğinde Amerika Birleşik Devletleri'nde ilk emisyon regülasyonları son halini alıp yürürlüğe girmiştir. Dünyanın çeşitli bölgelerindeki kural koyucular kendi emisyon limitlerini belirleseler de kuralların öncüsü genel olarak Amerika Birleşik Devletleri, özellikle Kaliforniya eyaleti, ve Avrupa olmuştur. Emisyon regülasyonlarının Avrupa'da da benzer bir tarihçesi vardır. Burada da ilk regülasyonlar 1990'larda yürürlüğe girmiştir.

Emisyon regülasyonlarının ortaya çıktığı ilk günden bu yana limitler sürekli düşürülmüştür. Limitlerin sürekli daha aşağıya çekilmesi, motor ve egzoz sistemi teknolojilerindeki gelişmelerin sürükleyici kuvveti olmuştur. Bu tezin de konusu içerisinde, günümüzde ağır vasıta araçlar için Avrupa'da EURO VI ve Amerika'da US10 regülasyonları geçerlidir. Günümüz regülasyonlarını karşılamak için kullanılan başlıca egzoz sistemi teknolojileri şunlardır: dizel oksidasyon katalizörü, dizel partikül filtresi, seçici indirgeme katalizörü ve amonyak indirgeme katalizörü. Bu teknolojilerin detayları tezin içerisinde verilmiştir.

Günümüzdeki hedef, yakıt emisyonlarını daha fazla düşürmek ve emisyon üretmeyen temiz taşıtlara ulaşmaktır. Bu amaç doğrultusunda önümüzdeki 10 sene içerisinde taşıt kaynaklı emisyonlarda ve sera gazı salınımında ciddi düşüşler beklenmektedir. Bu düşüşü sağlamak için gelecek yeni kuralları tartışılmaktadır ve yeni kuralların bir kısmına karar verilmiştir. Buna göre gelecek regülasyonlarda nitrojen oksit emisyon limitinde 90% düşüş beklenmektedir. Bununla birlikte sera gazlarının iklim değişikliği üzerindeki yıkıcı etkisi göz önünde bulundurularak, karbon dioksitin de sınırlandırılması ve bu sınırın günümüz değerlerinden 5% ile 30% arasında daha düşük olması beklenmektedir. Bu yeni gelecek limitler, motor ve egzoz sistemlerinde daha ileri teknolojilerin ortaya çıkarılmasını zorunlu kılmaktadır.

Konvansiyonel motor ve egzoz sistemlerindeki iyileştirmeler, artık ısının verimli işe dönüştürülmesi ve pek çok yeni teknoloji, bu alanda gerekli emisyon iyileştirmelerini sağlamak için çalışılmaktadır. Bunlarla birlikte konvansiyonel taşıtlardan, hibrit ve elektrikli araçlara geçiş buradaki temel çalışma alanlarından birini oluşturur.

Bu tez çalışmasında bu amaçla konvansiyonel taşıt sistemlerinde, emisyon kontrolünde kullanılan motor ve egzoz sistemi elemanlarının elektrikli versiyonları ile değiştirilmesi, yeni elektrikli elemanların sisteme farklı kombinasyonlarda eklenmesi ve bu değişimlerin taşımacılıkta önemli bir yer tutan, aynı zamanda da dizel emisyonlarına önemli bir katkısı bulunan uzun yol tırlarındaki dizel emisyonlar üstünde nasıl bir değişiklik yarattığı incelenmiştir. Bu çalışmada üç eleman, bu üç elemanın tek başına ve çeşitli kombinasyonlarda kullanım senaryoları çalışılmıştır. Üzerinde çalışılan üç eleman şunlardır: elektrikli turboşarj, egzoz gaz sirkülasyonu pompası ve elektrik ısıtıcı katalizör.

Tez çalışması simülasyon ortamında yapılmış, gerçek araç ya da motor üzerinde deneyler yapılmamıştır. Çalışma metodu olarak 13 l konvansiyonel ağır vasıta motor egzoz sistemi modelinin simülasyon sonuçları, eklenen yeni elemanlı sistem modellerinin simülasyonlarının sonuçlarıyla karşılaştırılması seçilmiştir. Buna ek olarak, elde edilen sonuçların gelecek emisyon limitlerini karşılayıp karşılayamadığı incelenmiştir. Yeni sistemlerin dışarıdan bir enerji kaynağına ihtiyacı duyup

duymadığını görmek için, sistemlerin enerji dengesi incelenmiştir. Son olarak emisyonlardaki en iyi sonucu verecek sistem tasarımı ortaya konmuştur.

İlk olarak, karşılaştırmalı metodun temelini oluşturacak konvansiyonel sistem modellenmiş ve simülasyonu yapılmıştır. Tüm simülasyonlar AVL Cruise-M programında yapılmıştır. Avrupa ve Amerika emisyon limitleriyle sonuçları kıyaslayabilmek için, bu regülasyonların emisyon çevrimlerine göre simülasyonlar yürütülmüştür. Konvansiyonel sistemin sonuçları güncel Avrupa ve Amerika limitlerinin altında kalarak, sistemin günümüzdeki bir taşıtın modeli olarak kullanılabileceğini göstermiştir. Buna ek olarak, sonuçlar gelecek limitlerle de karşılaştırılmış, sistemin nitrojen oksit ve karbon dioksit limitleri açısından yeni limitleri karşılamakta başarısız olduğu ortaya konmuştur.

Tezin devamında, elektrikli komponentlerin eklendiği modeller kurulmuş ve simülasyonları yapılmıştır. 3 elektrikli komponentin yalnız kullanımlarının, birbirleri ile etkileşimini ve sistem üzerindeki toplam performanslarını görmek için çeşitli kombinasyonlarının denemeleri yapılmıştır. Toplam 7 farklı sistem tasarımı, 2 farklı emisyon çevriminin soğuk başlangıç ve sıcak başlangıç koşullarıyla test edilmiştir.

Elde edilen emisyon çevrimi sonuçları neticesinde, tasarımların bazılarının karbon monoksit, hidrokarbon ve katı partikül emisyonları açısından konvansiyonel sistemden daha iyi sonuç verdikleri ve gelecek emisyon limitlerini sağlamada başarılı oldukları görülmüştür. En büyük iyileştirme karbon dioksit ve nitrojen oksit emisyonlarında beklendiği için optimum sistem seçimi bu kritere göre yapılmıştır. Buna göre elektrikli turbo şarj ve elektrik ısıtıcı katalizörün birlikte kullanılması bu emisyonlar açısından en iyi sonucu vermiştir. Bununla birlikte, türbin tarafından üretilen, kompresör ve elektrikli katalizör tarafından tüketilen güçlere bakıldığında, sistemin dış bir enerji kaynağına ihtiyaç duymadığı gösterilmiştir. Son olarak optimum sistem gelecek emisyon limitleriyle karşılaştırıldığında, Amerika için gelecek emisyon limitlerine yakın sonuçlar verse de limitlerin altına inemediği, ancak gelecek Avrupa limitlerini sağlamada başarılı olduğu gösterilmiştir.

Son olarak gelecekte konu ile bağlantılı incelenebilecek araştırma konuları paylaşılmıştır. Önümüzdeki yıllarda elektrikli araçlara ve alternatif yakıtlara ilgi artıyor olsa da muhtemelen uzun yol ağır vasıta araçların önemi ulaşım ve taşımacılıkta devam edeceği ve yakın gelecekte bu alanda dizel yakıtların kullanımının aniden düşüşü öngörülemeyeceği için daha verimli, daha temiz dizel sistemlerin geliştirilmesinde çalışmalara ihtiyaç vardır.



1. INTRODUCTION

Transportation is one of the basic needs of people. From a historical view, people supplied this need with animals up to the 20th century. Like many other topics, the shape of transportation changed by an invention just before the 20th century. In 1885, the first fuel-based vehicle with a four-stroke engine, advanced electric coil ignition, and a transmission system was created by Karl Benz who is the father of the modern car, also was patented on 29 January 1886 which was known as the Benz Patent Motorwagen [1]. Karl Benz's first car can be seen in the figure below.



Figure 1.1 : The first car created by Karl Benz [2].

An engine generates power by consuming fuel. There are several different fuel options for engines. Traditionally, it is thought that if there is a term as engine, it consumes petrol or diesel. The reason for this approach is that petrol and diesel still have the highest share of the fuels despite the increasing trend of electricity and alternative fuels. In 2020, the total share of petrol and gasoline for passenger cars is around 80%, and the share of diesel is around 30% without concerning hybrid vehicles [3]. If the commercial vehicles are considered the share of diesel will be much higher. The figure below shows an example of the share of diesel in trucks registered in the European Union.

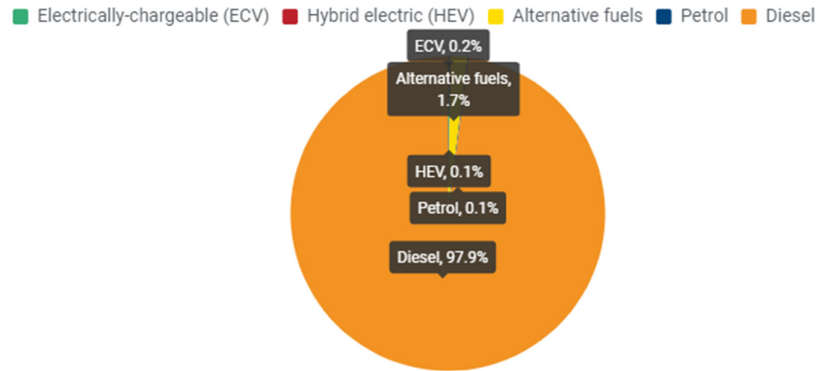


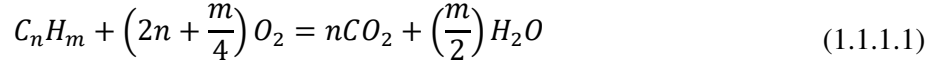
Figure 1.2 : The share of diesel in trucks registered in the European Union [3].

1.1 Diesel Emissions

The diesel engine is an internal combustion engine. Like other internal combustion engines, it converts chemical energy in the fuel into mechanical power. Chemically, diesel is composed of hydrocarbons. That's why the diesel exhaust gas must contain carbon dioxide (CO_2), water vapor (H_2O), and unused charge air theoretically. Although those are the primary product of diesel combustion, the diesel exhaust gas has also some pollutants which can either be toxic or have negative environmental effects because of incomplete combustion, other reactions between mixture components, combustion of lubricant and its additives, and combustion of non-hydrocarbon components of diesel fuel such as sulfur compounds or several fuel additives. The most important and regulated pollutants are unburned hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NO_x), and particulate matter (PM) [4]. In addition to those pollutants, some non-pollutant greenhouse gasses such as nitrous oxide (N_2O), which is commonly known as laugh gas, and methane (CH_4) will take place in upcoming regulations [5]. Because diesel exhaust tends to be high NO_x and PM, their control is the most challenging part.

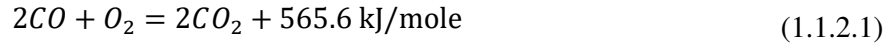
1.1.1 Hydrocarbons (HC)

HC in the diesel exhaust gas mainly comes from unburned fuel and lubricating oil. In the regulations, limiting total hydrocarbons (THC) or non-methane hydrocarbons (NMHC), which methane (CH_4) is excluded, is the most common method. HC can be induced to CO_2 by oxidation process according to the following equation.



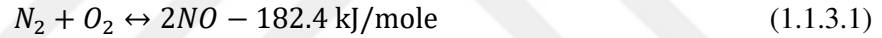
1.1.2 Carbon monoxide (CO)

CO is a product of fuel that is not burned properly. For diesel engines, CO is relatively low according to other emissions, and it can be oxidized to form CO₂ by the following equation.

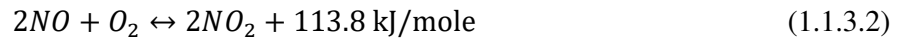


1.1.3 Nitrogen oxides (NO_x)

NO_x is the composition of nitric oxide (NO) and nitrogen dioxide (NO₂), and the total of two gasses limited in the regulations. At high temperatures and pressures like in the diesel engine cylinder NO forms from oxygen and nitrogen in the air according to the following equation.



The equilibrium of the chemical reaction shifts to the left side at low temperature and pressures like diesel exhaust gas; however, the decomposition rate is very close to zero, so NO_x control becomes the most challenging part due to the reasons mentioned above [6]. NO can also be oxidized to form NO₂ according to the following equation.



1.1.4 Particulate matter (PM)

PM is one of the most challenging emission control for diesel engines. For older diesel vehicles, it can be seen as black smoke behind the vehicles. PM samples are collected from the diluted and cooled exhaust gas, so it includes both solid and condensed liquid particles. Those particles are mainly elemental carbon, heavy hydrocarbons, and hydrated sulfuric acid. The diameter of particles has importance for the regulations. PM is composed of both small nuclei particles ~0.04µm and accumulation of nuclei up to 1µm [7]. PM nuclei and accumulated version can be seen figure below.

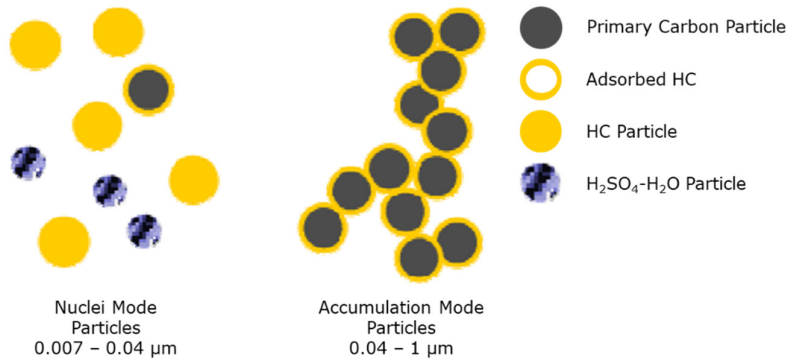


Figure 1.1.4.1 : Schematic of diesel particulate matter [7].

1.2 Emission Control

Because of the non-ideal combustion of diesel, diesel engines like other internal combustion engines generate some pollutants and greenhouse gasses. Although those gasses are hazardous for human and environmental health, they are not considering until the number of cars in the streets increasing significantly. In the 1970s and 1980s, rule-makers took gasoline car emission as their primary target to decrease air pollution. Therefore, the first emission regulations were published based on four acts: the Clean Air Act (CAA) of 1967, the CAA of 1970, and its two amendments carried out in 1977 and 1990 [8]. To satisfy the emission standards in the regulations, the exhaust aftertreatment systems took place in the vehicles, and the development of this technology has become important from the early 1970s until today. Now, the fundamental components, which are known as catalysts, of diesel aftertreatment systems will be introduced. A standard diesel aftertreatment system is illustrated in the figure below.

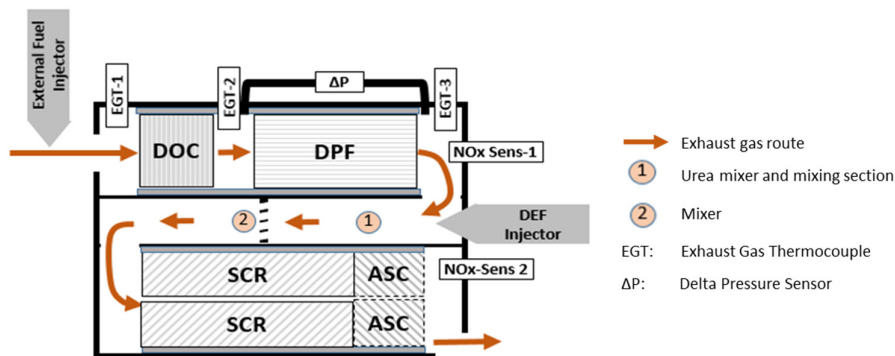


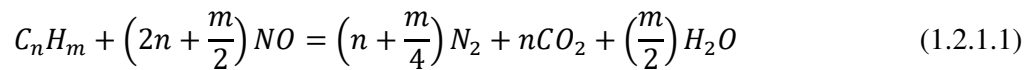
Figure 1.2.1 : Illustration of a diesel aftertreatment system.

Before introducing the components, the fundamental terms are explained below.

- **Conversion efficiency:** It shows the effectiveness of catalytic reaction. It is represented as the percentage of concentration of a pollutant at the inlet of the catalyst to its concentration at the outlet.
- **Light-off temperature:** It is the minimum temperature to initiate the catalytic reaction.
- **Catalyst window:** The high temperature may cause a decrease in the conversion efficiency of the catalyst. For those, the temperature range that the catalyst operates at high efficiency is defined as catalyst window.
- **Space velocity:** It is defined as the gas volume per time per unit of volume of the catalyst. It is another important factor that affects conversion efficiency. Mainly, higher space velocity causes lower efficiency.
- **Noble metal loading:** It is another important parameter with an effect on catalyst performance. Noble metals in the catalysts are platinum group metal (PGM) such as platinum (Pt), palladium (Pd), and rhodium (Rh). The PGM loading is represented as the ratio of the mass of the metal per cubic foot of the catalyst substrate as Pt:Pd:Rh. For example, 90g, 2:1:0 means that Pt is double of Pd and no Rh loading, so the catalyst substrate loaded with 60 g/ft³ Pt and 30 g/ft³ Pd.

1.2.1 Diesel oxidation catalyst (DOC)

In 1994, the first DOCs have begun to be implemented in heavy-duty vehicles in the USA to converting PM into a small amount of CO and HC, then oxidize them into CO₂ and water without producing sulfur trioxide to satisfy the regulations until 2003 [9]. Also, DOC oxidizes some amount of NO in the exhaust gas to NO₂. This NO₂ is important for the following component which is the selective catalytic reactor (SCR). DOCs are generally coated with a washcoat which is made of support material, for example, γ -AL₂O₃, and PGM which can be Pt and/or Pd [10]. Another function of the DOC is NO_x reduction by using the HC in the exhaust gas. However, it occurs only in a limited temperature range according to the following formula.



With zeolite addition, CO conversion of the DOC can be extended to a lower temperature, and it helps for improving the cold start performance [10].

A picture of a DOC from a supplier is shown in the figure below.



Figure 1.2.1.1 : Picture of a DOC [11].

1.2.2 Diesel particulate filter (DPF)

Because of the dangers of PM on human health and the environment, it is restricted by regulations day by day. Today, the restriction of PM emissions continues. The component used widely in diesel aftertreatment systems for reducing PM emissions at the tailpipe is DPF. DPF is a type of wall-through filter in which exhaust gas flows through the small walls in the DPF. Generally, a DPF can filter 95% of the PM, but some amount of PM is stored in the DPF intentionally for better conversion efficiency [12]. On the other hand, too much PM in the DPF can cause blockage, and it causes a high pressure drop through the DPF that can cause engine operation failure [13]. For avoiding that the PM must be removed from DPF in some periods which is called DPF regeneration. There are two types of DPF regenerations: passive and active. Active regeneration is the removal of PM in DPF periodically by controlled oxidation, and it happened mostly at higher temperatures like above 550 °C [14]. Passive regeneration occurs continuously at exhaust gas temperature to provide PM oxidization in the filter, and it is assisted by DOC which provides NO₂ for PM oxidization in DPF [15]. A DPF example with wall-through flow characteristics is shown figure below.

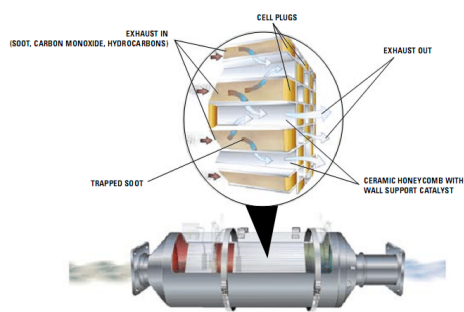


Figure 1.2.2.1 : DPF representation with wall-through flow [16].

1.2.3 Selective catalytic reduction (SCR)

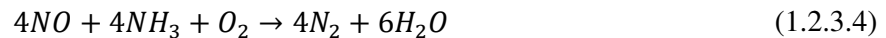
It is a process that conducts the reduction of NO_x with ammonia directly or using an ammonia pre-cursor. SCR catalysts are also called SCR generally. The SCR was applied firstly on stationary engines. The thermal power plant in Japan in the late 1970s, rapidly increasing usage in Europe in the 1980s, and gas turbines in the USA in the 1990s can be given some examples of SCR usage in the industry [17]. Usage of SCR in the vehicles came later. With the proposal of Euro V and JP 2005 which both have 2 g/kWh NO_x at tailpipe for heavy-duty trucks and busses, urea-based SCR has become the base and most common technology among manufacturers [17]. Daimler-Crysler in Europe and Nissan Diesel in Japan put the first SCR in their heavy-duty trucks and busses in 2004 [17]. Because the thesis focuses on heavy-duty trucks, the urea-based SCR system will be explained briefly.

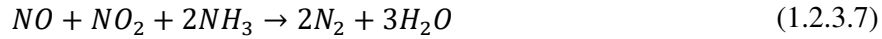
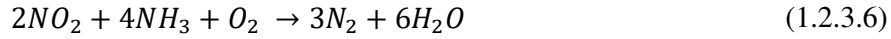
Solvents of urea with water are the most common choice because it is not harmful to the environment, storing and loading the vehicle is easy, and it is easily accessible finally [17]. There are some alternatives to urea solution such as solid urea, carbamate salts, and various amines [17]. The urea solutions that are commercially and commonly called AdBlue® are the first and most common products because of the reasons mentioned above.

In the SCR process, the urea solution is injected into the exhaust gas firstly, then it goes to a section which is generally known as a mixer that provides homogenous distribution of the decomposed ammonia. Urea decomposed in the exhaust gas to provide necessary ammonia for SCR according to the following equation.



Then, several reactions occur in the SCR inducing the NO_x in N₂. Those equations are given below.





3rd equation is the basic reaction. Equation 4 is the most common reaction [17]. Reactions from 5 to 7 reduce NO₂ also. Despite the NO₂ concentration is not high mostly, NO₂ concentration is increased with the help of DOC for some SCR systems because the last reaction is the fastest one, and it helps the NO_x conversion at lower temperatures [17].

Finally, the most common types of SCR catalyst will be introduced. There are three most common SCR catalysts: Pt-based, vanadia-based, and zeolite-based. Pt-based catalysts are effective at low temperatures, and conversion efficiency reduces above 250°C, so the vanadia-based catalysts were selected instead of Pt; however, it is not as effective as needed for higher temperatures above 450°C [17]. That's why zeolite-based catalysts have been developed that can operate at higher temperatures in the 1990s [17]. The catalyst windows of those SCR technologies are shown figure below.

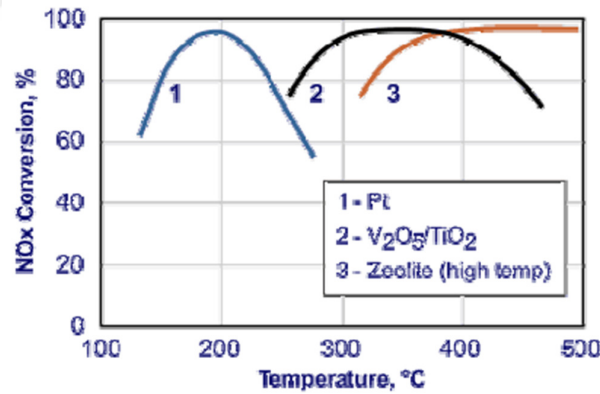


Figure 1.2.3.1 : Catalyst window of different SCR technologies [17].

1.2.4 Ammonia slip catalyst (ASC)

Generally, the last component of today's diesel aftertreatment systems is ASC. The main purpose of ASC is to convert the unwanted NH₃ at the outlet of SCR. This phenomenon is called the NH₃ slip. 3 possible situations can cause NH₃ slip such as incompleting reactions in SCR, releasing of NH₃ stored in SCR due to temperature deviations, and decomposition of urea at the outlet of SCR [18].

1.3 History of Emission Regulations

When the history of emission standards is examined, it seems that there are two major regions that guided to other regulations. Before those two will be explained briefly, the timetable of some legislation is given in the figure below.

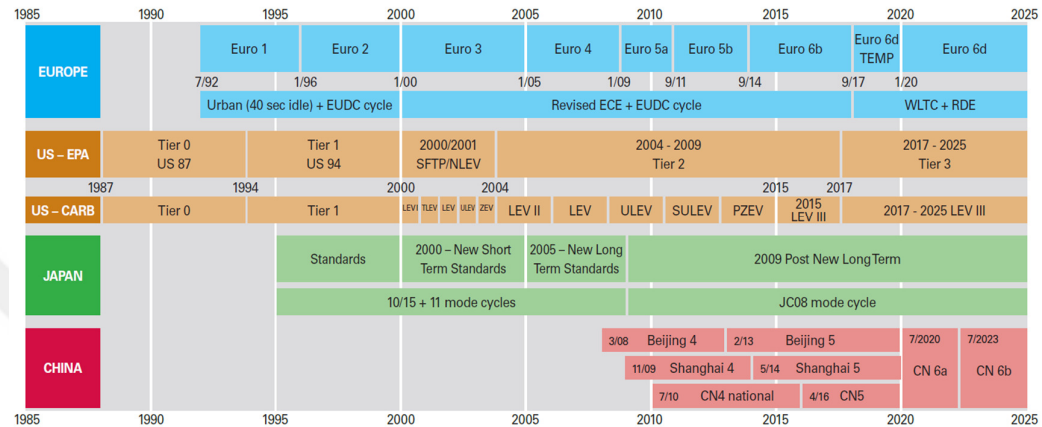


Figure 1.3.1 : Timetable of some legislations [19].

1.3.1 USA

The debate of emission regulations grounds the significant air pollution problem in California USA. The problem was so big that people living in California believed that they were attacked by chemical weapons of the Japanese in the middle of World War II in 1943 because of the thick smog which made eyes irritated, lung burn, and nausea on people [20]. There are many photos of those days in California, and one example is shown in the figure below.



Figure 1.3.1.1 : A view of downtown Los Angeles in 1948 [20].

For the solution of the problem in 1967, some politicians and pioneers from California came together, and they led the foundation of the Mulford-Carrell Air Resource Act, which then brought out the California Air Resources Board (CARB); moreover, the Federal Air Quality Act was executed in the same year, and gave California permission for more stringent air quality rules because of its problem is bigger than other states [21]. In 1968, Clean Air Act (CAA) regulated HC and CO emissions and appointed Environmental Protection Agency (EPA) to define and control regulations; moreover, CO and HC limits were decreased by 10%, and NO_x was included in the regulation in 1973 [22]. However, due to the necessary technology unavailable, manufacturers could not satisfy the limits, so they were postponed until 1981 for HC and CO, and 1992 for NO_x [22]. To sum up, a chronological list of all EPA standards will give too much detail, and it is not the main topic of this work. Thus, the summary of EPA regulations can be seen in the figure below.

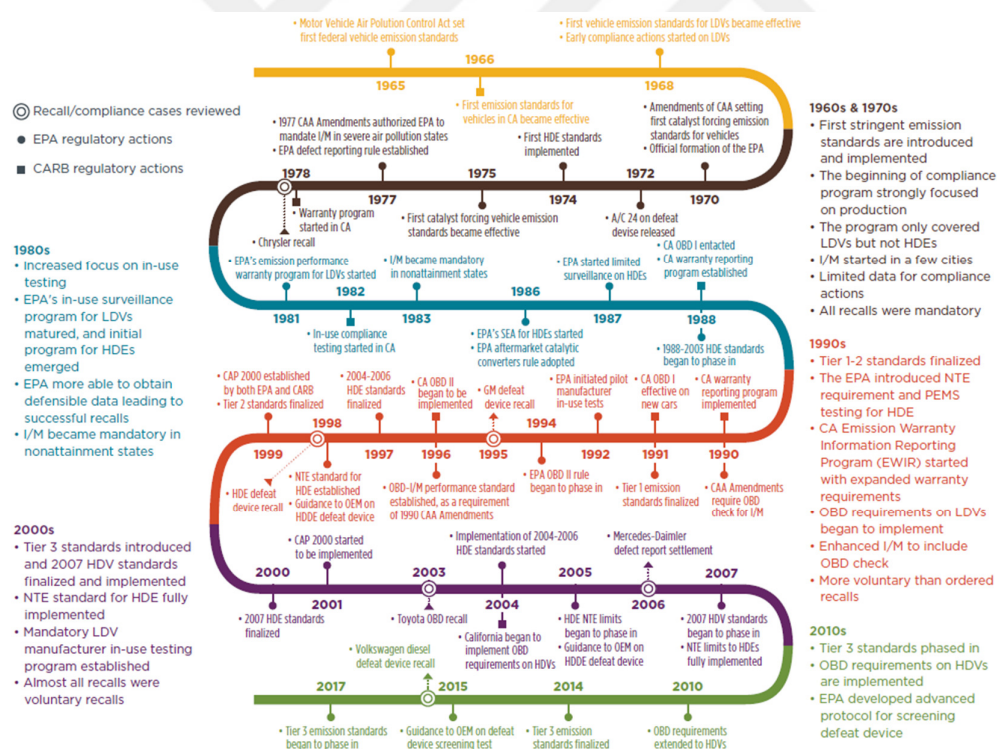


Figure 1.3.1.2 : The summary of EPA regulations in the USA [23].

1.3.1.1 California

Here, California needs to be explained shortly and separately because it has also more challenging rules on its own. If any manufacturer wants to sell its vehicle in California, it also has to satisfy the rules of CARB. Even though CARB applied the same

regulation with other states until 1993, they pushed the limits through rapidly decreasing such that vehicles with zero-emission would be mentioned until 1998 [22]. CARB announced that any manufacturer planned to sell vehicles in California must describe their vehicles according to the following table. The explanation of abbreviation in the table: model year (MY), transitional low emission vehicle (TLEV), low emission vehicle (LEV), ultra-low emission vehicle (ULEV), zero-emission vehicle (ZEV), non-methane organic gasses (NMOG).

Table 1.3.1.1.1 : CARB emission standards [22].

Emissions [g/km]	Durability [km]	MY 1993	TLEV	LEV	ULEV	ZEV
NMOG	80000	0.4	0.2	0.12	0.06	0
	160000	0.5	0.25	0.14	0.09	0
CO	80000	5.44	5.44	5.44	2.72	0
	160000	6.72	6.72	6.72	3.63	0
NO _x	80000	0.64	0.64	0.32	0.32	0
	160000	1.6	0.96	0.48	0.48	0

Also, they must introduce the vehicles in the steps showing figure below.

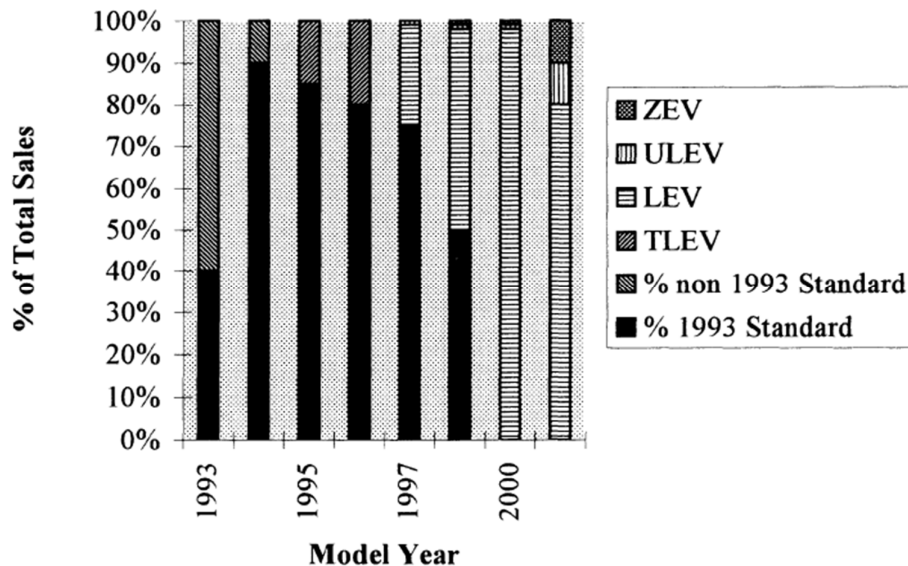


Figure 1.3.1.1.1 : Timetable of vehicles in California to new standards [22].

From the foundation of CARB to today, they are trying to implement the best rules for better human and environmental health. Therefore, they took the responsibility of

greenhouse gas, which causes climate change, the reduction from the 2000s, and they are intended to be world pioneer against climate change by joining climate agreements with other countries and connecting cap-and-trade programs with Quebec [21].

1.3.2 Europe

In Europe, the stages of emission standards begin with Euro 1 and EURO I to Euro 6 and EUROVI which are the current regulations with amendments today. Two different namings indicate that standards with Arabic numbers are for light-duty and passenger cars in the unit of g/km or mg/km, and with Roman numbers are for heavy-duty engines in the unit of g/kWh or mg/kWh. European Union has regulated heavy-duty emission by EURO standards since 1992. Development of technologies related to engines was enough for EURO I, II, and III, but the development of catalyst technologies was needed after EURO IV.

Mainly, there are two different standards for two different testing conditions: steady-state testing and transient testing. In the tables below, implementation dates and emission standards of heavy-duty engines corresponding to the duty cycle for steady-state and transient are summarized.

Table 1.3.2.1 : Steady-state testing emission standards in Europe [24].

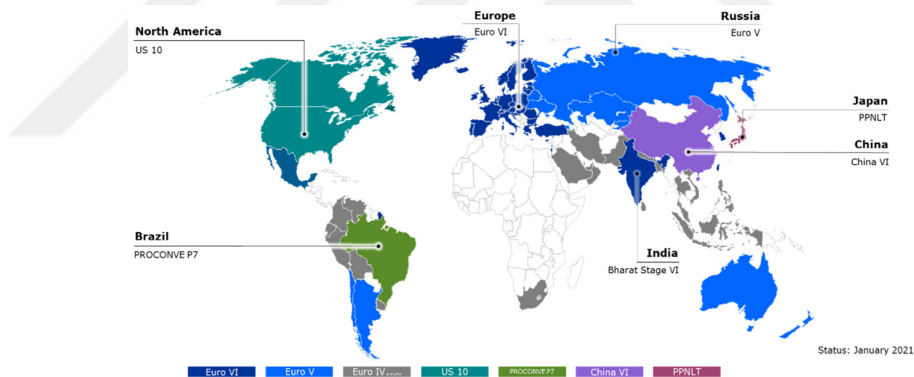
Stage	Date	Test	CO g/kWh	HC g/kWh	NO _x g/kWh	PM g/kWh
EURO I	1992, ≤85 kW	ECE R-49	4.5	1.1	8.0	0.312
	1992, >85 kW		4.5	1.1	8.0	0.36
EURO II	1996	ECE R-49	4.0	1.1	7.0	0.25
	1998		4.0	1.1	7.0	0.15
EURO III	1999	ESC& ELR	1.5	0.25	2.0	0.02
	2000		2.1	0.66	5.0	0.1
EURO IV	2005	ESC& ELR	1.5	0.46	3.5	0.02
EURO V	2008	ESC& ELR	1.5	0.46	2.0	0.02
EURO VI	2013	WHSC	1.5	0.13	0.4	0.1

Table 1.3.2.2 : Transient testing emission standards in Europe [24].

Stage	Date	Test	CO g/kWh	NMHC g/kWh	NO _x g/kWh	PM g/kWh
EURO III	1999	ETC	3.0	0.4	2.0	0.02
	2000		5.45	0.78	5.0	0.16
EURO IV	2005	ETC	4.0	0.55	3.5	0.03
EURO V	2008	ETC	4.0	0.55	2.0	0.03
EURO VI	2013	WHTC	4.0	0.16	0.46	0.01

1.4 Current Legislations

The current heavy-duty engine emission regulations over the world are shown in the figure below.

**Figure 1.4.1 : Global emission regulations.**

As the main focus of the work of the thesis, current legislation in the USA and Europe will be explained briefly.

1.4.1 USA

As it is mentioned earlier, there are two regulatory forces in the USA: EPA and CARB. Generally, CARB has added a more stringent set of rules in addition to EPA standards. Thus, the common rules and limits will be given under EPA legislation. Then, rules and limits different for CARB will be explained.

As well as in Europe, engine dynamometer tests are required for certification. Results are evaluated in the unit of g/bhp-hr different than Europe. Three testing cycles are using in the USA for emission regulations.

- Transient Federal Test Procedure (FTP): It is the fundamental testing cycle.
- Ramped-Mode Cycle Supplemental Emission Test (RMC-SET): The steady-state test to ensure the engine is still under limits during steady conditions. The limits are the same as FTP.
- Not-to-Exceed (NTE) Test: The engine can be testing at any point, which can be steady, transient, or changing environmental conditions, in a pre-defined NTE region. NTE limits are 1.5 times FTP limits [25].

The latest heavy-duty emission standard, which is valid for engines from 2007 and later, was published on 21 December 2000 by EPA, and CARB also implemented the same rules in October 2001 [25]. The latest standards brought significant decreases for PM and NO_x. Those limits are given in the table below.

Table 1.4.1.1 : US heavy-duty engine emission standards [26].

Year	NMHC	NMHC+NO _x	NO _x	PM	CO	Idle CO
	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr	% exhaust gas flow
2007	0.14	2.4 (or 2.5 with a limit of 0.5 on NMHC)	0.2	0.01	15.5	0.5

1.4.2 Europe

The latest and having lowest heavy-duty emission limits standard is EURO VI which was entered into force on 1 January 2013 and led to 95% NO_x reduction and 97% PM reduction [27]. Figure 1.4.2.1 shows the reduction of limits for NO_x and PM.

EURO VI legislation has important features such that significant reduction of NO_x and PM, the introduction of particulate number (PN) limit first time, the introduction of NH₃ limit first time, and introduction of the new test cycles: WHSC and WHTC[28].

The emission limits for EURO VI are given in table 1.4.2.1.

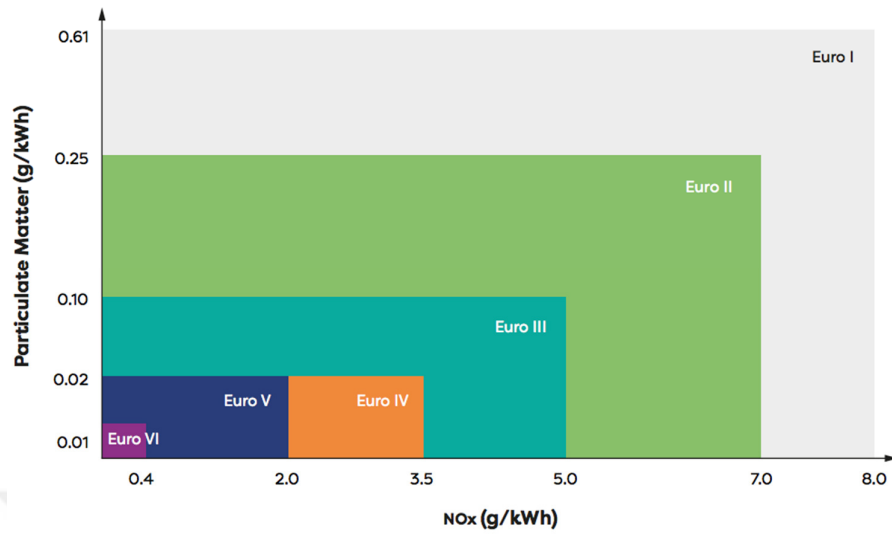


Figure 1.4.2.1 : Reduction of NO_x and PM limits through Euro standards [27].

Table 1.4.2.1 : EURO VI emission limits.

Test	CO	THC	NO _x	NH ₃	PM	PN
Cycle	mg/kWh	mg/kWh	mg/kWh	ppm	mg/kWh	#/kWh
WHSC	1500	130	400	10	10	8x10 ¹¹
WHTC	4000	160	460	10	10	8x10 ¹¹

1.5 Upcoming Legislations

The increasing world population creates more need for transportation consistently. As a result of that, the contribution of the greenhouse gasses and pollutants to the pollution become multiplying day by day. Against this dangerous problem, solutions have to be developed continuously. The most crucial segment of this continuous development process is the encouragement of new legislation by reducing emission standards and leading to new technologies. Because the developments of legislations in the USA and Europe guide others, upcoming features of USA and Europe legislations, which some are already decided and some are still in discussion, will be explained here. The main focuses of upcoming legislations are CO₂ and NO_x reduction. Before continuing to them, expected upcoming legislations for regions can be seen in the figure below.

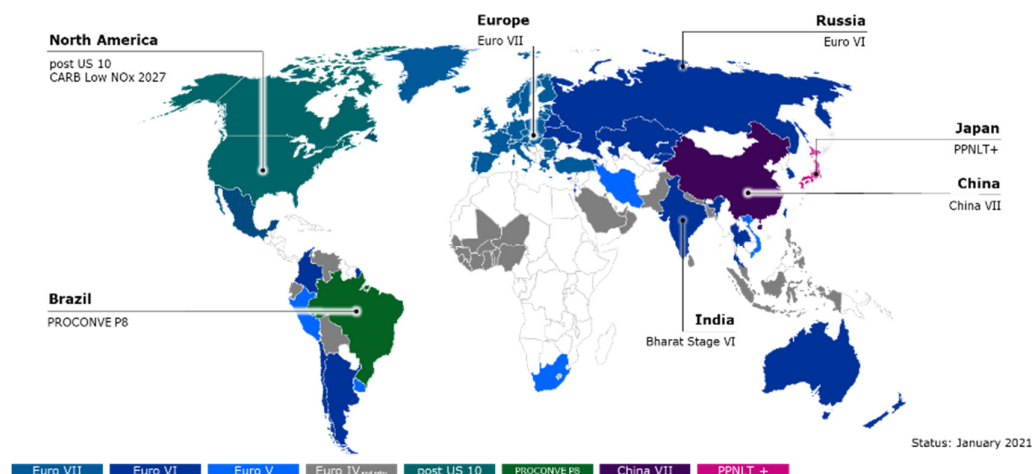


Figure 1.5.1 : Global upcoming emission regulations.

1.5.1 USA

In the USA, both EPA and CARB are working to define and finalize the emission standards of the 2020s for better air quality. When the emission reduction studies are looked at in chronological order, CARB announced the mobile source strategy, which has importance to obtain federal health-based air quality standards for ozone in 2031 and smaller particulate matter in next years, in 2016 [29]. Then, according to that strategy, they asserted that the 90% lower NO_x than today's limit could be achieved because the optional low-NO_x standards, which is 0.02 g/bhp-hr, became promotive for manufacturers, and some already certified their engines below this standard in 2016 [29]. Thus, they offered heavy-duty omnibus regulation. In addition, because vehicles purchased outside of California have a significant contribution to the pollution in the state, they asked for a more stringent limit of NO_x for other states.

Although the NO_x emissions were reduced by around 40% from 2010 to 2018 in the US, EPA claimed that heavy-duty vehicles will become the highest source of the NO_x of the transportation in the next decade, and pronounced the Cleaner Trucks Initiative (CTI) on 13 November 2018 [30]. CTI studied both engine improvements such as cylinder deactivation and late intake valve closing which could support aftertreatment components for better emission control under low operation conditions, and aftertreatment system technology developments [30]. As a result of CTI, the Advance Notice of Proposed Rule (ANPR) was published by EPA on 6 January 2020. The ANPR proposed to take actions such as lower NO_x and other emission limits, test cycle and procedure advancement for not only certification but also in real-world emission

reduction, certification, and in-use testing protocol improvements, paying regard to longer emission components in-use life and warranties, showing manufacturers to achieve cleaner technologies for today and tomorrows is not hard as it is feared [30]. The ANPR mentioned that implementation of new technologies should provide at least 50% emission reduction, even 90% seems possible, according to current FTP and RMC cycles, and diesel engines must meet new limits according to those cycles; in addition to that, a low-load cycle (LLC) and its standard is under consideration for better control emission for low operation conditions like driving a city bus in urban traffic [30].

Even EPA does not give exact values for new emission limits in the ANPR, they show the direction of the upcoming regulation. On the other hand, CARB announces its proposals of the new set of rules and limits step by step for both California and other 50 states in the heavy-duty engine and vehicle omnibus regulation. The actions of CARB's new heavy-duty regulation are separated into 3 steps: step1 (2022-2023), step2 (2024-2026), and step3 (2027-later). According to CARB's report, new rules and standards can be summarized as

- Step 1: limit change of NTE regions and using mowing average window (MAW) for in-use testing
- Step 2: For in-use testing, the MAW method with 300s window size divided into 3 bins (cold start excluded), and NO_x limits according to table 1.5.1.1.
- Step 3: Longer useful life and warranty for all engine classes, for in-use testing, MAW method with 300s window size divided into 3 bins (cold start included), and NO_x limits according to table 1.5.1.2 [31].

Table 1.5.1.1 : 2024 – 2026 CARB NO_x standards [31].

Regions	FTP (g/bhp-hr)	RMC SET (g/bhp-hr)	LLC (g/bhp-hr)	Idling (g/hr)
California	0.05	0.05	0.2	10
50-State	0.1	0.1	0.3	10

Table 1.5.1.2 : 2027 and later CARB NO_x standards [31].

Regions	FTP (g/bhp-hr)	RMC SET (g/bhp-hr)	LLC (g/bhp-hr)	Idling (g/hr)
California	0.02	0.02	0.05	5

As mentioned earlier, greenhouse gas reduction is an important issue as NO_x reduction. Therefore, EPA published current and next CO₂ limits in 2 phases. The CO₂ limits of phase 1 must be met until 2017, and limits of phase 2 must be met until 2027 [32]. Those limits are given in the following table.

Table 1.5.1.3 : Greenhouse gasses phase 1 and 2 CO₂ limits in g/ bhp-hr [33].

Model Years	Light Heavy-Duty	Medium Heavy-Duty Vocational	Heavy Heavy-Duty Vocational	Medium Heavy-Duty Tractor	Heavy Heavy-Duty Tractor
2014-2016	600	600	567	502	475
2017-2020	576	576	555	487	460
2021-2023	563	545	513	473	447
2024-2026	555	538	506	461	436
2027 and later	552	535	503	457	432

To sum up, 90% percent NO_x and ~5% CO₂ reduction are expected for new regulations in the USA. That emphasizes the importance of developments in diesel engine and aftertreatment technologies.

1.5.2 Europe

Euro VII is the upcoming legislation for Europe. Although it is not finalized yet, there are many studies to define the limits and rules for this new legislation. Consortium for Ultra Low Emission Vehicles (CLOVE) is the most important contributor to specifying Euro VII standards. CLOVE is composed of professionals from academia, manufacturers, and automotive technology developers for emissions. The members of the consortium are:

- LAT/AUTH: It is a university laboratory experienced with emission testing.
- EMISSIA: It is an expert on environmental regulations.

- FEV: It is an automotive engineering service company.
- Ricardo: It is an expert company for engineering and environmental consultancy.
- TNO: It is an expert for vehicle testing, and close to Dutch authorities.
- TUG: It is a technical university in Austria Graz.
- VTT Technical Research Centre of Finland Ltd: It is a non-profit, government-owned company expert on engine and vehicle emissions [34].

Clove shares its proposal in the Advisory Group on Vehicle Emission Standards (AGVES) meetings. The latest AGVES meeting occurred on the 4th of April 2021. The latest proposed standards of CLOVE will be given from that meeting.

CLOVE aimed to obtain a standard to satisfy almost all driving conditions, CO₂ certification needs, similar standards with light-duty and passenger car standards, and rational limits that can be achieved by studied technologies in the defined duty-cycles. As a result, they offer separate limits for cold, hot, and low load operations; also, different judgments for DPF regeneration [35].

CLOVE describes 2 different testing conditions and 3 different limits. The test is evaluated differently according to the total work of the cycle. If the cycle work is less than 3 times its WHTC work, the cycle emission value will be calculated as total emission over the cycle divided by 3 times WHTC work, which is reference work, and compared with the budget limit. On the other hand, if the cycle work is greater than 3 times WHTC work, the cycle emission values for cold and hot will be calculated according to the MAW method. The length of each window is equal to 1 WHTC work. Each window starts at each second and ends where its total work equals 1 WHTC work. The evaluations of colds and hot MAW methods are different. For the cold evaluation, all windows from second 0 to the end of the cycle must below the cold limit. For hot evaluation, windows start with the beginning of the hot condition, and they are sorted in ascending order. Then, the window mg/kWh emission value at 90% must be below the hot limit. Moreover, the minimum window average power threshold limit like for Euro VI standard is canceled, and the new rule is that if the average power of the window below 10% of engine rated power, the average power of the window is taken as 10% of rated power, which is reference power, then the window duration is calculated as 1 WHTC work divided by reference power. Finally, CLOVE does not decide the final limit values for three conditions. Thus, they have proposed two levels

of limits as HD2 and HD3 [35]. The test evaluation methods are summarized in the following figure. Also, CLOVE's HD2 and HD3 limits for three different conditions are given in the following tables [35].

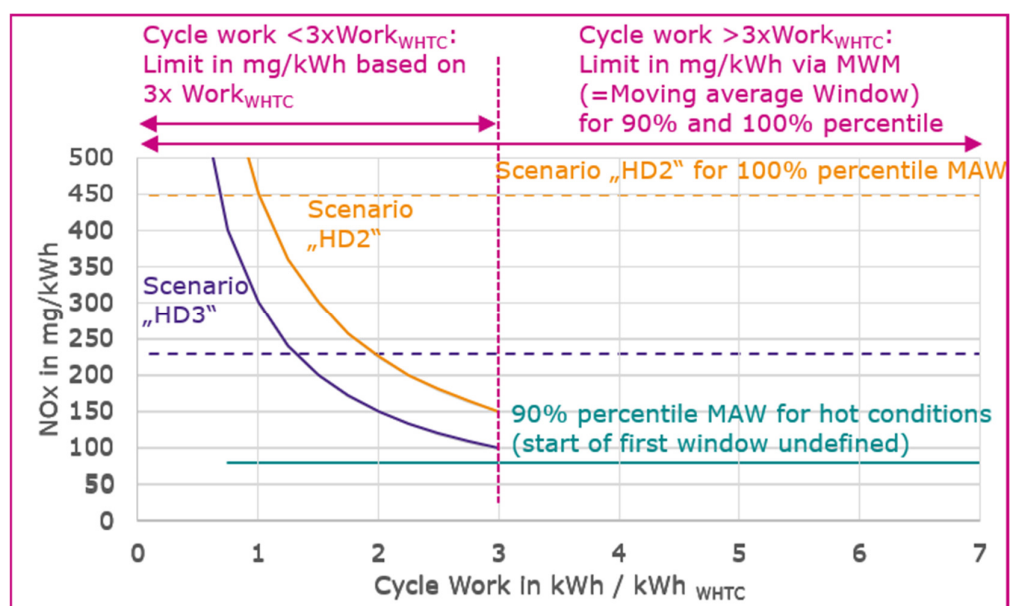


Figure 1.5.2.1 : CLOVE's Euro VII emission calculation methods.

Table 1.5.2.1 : CLOVE's Euro VII HD2 limits [35].

Test	NO _x	CO	NMOG	NH ₃	PM	SPN ₁₀	oGHGs	N ₂ O	CH ₄
Condition	mg/kWh	mg/kWh	mg/kWh	ppm	mg/kWh	#/kWh	mg/kWh	mg/kWh	mg/kWh
Budget	150	1250	75	65	10	2x10 ¹¹	40000	140	30
Cold	450	4000	225	65	10	6x10 ¹¹	50000	160	100
Hot	80	50	25	65	20000	1x10 ¹¹	20000	60	50

Table 1.5.2.2 : CLOVE's Euro VII HD3 limits [35].

Test	NO _x	CO	NMOG	NH ₃	PM	SPN ₁₀	oGHGs	N ₂ O	CH ₄
Condition	mg/kWh	mg/kWh	mg/kWh	ppm	mg/kWh	#/kWh	mg/kWh	mg/kWh	mg/kWh
Budget	100	1250	75	65	10	2x10 ¹¹	40000	140	30
Cold	230	2000	55	65	10	6x10 ¹¹	50000	160	85
Hot	80	50	25	65	20000	1x10 ¹¹	20000	60	50

It seems that the main difference between the two limit proposals is the NO_x limit is much lower for HD3. In the future, satisfying the NO_x limit for Euro VII will become

so challenging, and high technology diesel engines and aftertreatment systems will be required if the HD3 proposal is accepted.

1.6 Heavy-Duty Diesel Electrification

Air pollution and climate changes are major significant problems for today and the next decades. The increasing number of vehicles makes bigger this problem. Also, diesel engines are one of the most important contributors to this danger. That's why upcoming emission legislation is more stringent and has to be much more stringent in the next decades. Zero-tailpipe emission vehicles like battery electric vehicles may seem the solution to this problem. However, it should be concerned that material requirements and manufacturing conditions of batteries can conclude an adverse effect [36]. Thus, diesel engine and aftertreatment system improvements including hybridization and electrification could be an optimal solution for today's technology.

As a definition hybrid system can be described as a system composed of elements of two different systems. In that aspect, a hybrid electric vehicle (HEV) can be defined as a vehicle that uses a powertrain to produce power from two or more different sources at least one of the electrical [37]. There are many hybrid electric vehicle configurations such as parallel hybrid systems, series hybrid, plug-in hybrid, range extender, etc. Because this thesis focuses on electrification of the diesel powertrain and aftertreatment systems, hybrid electric vehicles are not explained more.

As mentioned earlier, CO₂ and NO_x reduction are the biggest challenges of upcoming regulations of diesel heavy-duty engines. To overcome this challenge, some investigated strategies can be summarized as powertrain and aftertreatment electrification, internal combustion engine (ICE) improvements, using hydrogen combustion engines, or fuel cell electric engines [38]. When diesel electrification which is one of the solutions is considered, it can be investigated under two categories: engine electrification and aftertreatment electrification.

1.6.1 Diesel engine electrification

To satisfy new CO₂ and NO_x limits, several technology developments are under discussion. The effects of those technologies on CO₂ and NO_x are summarized in the following figure according to Rodriguez and Posada's study [39].

	Short description	Impact on CO ₂ / GHG	Low NO _x into SCR	Fast warm-up	Stay warm	High conv. efficiency
Engine technologies	Air gap insulated manifold	Insulates the exhaust manifold and reduces heat losses before the SCR inlet during cold-start.	⇒	X		
	Cylinder deactivation	Deactivating cylinders at low loads increases exhaust temperatures of the firing cylinders.	⇓	X	X	
	Dual urea dosing	Improves NO _x conversion in high-load operation and enables the use of close-coupled SCR.	⇒			X
	Ducted fuel injection	Eliminates trade-off between soot and NO _x , allowing higher EGR rates and less-frequent DPF regeneration.	⇒	X		
	EGR (backpressure)	Exhaust gases recirculation (EGR) reduces NO _x formation during combustion by diluting the intake air.	⇑	X		
	EGR pumps	Allow accurate control of EGR rates and eliminate the increase in backpressure to drive the EGR flow.	⇓	X		
	Coolers bypasses	Bypassing hardware with high thermal inertia reduces heat losses upstream of the SCR during cold-start.	⇒	X		
	Electric boosting	Electric motors built into the turbo improve transient response, reducing NO _x peaks. 48V required.	⇓	X		
	Fast idle	Accelerates warm-up by increasing the flow of hot exhaust gases in cold-start.	⇑	X		
	Mild-hybrid (48 Volts)	Increases exhaust temperatures (higher engine load), improves transient NO _x , and enables other measures.	⇓	X	X	
	Post / late injection	Increases the exhaust temperature and reduces engine-out NO _x at the cost of higher fuel consumption.	⇑	X	X	
	Stop/start	Prevents cooling of the SCR during idle by stopping the flow of cool exhaust gases. 48V required.	⇓		X	
	Variable valve actuation	Enables temperature management by early exhaust valve opening, intake valve closing modulation.	⇓	X	X	

Figure 1.6.1.1 : Diesel engine improvements [39].

For the electrification aspect, two components in the list are electrified: exhaust gas recirculation (EGR) pumps and electric boosting which can also be named electric turbocharger or e-turbo shortly. Firstly, EGR systems are investigated, then the turbocharger and e-turbo will be mentioned.

1.6.1.1 EGR system

Some of the exhaust gas is recirculated into the combustion chamber to reduce peak fire temperature and the amount of oxygen in the cylinder. This helps to reduce NO_x produced during combustion. Less oxygen and less temperature cause less NO_x generation. EGR systems are used for this purpose. Reifarth explained some EGR systems in his doctoral thesis. There two main EGR systems: short-route or high-pressure and long-route or low-pressure systems. In the high-pressure EGR, the exhaust gas is recirculated from upstream of the turbocharger. The advantages of the system are simplicity and fast response. On the other hand, it causes the loss of some useful exhaust energy for turbo and may cause soot deposition in the intake system. In the low-pressure EGR, the exhaust gas is recirculated from either downstream of the turbocharger or DPF outlet. This system provides better fuel economy so that lower CO₂ reduction by allowing the turbo to use all exhaust energy and providing lower temperature at the intake manifold. However, it has the risk of compressor damage,

slow response to EGR demand, and needs throttling or a valve to increase pressure to flow EGR through the intake manifold. The drawback of a low-pressure EGR system can be avoided by using an EGR pump. This also allows the EGR rate independent from the engine operation point. The only disadvantage of EGR pumps is power resource need. It can be supplied from the crankshaft mechanically or the generator electrically. Both cases cause fuel consumption to increase, so the system must be implemented carefully [40]. The schematic of an EGR pump system can be seen in the figure below. 1 is EGR-cooler, 2 is charge air cooler, 3 is DPF, 4 is EGR valve, and 5 is EGR pump.

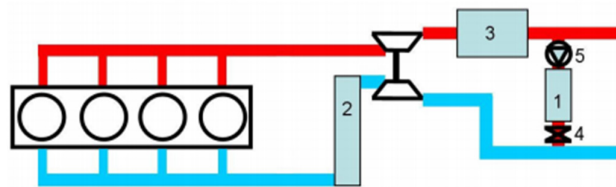


Figure 1.6.1.1.1 : Schematic of an EGR pump system [40].

1.6.1.2 Turbocharger

Turbochargers are common elements of diesel engines to supply more air charge into the combustion chamber. It compresses the air to increase its pressure and volumetric efficiency. Except for housing elements and shaft, it is basically made up of two elements: turbine and compressor. The compressor side pressurizes the air by using the energy of hot and high-pressure exhaust gas while it flows through turbine wheels. An example of a turbocharger can be seen in the following figure.

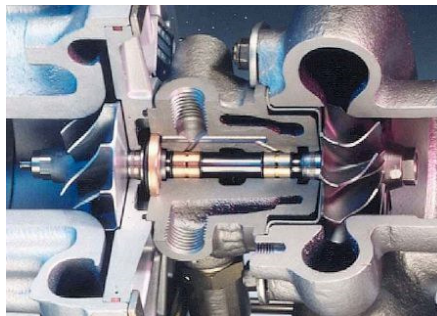


Figure 1.6.1.2.1 : Turbocharger with an inside view [41].

The main negative effect of turbochargers is the slow acceleration response which is known as turbo-lag. The turbo-lag can be compensated and transient response can be improved by using electric turbochargers with other benefits such as higher engine

power output and energy saving [42]. There are different types of e-turbo systems having different advantages and disadvantages such as electrically assisted turbocharger, electric compressor, electrically split turbocharger, and Turbocharger with an additional electrically driven compressor [42]. Those examples can be seen in the figure below.

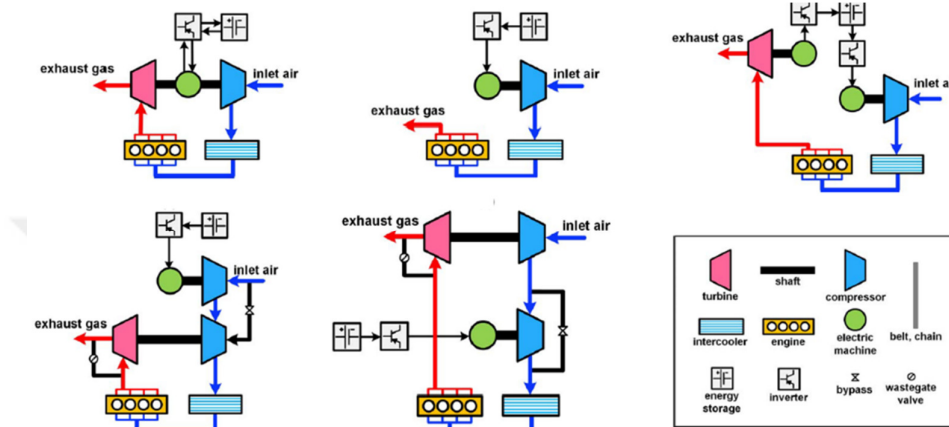


Figure 1.6.1.2.2 : Different types of electric turbocharger systems [42].

1.6.2 Diesel aftertreatment electrification

Different than engine technologies, aftertreatment technologies mainly focus on the reduction of pollutant emissions rather than CO₂ reduction. NO_x reduction is one of the most important duties. The effects of new aftertreatment technologies on NO_x reduction are summarized in the following figure according to Rodriguez and Posada's study [39].

	Short description	Impact on CO ₂ / GHG	Low NO _x into SCR	Fast warm-up	Stay warm	High conv. efficiency
Aftertreatment technologies	Burner	Burns additional fuel in the exhaust and increases exhaust temperature at the inlet of the SCR.	↑	X	X	
	Close-coupled SCR	Positioning an SCR unit close to the engine makes possible significantly faster warm-up.	⇒	X		
	Electric catalyst heating	Accelerates warm-up and ensures operating temperature independent of engine load.	↑	X	X	
	Heated urea dosing*	Enables urea dosing at lower temperatures without formation of deposits in the SCR inlet.	⇒	X		X
	Improved SCR chemistries	Improved formulations increase the NO _x performance at low temperatures and reduce N ₂ O formation.	↓	X		X
	Larger SCR volume	Larger SCR volumes can increase conversion efficiency but require more thermal management.	⇒			X
	Passive NO_x adsorbers	Trap NO _x during cold-start and release it once the SCR is warm enough. Require periodic regeneration.	↑	X		
	SCR on DPF (SCRf)	Integrating the SCR into the DPF substrate enables faster warm-up as it puts the SCRf closer to the engine.	⇒	X		
	Seventh injector	Injects fuel directly in the exhaust which is oxidized by the DOC increasing the exhaust temperature.	↑	X	X	

Figure 1.6.2.1 : Diesel aftertreatment improvements [39].

The most important factor affecting the SCR performance is the temperature. For higher NO_x conversion efficiency, SCR should be heated as soon as possible to the light-off temperature at least and kept in the catalyst window range. The only heat source of SCR is the temperature of exhaust gas. Thus, the SCR performance strongly depends on engine operation conditions. Another component that performance relies on exhaust temperature is DOC. It should also be heated as soon as possible over its light-off temperature for HC conversion. The thermal management of aftertreatment components can easily be controlled with electric catalysts which are also known as e-cat. Formerly, the main purpose of e-cat was rapid heating to reach light-off temperature, then it becomes useful for the whole operation because newly developed diesel engines provide less temperature and exhaust temperatures are around light-offs [43]. The heating effect of two electrically heated catalysts, which is named in EmiCat here, at two power levels, which are 1 kW and 2 kW, are shown in the figure below.

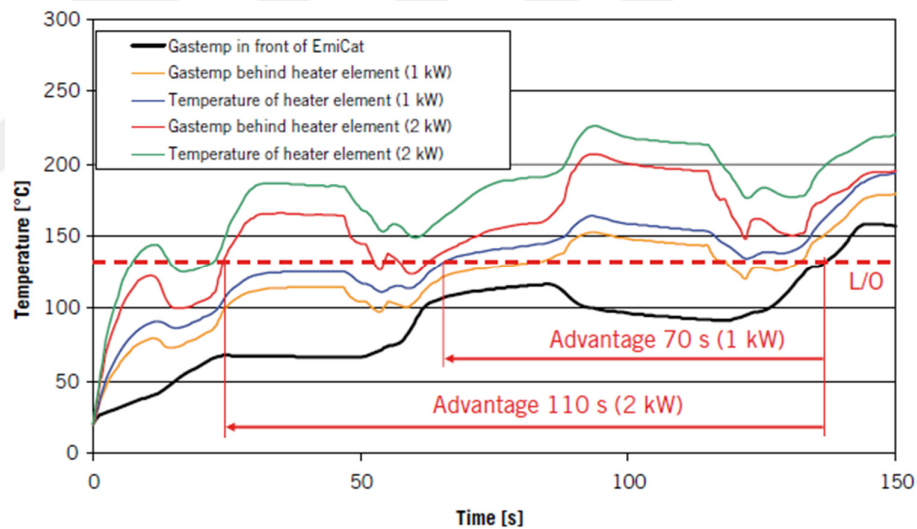


Figure 1.6.2.2 : Electrically heated catalyst temperature example [43].

In summary, electrically heated catalysts have great potential to enable better thermal management without depending on engine operation conditions.

1.6.3 Effect of electrification on diesel emissions

Here, three examples of the effect of electrification on diesel emission according to three components mentioned before will be given from studies in the literature.

The first study shows the great impact of e-cat on NO_x conversion. It states that around 30% NO_x reduction in total at the tailpipe is achieved [43]. The result can be seen in the figure below.

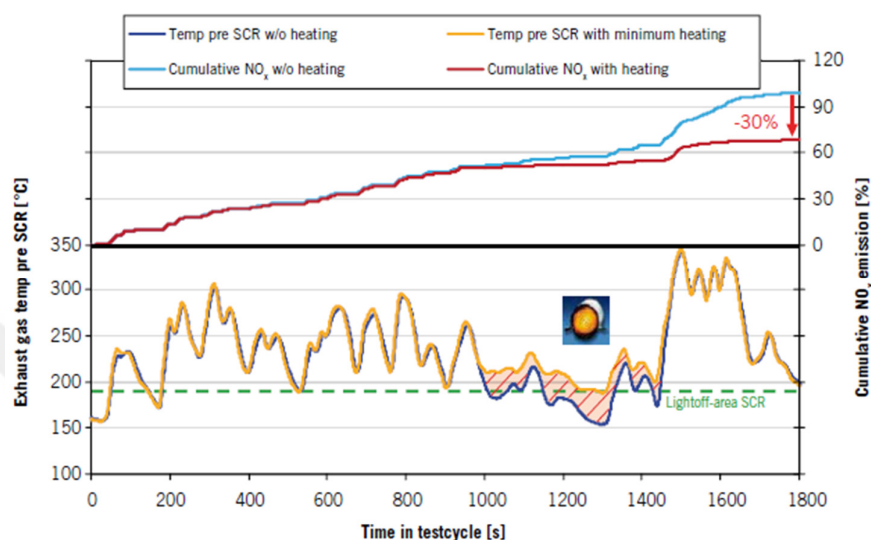


Figure 1.6.3.1 : Effect of e-cat on NO_x conversion [43].

The second study shows the impact of the electric turbocharger on fuel consumption and CO₂ reduction. In the study, it is used in two modes as the motor which provides an air boost to the engine, and the generator which supplies power to auxiliaries. Results show that even the fuel consumption is worse at motor mode, 4% fuel consumption improvement and CO₂ reduction can be achieved overall [44]. Results in which the blue bar shows the base, the red bar shows motor mode and the green bar shows generator mode are given in the figure below.

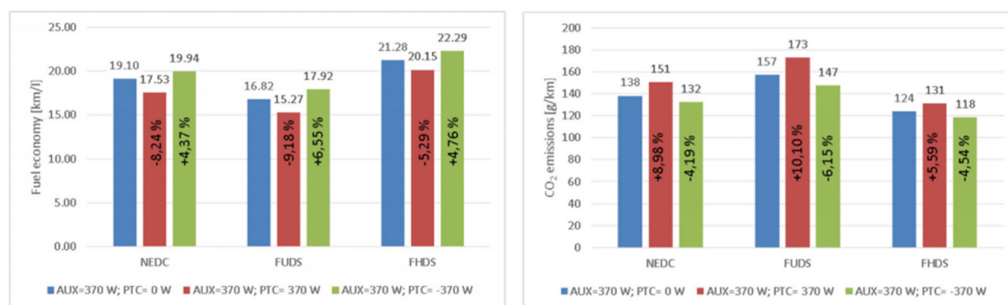


Figure 1.6.3.2 : Effect of e-turbo on fuel consumption and CO₂ reduction [44].

The last study investigates the combined impacts of e-turbo and EGR pump on fuel combustion over three different heavy-duty test cycles. Even the result does not indicate the own effect of the EGR pump, it represents the great potential of the EGR

pump using a combination of e-turbo over significant fuel saving [45]. The result in which the orange bar shows the electrified system as HD4 is given in the figure below.

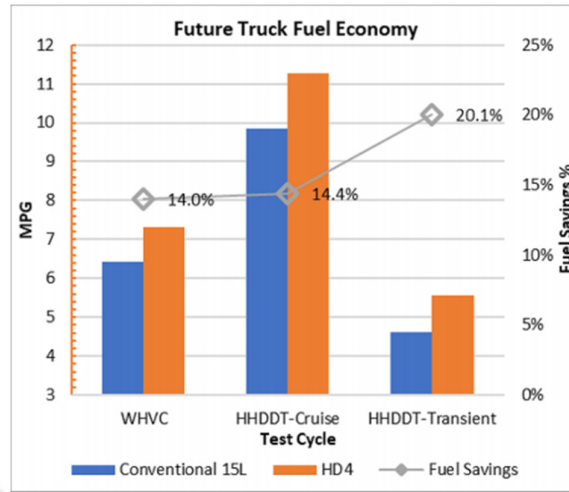


Figure 1.6.3.3 : Effect of EGR pump and e-turbo on fuel-saving [45].

To sum up, all three technologies have great potential to reduce pollutant emissions and greenhouse gasses. Therefore, they are valuable to investigate and develop more.

1.7 Purpose of Thesis

Upcoming legislations especially in the USA and Europe decrease pollutant emissions and greenhouse gasses significantly for all vehicle categories. Car manufacturers have to meet those new limits to be able to sell their vehicles. Several different engines and aftertreatment technologies are investigated to satisfy new limits by industry and academia. Long-haul heavy-duty vehicles have an important share in the cars sold and 4-wheel transportation. Also, their share of contribution to emissions is a significant level. In the literature, there is much research on new engine and aftertreatment technologies for heavy-duty engines and aftertreatment technologies. Generally, those technologies are investigated separately. However, the simulation of combined models, which represents the system level, has an increasing trend and significance due to both development phases of new powertrains to satisfy upcoming legislation with higher efficiency and sufficient performance and to enable faster, easier and more flexible calibration and validation processes [46]. The main purpose of this thesis makes a contribution to the literature by simulating a combined diesel powertrain and aftertreatment system and showing the effect of electrified components on diesel emissions. For this purpose, each component will be simulated separately and in some

combination on a combined diesel engine and aftertreatment model which is the representation of 13l heavy-duty long-haul powertrain and aftertreatment, and the simulation results will be evaluated to find an optimal system layout.

1.8 Thesis Outline

This thesis work is made up of three main sections.

In the introduction section, diesel emission basics and emission control systems are explained firstly, then the history of emission regulations, current, and upcoming legislations are mentioned, then the impact of diesel electrification on emissions and literature examples are shared, lastly, the purpose of the thesis is explained.

Chapter 1 is the second section. In this section, the aim of the combined model is explained. Then the modeling, simulation, and data evaluation platforms are introduced. Third, the heavy-duty engine and aftertreatment model is explained. Then, the simulation results are given and compared with current and upcoming legislation. Last, the chapter is summarized.

In chapter 2, the aim of the diesel electrification and simulated studies is explained. Then, different electrified system layouts, their components, and simulation models are introduced. Then the simulation results of each system are shared and compared with current and upcoming legislation, and also among different systems layouts. Lastly, the optimum system layout according to emissions is stated, and the chapter is summarized.

In the last chapter, the study is summarized, results are evaluated, and the scope of future works is investigated.

2. CONVENTIONAL DIESEL SYSTEM MODEL

Through Euro I and US Tier 1 to Euro VI and US 10, diesel engine and aftertreatment technologies differ to satisfy the in-use regulation. In this study, the term conventional defines the commonly used engine and aftertreatment system. The main powertrain and aftertreatment components of a heavy-duty long-haul truck according to current legislation can be listed as a 6-cylinder diesel engine, air-cooling system, turbocharger, high-pressure or low-pressure EGR, and auxiliaries for powertrain side and a DOC-DPF-SCR-ASC exhaust layout, mixer, and urea dosing system for aftertreatment side. For the comparison of the effect of diesel electrification on emissions, a conventional 13l heavy-duty powertrain and aftertreatment system is modeled. In this chapter, the aim of the combined model, introduction of tools for modeling, simulation, and data evaluation, model details, and simulation results will be given.

2.1 Purpose of Combined Model

Simulation studies are very valuable efforts for the development of new technologies. They provide the researchers with fast results, the ability to try many combinations, and the flexibility to make mistakes without giving damage to anything. For those reasons, this thesis is a simulation study.

As mentioned in the introduction section, there are many studies working on new engine and aftertreatment electrification technologies. However, most of all, focus on a single component in a standalone engine or aftertreatment models. On the other hand, a system-level simulation is an effective approach for both powertrain development and the calibration process. Riccio et al (2019) describe the advantages and challenges of using the combined model and they can be summarized as flexibility and re-use, more configuration variations, quasi-dimensional approach use for the aftertreatment model, shorter lead time, managing the co-simulation and its errors, and validation of both the engine and the aftertreatment models; moreover, they present the capability and accurate results of the combined model simulation by comparing the simulation results with experimental results [46]. In that paper, it is stated that the Hardware-in-

the-Loop (HiL) simulation was conducted by modeling a 13l engine and aftertreatment system which is composed of DOC and cDPF, and they are combined in the HiL environment as Functional Mockup Units (FMUs) [46]. Though that paper is the most similar work in the literature with this thesis study, the following reasons prove the originality of the thesis study. They can be listed as:

- HiL simulation is not used in this study.
- The conventional model can only be seen as similar to the model in the paper. However, it also dissociates with the model in the paper because the engine and the aftertreatment are combined under one model, and FMUs are not used. It can be said that the model in this study is more compact and easier to alter than the model in the paper.
- The aftertreatment system in the study includes an SCR while the paper does not include an SCR into the system.
- Finally and most importantly, this thesis study applies electrified components into the system and investigates the effect of electrification on emissions while the study in the paper aims to show the effectiveness of HiL simulation at the system level and to emphasize the benefits of using HiL simulation for calibration and validation activities.

Because of those reasons, this study works on a combined engine and aftertreatment model with the combination of electrified components. In addition to the benefits of using the combined model mentioned before, the following reasons to use the combined model in the study can be stated as the ability to see the effect of engine and aftertreatment components together on emissions, flexibility to try each component on its own, and many layout combinations, and a more realistic representation of an actual dynamometer test of a diesel powertrain and aftertreatment, although it causes higher model complexity that requires much more effort to build a model run correctly.

2.2 Modeling, Simulation and Data Evaluation Platforms

In this study, the AVL CruiseM, which is a modeling and simulation platform specialized for the automotive industry, for modeling and simulation, and AVL Concerto for data evaluation is used. Here, both of them are explained briefly.

2.2.1 AVL CruiseM

AVL CruiseM is a modeling and simulation program package. It enables the users to build a system in a model environment. It provides so many different simulation options with its very accurate and instantaneous subsystems that engine, aftertreatment, cooling and lubrication, drive train and chassis, electrical, and control.

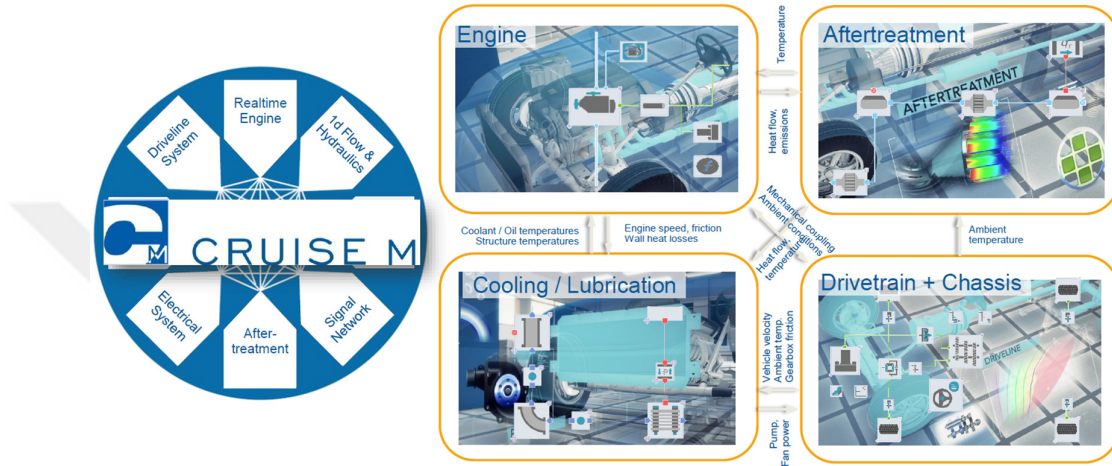


Figure 2.2.1.1 : AVL CruiseM simulation features.

AVL CruiseM allows multi-physics vehicle simulations effectively by numerical solutions which is capable of solving models with high complexity. Also, it has the ability to work with other platforms. This connectivity feature of AVL CruiseM supports its usage in so many areas such as both improvement studies like fuel consumption, emission and performance, and confirmation and calibration tasks in real-time like Hardware in the loop or test benches. Some AVL CruiseM applications can be given an example as engine development, electrified powertrain, aftertreatment development, vehicle energy management, and model-based testing, etc.

In the aspect of problem-solving with numerical methods, AVL CruiseM solvers provide strong options. The models can be simulated both explicitly and implicitly by different time-step alternatives like fixed, auto, or adaptive. Some of the solver alternatives in AVL CruiseM are Euler, Heun, Bogacki/Shampine, ARK-4, and Cash-Karp, etc.

AVL CruiseM has various components in its library for model generation. Introducing all of them is far beyond this study, but two components should be introduced

mentioned here to understand the models in the thesis well. They are MOBEO cylinder and MOBEO EAS.

The MOBEO cylinder components are combustion models for either Diesel or Gasoline engines. These models calculate the air charge, thermodynamic conditions, as well as different emissions, based on input information such as the main geometrical data, injection equipment, and boundary conditions of the cylinder. For higher accuracy, additionally, test data are required to parameterize the included sub-models. MOBEO cylinder describes phenomena in the cylinder is used: from the estimation of fresh air/residual gas trapped in the cylinder over the combustion process, towards the formation of emissions, the estimation of exhaust temperature and torque output. Complex parts of the combustion are simulated using generic models derived by AVL engineers from a large pool of measurement data of various engines, e.g.: in-cylinder pressure at spark timing – or at start of injection – is calculated using the polytropic process equation, from the closure of the inlet valve to the spark time – or to the start of injection – the necessary volumes are calculated knowing the corresponding piston position, while the polytropic coefficient is based on an empirical model. This approach combines the strength of both physical and empirical modeling: physical models can extrapolate, and empirical models are accurate within the covered parameter space and have high simulation speed. The calculation itself is zero-dimensional and mean value based, allowing real-time capabilities or even faster capabilities. In addition to the strong capabilities of the MOBEO cylinder, it has a user interface that is very easy to use. The MOBEO cylinder interface and the definition of some parameter groups can be seen in figure 2.2.1.2.

The power of the MOBEO cylinder can be emphasized by figure 2.2.1.3 which shows and model accuracy example that is taken from the AVL database. It shows the deviation between model and measurement for engine-out NO_x and CO_2 .

The MOBEO EAS components are models of exhaust aftertreatment systems for either Diesel or Gasoline engines. These models calculate the thermodynamic conditions, as well as catalytic reactions based on the main geometrical data, types of catalysts and the boundaries conditions of the EAS. The MOBEO EAS components might consist of different aftertreatment elements, such as pipes, filters, dosing devices and several different types of catalysts. Each MOBEO EAS component is a single self-contained AVL CruiseM block.

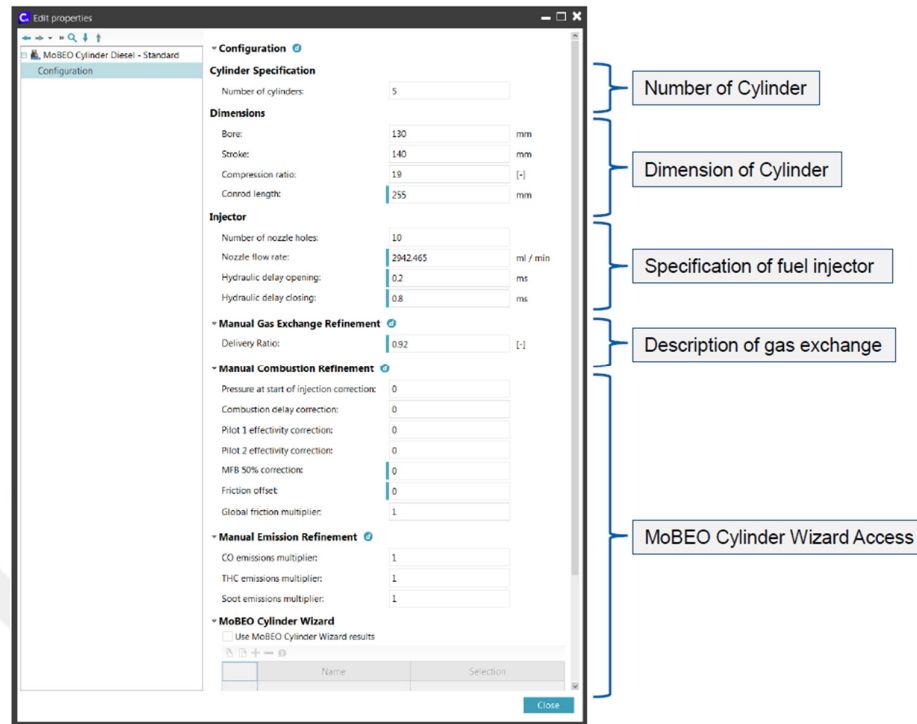


Figure 2.2.1.2 : MOBEO cylinder user interface.

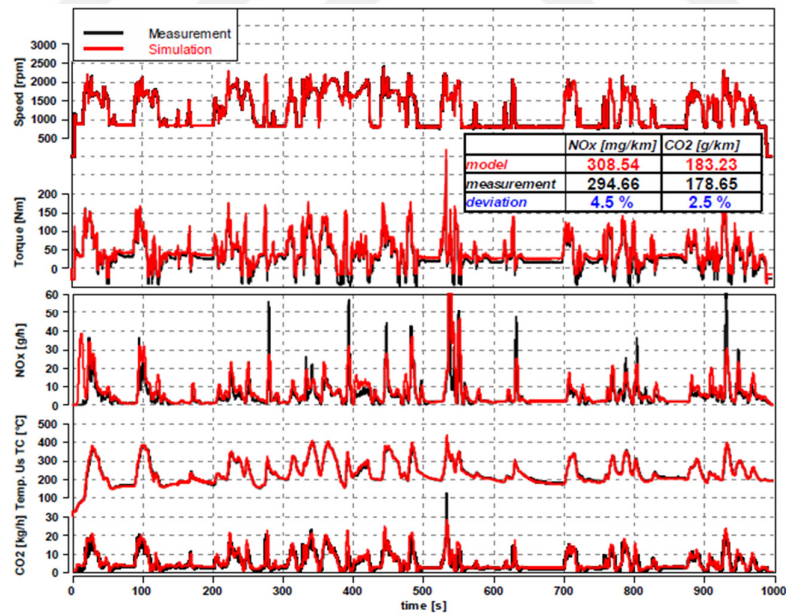


Figure 2.2.1.3 : An example of MOBEO cylinder simulation result.

The EAS is modeled as a sequence of aftertreatment sub-models components (e.g. pipes, dosing elements, catalysts and filters). Pipes, catalysts and filters are modeled as systems with one-dimensional discretization along a flow direction. This means that all states of the system are calculated and internally stored cell-wise. These states

include the temperature of the exhaust gas and the component material, concentration of the gaseous species in the exhausts, storage level of absorbed or otherwise non-moving species and the soot loading within the filters. The overall system layout, which ant configuration can be easily defined by the MOBEO EAS user interface, of the MOBEO EAS can be seen in the figure below.

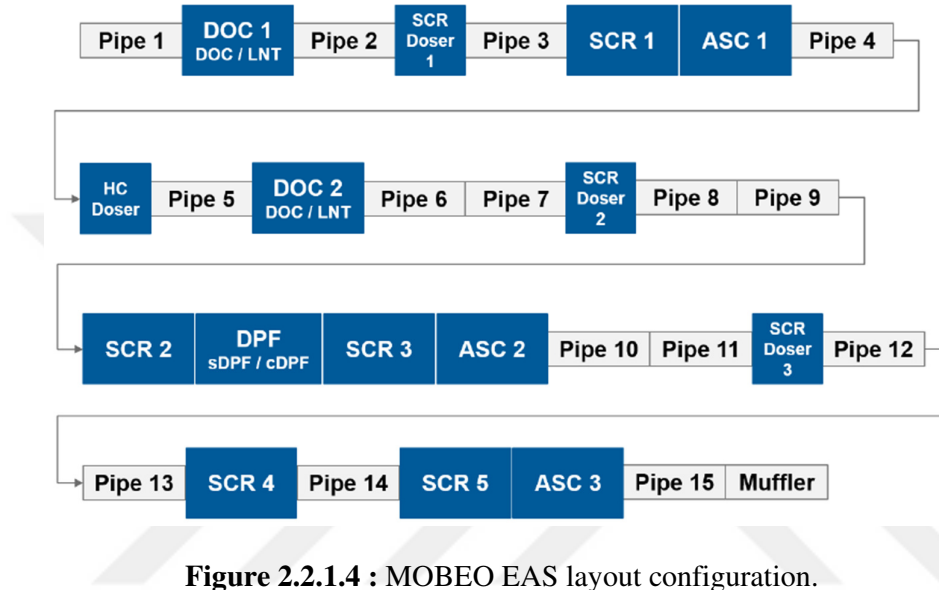
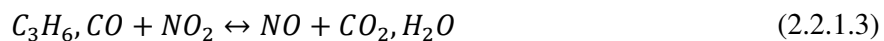


Figure 2.2.1.4 : MOBEO EAS layout configuration.

The models for gas and material temperatures include the convective heat transport by the exhaust gas flow and heat conduction parallel to the direction of the gas flow in the material. Heat exchange between gas and material is calculated based on Nusselt correlations, while heat transfer to the environment takes into account convection and radiation directly definable by the user in the graphical user interface.

Catalyst reactions are calculated cell-wise and modeled based on extended Arrhenius equations. The extensions include inhibition terms and other cross sensitivities. The reaction sets also include absorption/desorption and storage reactions. In the DOC, NO₂ formation, oxidation reactions, and NO₂ reduction are simulated according to chemical reactions given by the following chemical equations.



DPF model individually the exhaust gas flow in inlet and outlet channels. These flow models are connected by a wall-flow model. Mass flow distribution along the channel is used to estimate the amount of soot deposited in the filter. This is calculated depending on soot loading in the individual cell, temperature distribution and pressure loss. The flow in DPF is represented by the figure below.

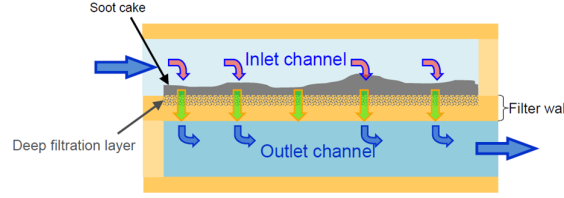


Figure 2.2.1.5 : The exhaust flow in a DPF.

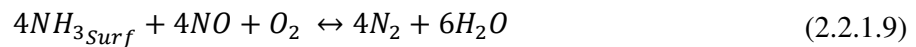
Also the wall-flow model includes the reaction of deposited soot with O_2 and NO_2 , based on an Arrhenius approach. Simply, those chemical reactions are shown in the equations below. Equations 2.2.1.4 and 2.2.1.5 define active regeneration, and equations 2.2.1.6 and 2.2.1.7 define passive regeneration.

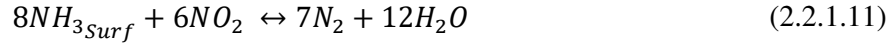
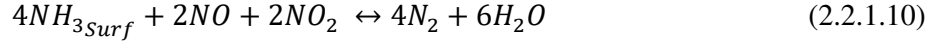


In the SCR, primary reactions are NH_3 absorption and desorption which are expressed in the following equation. Surf term means the SCR surface.

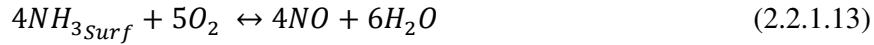
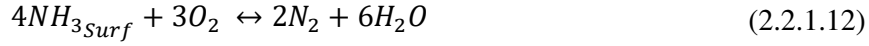


The absorbed NH_3 in the SCR surface is used for $deNO_x$ reactions. They are given in the SCR section of the introduction, but here three of them occur. Standard SCR reaction is given in equation 2.2.1.9, fast SCR reaction is given in equation 2.2.1.9, and slow SCR reaction is given in equation 2.2.1.10.





Besides, ammonia oxidation to N_2 (equation 2.2.1.12), ammonia oxidation to NO (equation 2.2.1.13), and N_2O formation (equation 2.2.1.14) occur in the SCR.



Each component in the model serves an important function. Especially, those two components explained above form the backbone of the engine and aftertreatment sides of the combined model.

2.2.2 AVL Concerto

AVL Concerto is the generic data evaluation platform for the visualization, analysis, and reporting of different types of data generated on testbeds (steady-state and transient measurement data, indicating data, emission data, etc.) or during testing using measuring systems in/on vehicles (such as ECU data, on-board sensor data, etc.) as well as data created during simulation. Due to its open interfaces, Concerto is the central tool for joining together data from all sorts of different sources. This applies equally to data from automation, measurement and simulation systems. The integration capability for third-party functions and algorithms allows to easily re-use existing knowledge. With the evaluation platform Concerto, for example, validating simulation data using reference measurement data can also be correlated easily. As a generic platform, Concerto supports the following actions:

- Data access modules (which files/server formats can be read) and data search functionality.
- Display objects (data display options).
- Basic calculation functionality (calculator, and scope of libraries).
- Use of toolboxes and apps, macros, formulas, and scripts.

By using AVL Concerto, many types of data can easily and understandably be visualized. Also, many data post-processes and evaluations can be done by using features of Concerto like calculator or script editor. Thus, because of the easiness and the powerful features of AVL Concerto for data evaluation and visualization, it is used in this study for the evaluation of simulation results and preparation of result graphs, charts. In the figure below, different types of data presentation methods of Concerto can be seen.

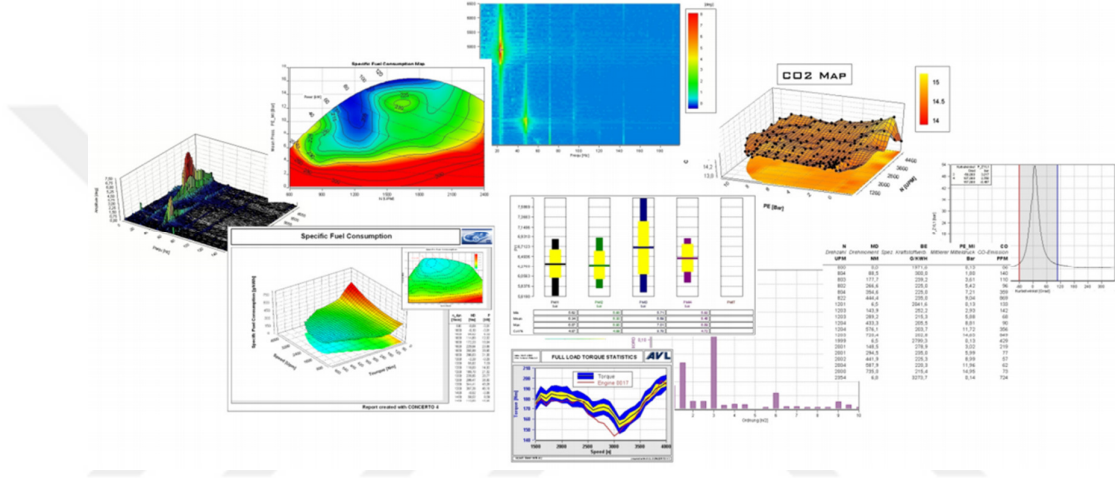


Figure 2.2.2.1 : AVL Concerto data presentation examples.

2.3 Conventional 13l Heavy-Duty Engine and Aftertreatment Model

This thesis work is based on a comparison of simulations of electrified components with a conventional heavy-duty powertrain simulation to present the effect of electrification on diesel heavy-duty diesel emissions. Therefore, a combined model of a conventional 13l heavy-duty powertrain, which is made of an engine, air path components, turbocharger, and back pressure valve, and an aftertreatment system, which is composed of DOC, DPF, SCR, and ASC, is built in AVL CruiseM. Before going through the simulation results, the model is explained.

2.3.1 Model components

This model is made by merging the aftertreatment system model with the engine model. Thus, there are two main sections in the model: engine side and aftertreatment side. The model setup in AVL CruiseM can be seen in the following figure.

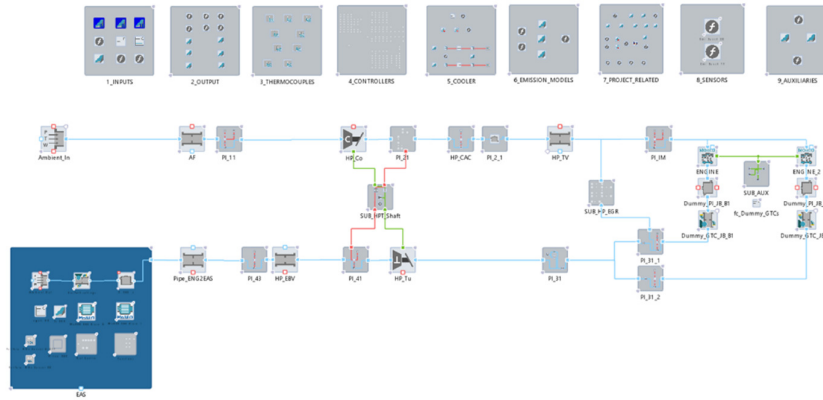


Figure 2.3.1.1 : Conventional model setup.

In the AVL CruiseM, there is some kind of connections. Four of them are used in this model. The blue lines show the gas flow connections. The green lines show the mechanical connections. The red bars show the thermal connections. Last but not the least, there is one more connection type which is the data-bus connection that is invisible normally. The data-bus connections provide the data information between components. For example, the amount of fuel injection is sent to the engine by a data-bus connection. The data-bus connection of inputs subsystem between elements can be seen in the figure below.

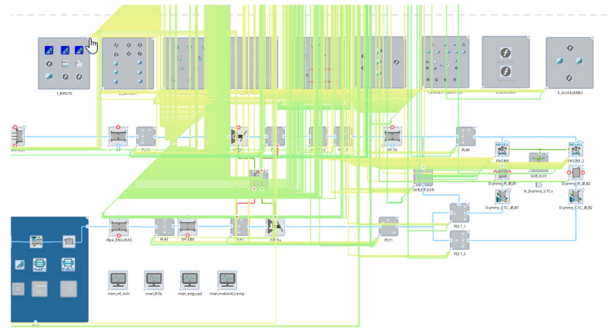


Figure 2.3.1.2 : Data-bus connection example.

The engine side can easily be seen by excluding the EAS subsystem that is shown in the blue rectangle. The engine side is the biggest and most complex part of the model. The segments which form the engine side are the information section, which is grey boxes at the top, intake model, engine model, turbocharger model, EGR model, model of auxiliaries, and exhaust model up to EAS.

The information section includes nine subsystems which are responsible for the arrangement of the inputs corresponding to simulation, arrangement of simulation

output data type, sensor models, and controller functions. The inputs subsystem arranges the input data corresponding simulation, makes injection corrections, and holds simulation reset conditions. The output subsystem adjusts the simulation output channels corresponding data type. The thermocouples subsystem includes the thermocouple models in the system. The controller subsystem includes control functions of each engine side component, and it works like a basic engine control unit (ECU). The cooler subsystem forms the engine cooling system model. The emission model subsystem has the engine out emission calculations according to input data, and corrections which are used in the engine controller functions to control engine-out emissions. The project-related subsystem has the functions and maps related to the engine model like signal corrections, EGR cooler specifications, etc. The sensors subsystem is composed of engine-out and tailpipe emission calculation functions. The last subsystem, auxiliaries, includes the maps and control functions of auxiliary components like oil pump, water pump, etc. The detailed view of the information section can be seen in the figure below.

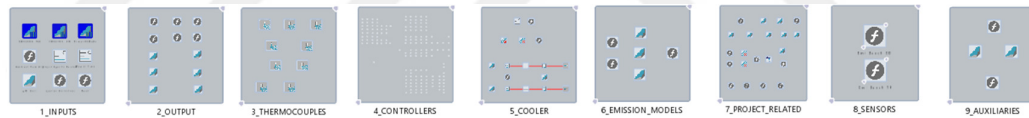


Figure 2.3.1.3 : The information section of the model.

The intake segment models temperature, pressure, mass flow, the concentrations of the species in the charge air. The first component supplies the ambient conditions. Plenums are used for thermal modeling which simulates the leakage and heat transfer at some specific points. Plenum 11 models the air at the inlet, and plenum 21 models the gas at the compressor outlet. After the compressor, the air cooling is modeled with high pressure charge-air-cooler model. Finally, the plenum intake manifold models the gas in which EGR is added. The detailed view of the intake segment is shown in the following figure.

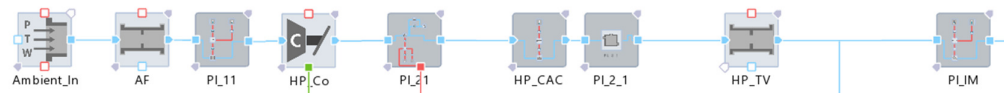


Figure 2.3.1.4 : Intake segment of the model.

The engine is modeled by using the MOBEO cylinder. The 6-cylinder engine is modeled by using two MOBEO cylinder block which each of them represents 3-

cylinder and connected mechanically because each side of the engine is connected to a separate exhaust manifold. The engine blocks are connected to the exhaust segment via components such as plenums and restrictions which define the physical and thermal properties of pipes. The figure of engine segment can be seen in the following figure and the engine properties are given in the following table. The engine properties are taken from the AVL database.

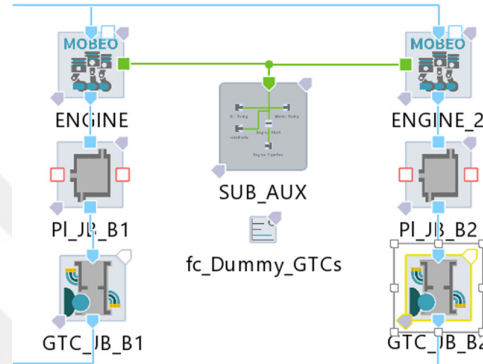


Figure 2.3.1.5 : Engine segment of the model.

Table 2.3.1.1 : Engine properties.

Property	Value	Unit
Engine volume	13	lt
Max. fuel injection pressure	2000	bar
Max. power	355	kW
Number of cylinders	6	-
Bore	130	mm
Stroke	162	mm
Compression ratio	18.5	-

The turbocharger model is built by joining a turbine and a compressor with a mechanical connection. The compressor and turbine maps are fed from the AVL database. The turbocharger model segment can be seen in figure 2.3.1.6.

A high pressure EGR model is used. It is located between the exhaust manifold outlet and the intake manifold inlet. The thermal and gas flow connections of the EGR system are shown in figure 2.3.1.7.

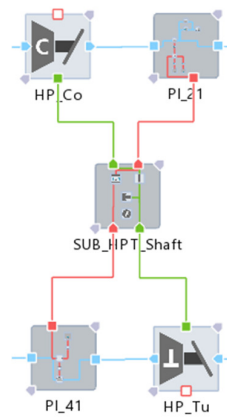


Figure 2.3.1.6 : The turbocharger model segment.

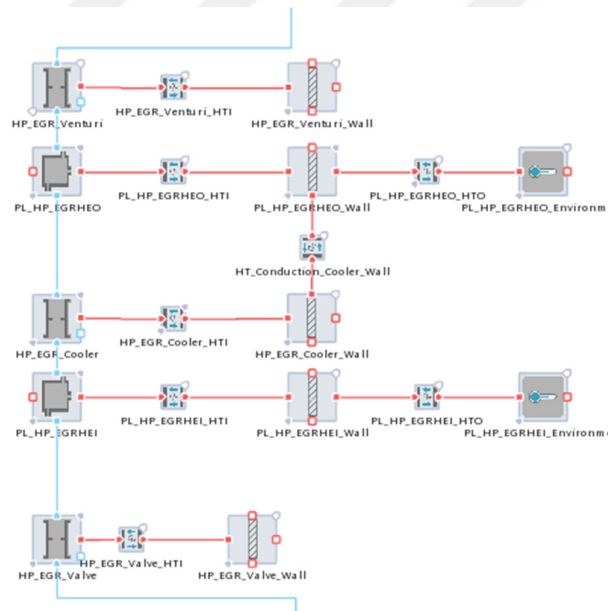


Figure 2.3.1.7 : The EGR system model.

The auxiliaries which are the oil pump, water pump, jake brake, and engine flywheel are modeled and connected to the engine crankshaft mechanically. The auxiliary system model is shown in the figure below.

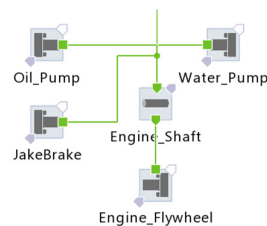


Figure 2.3.1.8 : The auxiliaries model.

The exhaust system model up to EAS is pretty similar to the intake model. The main different component is the exhaust back pressure valve (EBV) which regulates the intended pressure level before EAS. As same as the intake segment, the plenum and restriction components model the physical and thermal properties of pipes. The exhaust system model up to EAs is shown in the figure below.

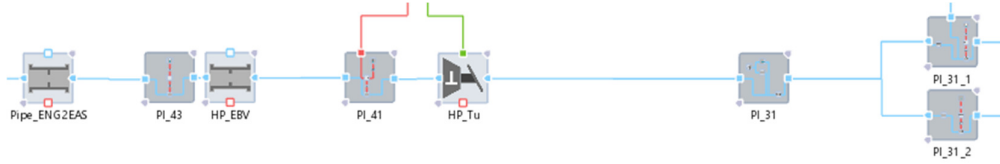


Figure 2.3.1.9 : The exhaust model up to EAS.

The other important section of the model is the aftertreatment side. The EAS model is simpler than the engine model. It consists of two MOBEO EAS blocks, components of pipes, a dosing controller, correction functions, and NO_x sensors. Although one of the EAS for a conventional system can be configured with one MOBEO EAS block, the reason for using two blocks is the preparation of other layout configurations for electrified systems. The EAS model is shown in the figure below.

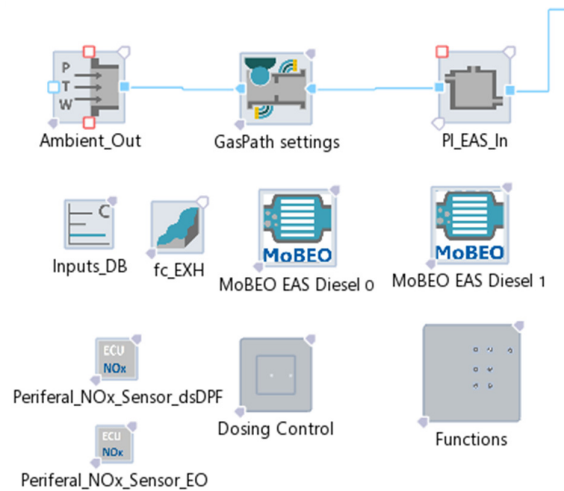


Figure 2.3.1.10 : The exhaust aftertreatment system model.

In the MOBEO EAS diesel 0 block, a conventional EAS for Euro VI heavy-duty powertrains is modeled. The system layout is DOC, DPF, SCR doser, SCR, and ASC respectively. The geometrical, physical and thermal properties of a benchmark system are taken from the AVL database. The specifications are given in the following table.

Table 2.3.1.2 : The properties of EAS components.

EAS Component	Volume	Cell Density	Wall Thickness	PGM Loading	PGM Distribution
DOC	7.4 lt	300 cpsi	5 mil	60 g/ft ³	(5:1:0)
DPF	11.1 lt	300 cpsi	9 mil	15 g/ft ³	(2:1:0)
SCR	19.3 lt	400 cpsi	4 mil	-	-
ASC	4.3 lt	400 cpsi	4 mil	2 g/ft ³	(1:0:0)

The model of two NO_x sensors provides the necessary NO_x data from engine-out and DPF downstream to the dosing control subsystem. The dosing control calculates the amount of urea that is injected into the system and checks the suitable conditions like temperature for urea injection. The functions subsystem includes some basic correction functions. The pipe configuration and the properties of them are also given in the MOBEO EAS block.

2.4 Drive Cycles

In this study, four drive cycles are used for the simulations to compare the simulation result according to current and upcoming heavy-duty regulations of Europe and the USA. The cold and hot forms of the world harmonized transient cycles (WHTC), and the federal test procedure (FTP) cycles are used in simulations.

WHTC is a standard part of Euro VI regulation. It is a transient engine dynamometer cycle. The WHTC, which its length is around 1800 s, is designed according to driver behaviors in some regions such as Europe, the US, Japan, and Australia [47]. The WHTC cycle with engine speed and torque normalization is given in figure 2.4.1.

The FTP is a standard part of the US and California regulations. It is also a transient engine dynamometer test. It covers the length of the 1200 s test which consists of four segments that represent dense start-stop events in urban traffic, relatively fewer stops in urban traffic with lots of cars, highway traffic crowd, and the first segment once again [48]. The FTP cycle with engine speed and torque normalization is given in figure 2.4.2.

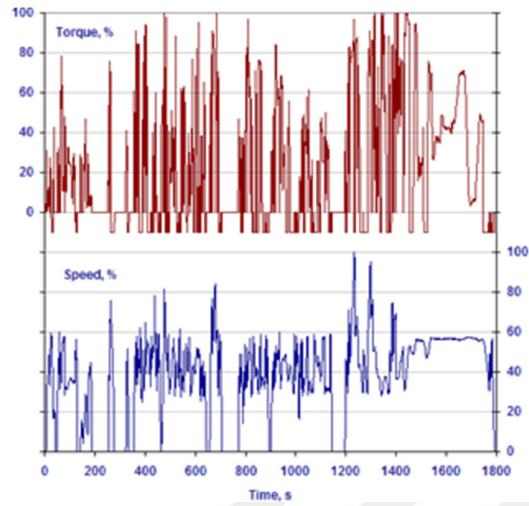


Figure 2.4.1 : The WHTC cycle [47].

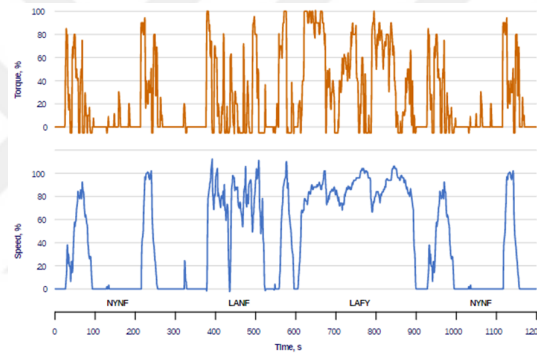


Figure 2.4.2 : The FTP cycle [48].

2.5 Model Inputs

Model components and their fundamental properties are explained in the model components section. For the simulation run, there is one more definition is needed: model inputs. If the model included the vehicle model, only speed and torque requests for corresponding drive cycles would be enough. However, the model is composed of the engine and the aftertreatment models, only engine speed and torque data are not enough to run the simulations.

The aftertreatment side does not need any external input data except for initial conditions because of the usage of the combined model. In the aftertreatment model aspect, the inputs of the model are engine-out conditions like the exhaust mass flow, exhaust temperature, pressures, gas component concentrations, etc. If a standalone model was used, those inputs would have to be feed into the model for corresponding cycles. However, the combined model usage overcomes this need. The only external

information fed into the aftertreatment components is their initial temperatures at the beginning of cold and hot tests. For cold tests, the initial temperatures of all components are assumed as air temperature in normal conditions (25 °C). For hot tests, the initial temperature of each component is assumed as the final temperature of each component at the end of the corresponding cold test. This assumption is based on the situation there is not enough time between cold and hot tests for significant temperature reduction of components. The component initial temperatures are given in the following table.

Table 2.5.1 : Initial EAS component temperatures for WHTC hot.

Pipe4	DOC	Pipe7	DPF	Pipe10	Pipe12	SCR	ASC	Pipe15
285 °C	280 °C	300 °C	310 °C	295 °C	280 °C	320 °C	365 °C	320 °C

Table 2.5.2 : Initial EAS component temperatures for FTP hot.

Pipe4	DOC	Pipe7	DPF	Pipe10	Pipe12	SCR	ASC	Pipe15
220 °C	250 °C	245 °C	245 °C	225 °C	205 °C	250 °C	250 °C	210 °C

Different from the aftertreatment side, the engine side requires lots of input data for corresponding cycles to simulate the powertrain. The required input data is taken from the AVL databases. Each input data for the corresponding drive cycle is fed into the model by using the multi-column map blocks of AVL CruiseM. Four map configurations are shown in the figure below.

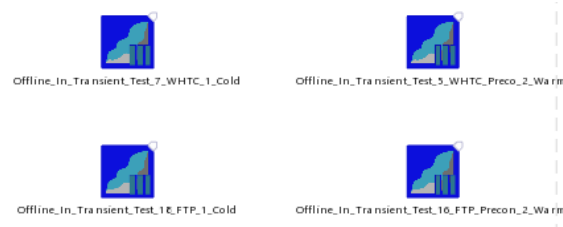


Figure 2.5.1 : The input data map configuration.

In addition to input data, model parameters are kept as simple as possible. There are lots of parameters for almost all elements like thermal characteristics parameters, emission refinement parameters, combustion correction parameters, etc. Some adjusted parameters can be given as an example such as heat transfer coefficients of EAS components, emission conversion performance parameters of EAS components.

The adjustments are implemented to catch some results, like component temperature range, rational emission concentrations at the outlet of some components, at an acceptable level for a benchmark conventional system. Besides, no boundary condition is defined because the AVL CruiseM works only in the physical boundary. For example, if the exhaust mass flow approaches exponentially higher values, the simulation stops and gives an error.

2.6 Simulation Results

The simulation results of a 13l heavy-duty engine and aftertreatment system according to four drive cycles, which are WHTC hot, WHTC cold, FTP hot, and FTP cold, is given under this section. Those results are investigated according to tailpipe emissions engine-out emissions, and fuel consumption. They are also compared with the current and upcoming legislation limits. The results of the conventional model will be the base values for comparison with electrified models. Finally, the system temperatures are investigated in the chapter summary.

2.6.1 Fuel consumption

The fuel consumption results of WHTC cold and hot simulations are shown in the figure below. The red lines represent the WHTC hot and the blue lines represent the WHTC cold.

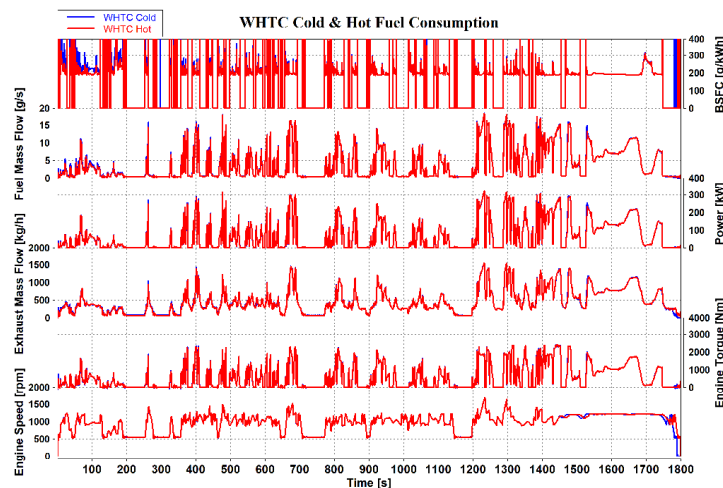


Figure 2.6.1.1 : WHTC cold and hot fuel consumption results.

The total fuel consumption, amount of fuel injected, and total work are given in the following table.

Table 2.6.1.1 : WHTC cold and hot total fuel consumption results.

Result	WHTC Cold	WHTC Hot
Total Work	32.33 kWh	32.31 kWh
Total Fuel	6833 g	6723 g
Total BSFC	211 g/kWh	208 g/kWh

The fuel consumption results of FTP cold and hot simulations are shown in the figure below. The red lines represent the FTP hot and the blue lines represent the FTP cold.

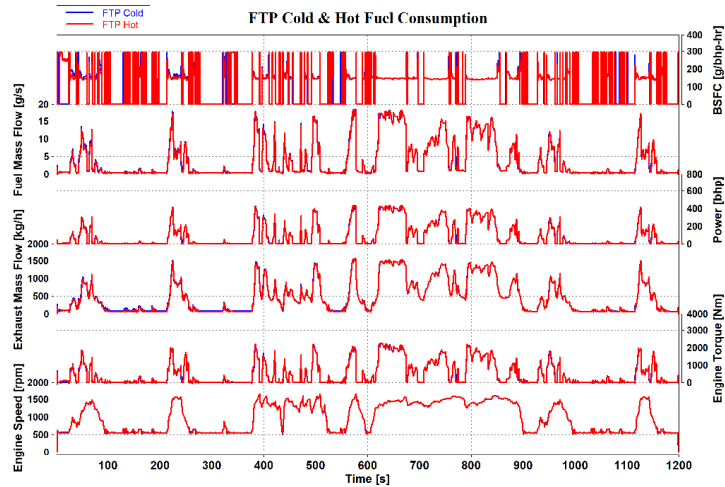


Figure 2.6.1.2 : FTP cold and hot fuel consumption results.

The FTP total fuel consumption results are given in the following table.

Table 2.6.1.2 : FTP cold and hot total fuel consumption results.

Result	FTP Cold	FTP Hot
Total Work	29.76 bhp-hr	29.89 bhp-hr
Total Fuel	4812 g	4725 g
Total BSFC	162 g/bhp-hr	158 g/bhp-hr

Each cycle is evaluated in its unit group. If the brake horsepower (bhp) is converted into a kW unit, then two cycles can be compared to each other, it is concluded that

they are not far from each other in BSFC comparison, which WHTC cold/hot is 211/208 g/kWh and FTP cold/hot is 216/212 g/kWh, although WHTC is longer cycle than FTP. Secondly, for both simulations, the cold results are slightly higher than the hot results as expected because more energy is needed to heat the system in cold tests.

2.6.2 CO₂ engine-out and tailpipe

The CO₂ results of WHTC cold and hot simulations are shown in the figure below. The red lines represent the WHTC hot and the blue lines represent the WHTC cold.

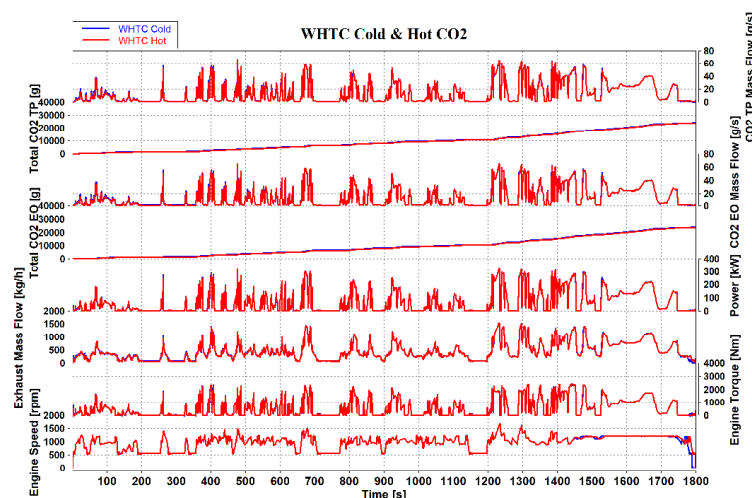


Figure 2.6.2.1 : WHTC cold and hot CO₂ results.

The total CO₂ results are given in the following table.

Table 2.6.2.1 : WHTC cold and hot total CO₂ results.

Result	Total Engine-out CO ₂	Total Tailpipe CO ₂	Engine-out BSCO ₂	Tailpipe BSCO ₂
WHTC Cold	23767 g	23930 g	735 g/kWh	724 g/kWh
WHTC Hot	23405 g	23589 g	740 g/kWh	730 g/kWh

The FTP total CO₂ results are given in the following table.

Table 2.6.2.2 : FTP cold and hot total CO₂ results.

Result	Total Engine-out CO ₂	Total Tailpipe CO ₂	Engine-out BSCO ₂	Tailpipe BSCO ₂
FTP Cold	16721 g	16821 g	562 g/bhp-hr	565 g/bhp-hr
FTP Hot	16421 g	16536 g	549 g/bhp-hr	553 g/bhp-hr

The CO₂ results of FTP cold and hot simulations are shown in the following figure. The red lines represent the FTP hot and the blue lines represent the FTP cold.

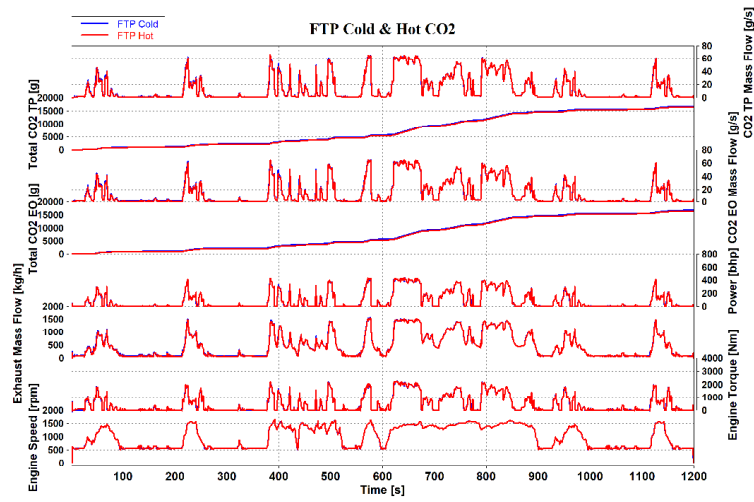


Figure 2.6.2.2 : FTP cold and hot CO₂ results.

2.6.3 NO_x engine-out and tailpipe

The NO_x results of WHTC cold and hot simulations are shown in the following figure. The red lines represent the WHTC hot and the blue lines represent the WHTC cold.

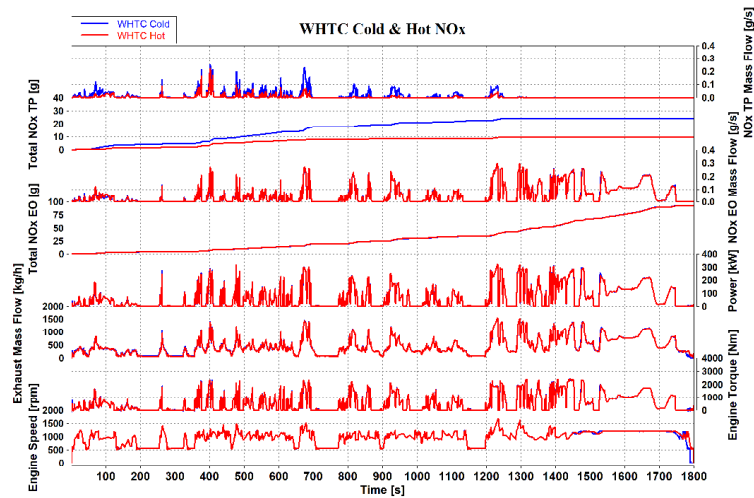


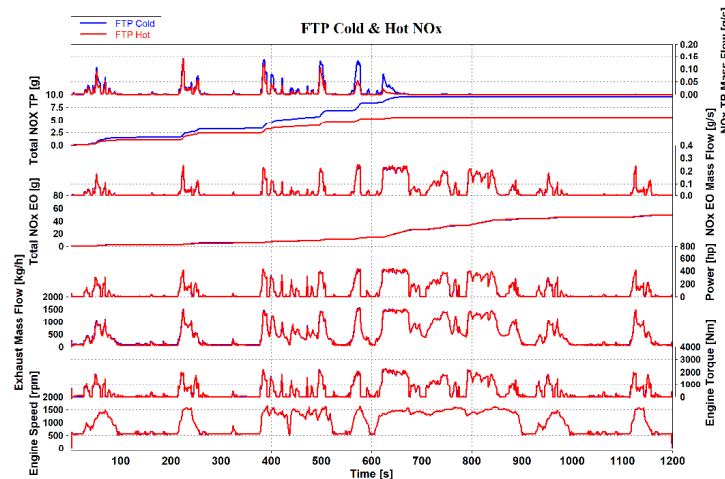
Figure 2.6.3.1 : WHTC cold and hot NO_x results.

The total NO_x results are given in the following table.

Table 2.6.3.1 : WHTC cold and hot total NO_x results.

Result	Total Engine-out NO _x	Total Tailpipe NO _x	Engine-out BS NO _x	Tailpipe BS NO _x
WHTC Cold	92.5 g	24.2 g	2.87 g/kWh	0.75 g/kWh
WHTC Hot	92.2 g	9.4 g	2.85 g/kWh	0.29 g/kWh

The NO_x results of FTP cold and hot simulations are shown in the figure below. The red lines represent the FTP hot and the blue lines represent the FTP cold.

**Figure 2.6.3.2 : FTP cold and hot NO_x results.**

The FTP total NO_x results are given in the following table.

Table 2.6.3.2 : FTP cold and hot total NO_x results.

Result	Total Engine-out NO _x	Total Tailpipe NO _x	Engine-out BS NO _x	Tailpipe BS NO _x
FTP Cold	48.6 g	9.6 g	1.63 g/bhp-hr	0.32 g/bhp-hr
FTP Hot	48.8 g	5.5 g	1.63 g/bhp-hr	0.18 g/bhp-hr

2.6.4 Other engine-out and tailpipe emissions

The other emissions evaluated are CO, total hydrocarbon (THC), non-methane hydrocarbon (NMHC), PM, N₂O, and NH₃. The WHTC cold and hot engine-out and tailpipe results are given in figures 2.6.4.1 and 2.6.4.2. Blue lines represent the WHTC cold and the red lines represent the WHTC hot cycles.

The WHTC cycle results of other emissions for hot and cold tests are given in table 2.6.4.1. The NH₃ is evaluated according to its average value.

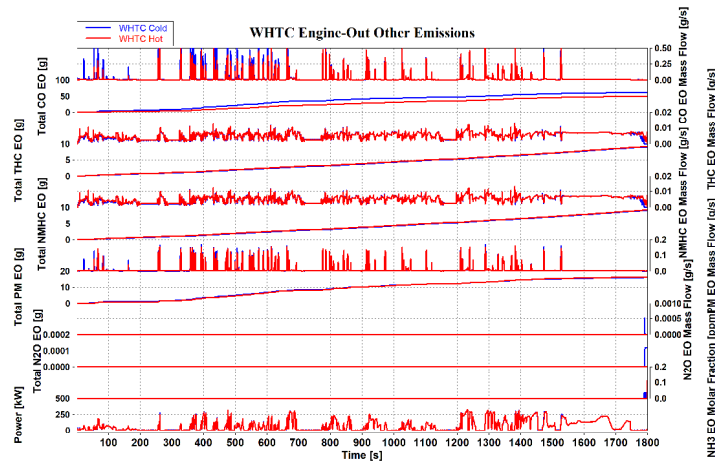


Figure 2.6.4.1 : WHTC engine-out other emissions.

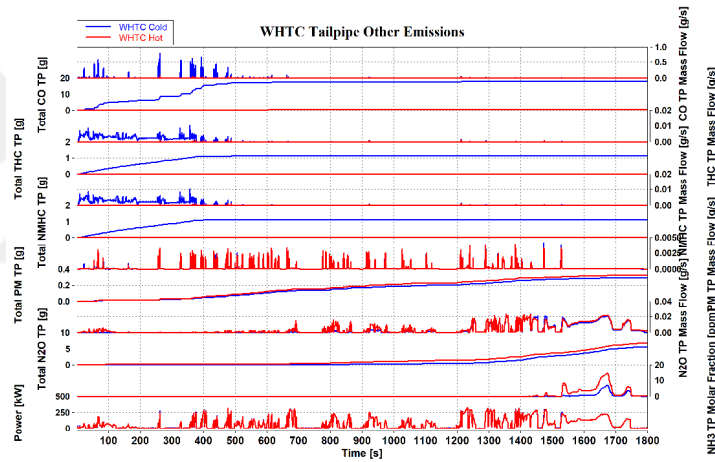


Figure 2.6.4.2 : WHTC tailpipe other emissions.

Table 2.6.4.1 : WHTC cold and hot other emissions cycles results.

Result	CO	THC	NMHC	PM	N ₂ O	NH ₃
	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	ppm
WHTC Cold EO	1.931	0.277	0.277	0.493	0	0
WHTC Cold TP	0.555	0.035	0.035	0.009	0.172	0.177
WHTC Hot EO	1.558	0.283	0.283	0.499	0	0
WHTC Hot TP	0.021	0	0	0.01	0.208	0.613

The FTP cold and hot engine-out and tailpipe results are given in the following figures. Blue lines represent the FTP cold and the red lines represent the FTP hot cycles.

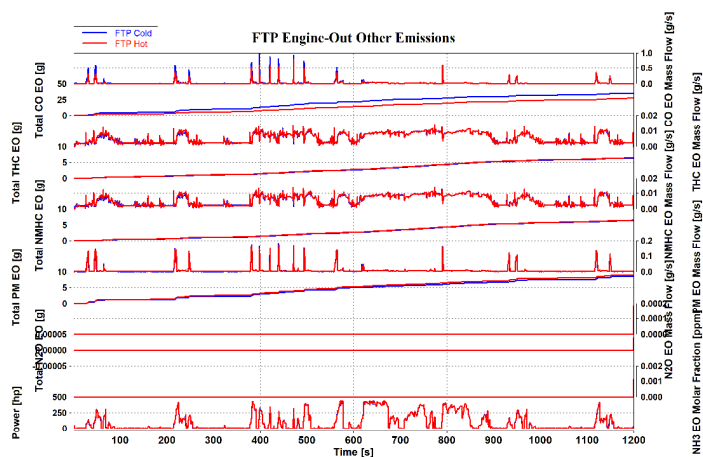


Figure 2.6.4.3 : FTP engine-out other emissions.

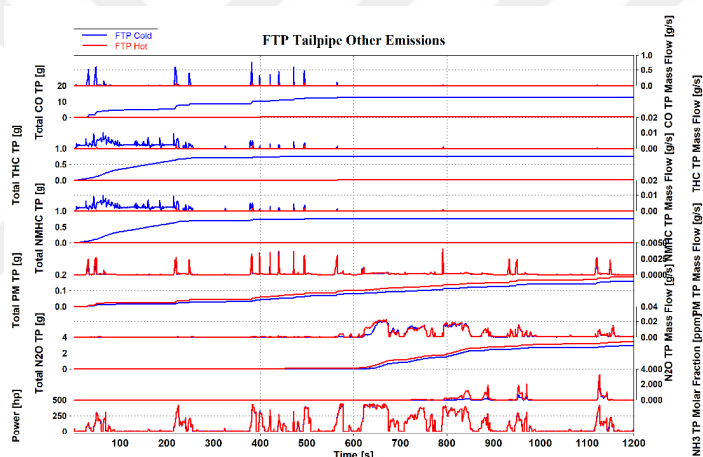


Figure 2.6.4.4 : FTP tailpipe other emissions.

The FTP cycle results of other emissions for hot and cold tests are given in the following table. The NH_3 is evaluated according to its average value.

Table 2.6.4.2 : FTP cold and hot other emissions cycles results.

Result	CO	THC	NMHC	PM	N ₂ O	NH ₃
	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr	ppm
FTP Cold EO	1.191	0.214	0.214	0.283	0	0
FTP Cold TP	0.429	0.025	0.025	0.005	0.099	0.022
FTP Hot EO	0.916	0.216	0.216	0.3	0	0
FTP Hot TP	0.025	0	0	0.006	0.115	0.061

2.6.5 Current legislation comparison

2.6.5.1 Europe

For Euro VI, there is not any CO₂ limit, so only tailpipe pollutant emissions are compared with the regulation limits. The total result of the WHTC cold and hot cycles is calculated by taking 14% of cold and 86% of the hot result. The pollutant limits for WHTC and the total WHTC simulation results are given in the table below.

Table 2.6.5.1.1 : Simulation comparison with Europe's current limits.

	CO	THC	NO _x	NH ₃	PM
	g/kWh	g/kWh	g/kWh	ppm	g/kWh
EU VI Limit	4	0.16	0.46	10	0.01
Simulation Result	0.01	0.05	0.36	2.7	0.001

The results show that the model satisfies current Europe's pollutant emissions, so it can be used as a Euro VI benchmark system.

2.6.5.2 USA

The total result of the FTP cold and hot cycles is calculated by taking 1/7 cold and 6/7 hot results. The pollutant limits for FTP and the total FTP simulation results are given in the table below.

Table 2.6.5.2.1 : Simulation comparison with the USA's current limits.

	CO	NMHC	NO _x	NMHC+ NO _x	PM
	g/bhp-hr	g/ bhp-hr	g/ bhp-hr	bhp-hr	g/ bhp-hr
US 10 Limit	15.5	0.14	0.2	2.4	0.01
Simulation Result	0.08	0.004	0.2	0.21	0.006

The results show that the model satisfies current USA pollutant emissions, so it can be used as a benchmark system for the USA legislation. However, the NO_x is on the limit, so it is critical to increasing NO_x conversion efficiency.

In addition to pollutant limits, the CO₂ limits must be met in the USA. The comparison of CO₂ limits for HHD vocational with simulation results is given in the table below.

Table 2.6.5.2.2 : Simulation comparison with the USA's current CO₂ limit.

CO ₂	
g/ bhp-hr	
2017 – 2020 Limit	555
Simulation Result	555

The system is successful to meet the current CO₂ limit in the USA. However, it is on the limit value, so the CO₂ reduction has high importance.

2.6.6 Upcoming legislation comparison

2.6.6.1 Europe

For Euro VII, The pollutant limits have not been defined yet. Also, limiting the CO₂ is under discussion, but the level of the limit is far from away to be defined for today. Only there is an information for NO_x limit and evaluation procedure. However, it should be noted it is also not finalized, so it is not a solid rule. One fact is clear that the next limits will be much lower than today's limits. According to available information, the simulation can be judged according to the HD2 and HD3 budget limits to see the situation even it is not an ISC test because the test length is lower than 3 times WHTC work. Both cold and hot simulation results will be compared with HD3 to see the worst-case scenario because there is not any distinction between cold and hot under budget criteria. The NO_x limit for HD3 budget criteria and the WHTC simulation results are given in the table below.

Table 2.6.6.1.1 : Simulation comparison with Europe's upcoming NO_x limit.

NO _x	
g/kWh	
EU VII	0.1
Budget HD3 Limit	
Simulation Result	0.75
WHTC Cold	
Simulation Result	0.29
WHTC Hot	

Even the hot cycle result cannot satisfy the upcoming limit, and the cold cycle result is so far away from the limit. The possible solutions to the problem are rapid EAS heat up, lower level of engine-out NO_x, and EAS component improvements.

2.6.6.2 USA

For the decision of the level of upcoming pollutant emissions in the USA, it is expected that CARB's proposal will be a pathfinder. Therefore, the conventional system result is compared with CARB's NO_x proposals for 2024-2026 and 2027 later. Although there are 3 separate limits, only FTP is compared. The limits and simulation result are given in the table below.

Table 2.6.6.2.1 : Simulation comparison with the USA's upcoming limits.

	Simulation	California 2024-2026	50-State 2024-2026	California 2027 later
FTP NO _x g/ bhp-hr	0.2	0.05	0.1	0.02

The system is not capable of satisfying the USA's expected upcoming NO_x standards. The possible solutions mentioned for Euro VII are valid here also.

According to the 2nd phase of the USA's GHG program, the reduced CO₂ limits must be met step by step. The comparison of CO₂ limits for HHD vocational with simulation results is given in the table below.

Table 2.6.6.2.2 : Simulation comparison with the USA's upcoming CO₂ limit.

	CO ₂ g/ bhp-hr
2021 – 2023 Limit	513
2024-2026 Limit	506
2027 and later Limit	503
Simulation Result	555

Although the system is sufficient for the current CO₂ standard, the system performance should be increased to meet upcoming limits. Here, the most important factor is fuel

consumption reduction. The application of new engine-related technologies like an electrical turbocharger, EGR-pump could help to satisfy upcoming legislation while similar power output is held and be under pollutant emission limits.

2.6.7 Chapter Summary

The main objective of this study to show the impact of diesel electrification on diesel emission improvement. Because of the noteworthy contribution of heavy-duty diesel vehicles, a 13lt long-haul truck is considered for evaluation. The method of study is the comparison of simulations which are electrified, models and conventional models. Therefore, a 13lt conventional diesel combined powertrain and aftertreatment system is modeled.

The purpose of combined model usage is to represent a real engine dynamometer test-bed and to see both engine and aftertreatment applications together. For modeling and simulation, the AVL CruiseM is used in the study. Also, for data evaluation, the AVL Concerto is used. The model is simulated for Europe's WHTC cold/hot cycles and the USA's FTP cold/hot cycles. The cycle results are compared with current and upcoming legislative standards.

The conclusions of the conventional model results can be summarized as

- For WHTC and FTP, the system can meet the current pollutant emission standards, so it shows its capability to be a benchmark model.
- The conventional system is not capable of satisfying upcoming pollutant standards and needs further improvements.
- For the USA's CO₂ standards, the system is successful to satisfy the current limit. However, it is above than upcoming limits. Thus, some improvements are needed.

There is one more important issue, which is not mentioned in the simulation results, for system evaluation. It is component temperatures and heat-up time. The mean substrate temperatures of EAS components for WHTC and FTP cold tests are shown in the figure below.

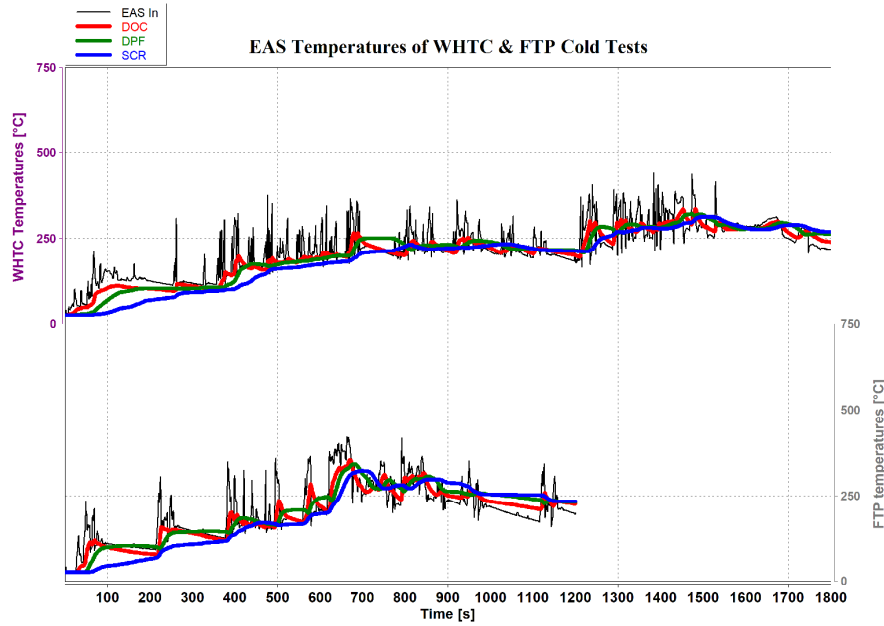


Figure 2.6.7.1 : EAS components temperatures from cold tests.

The only heating source of the components is the exhaust gas temperature which strongly relies on the engine operation point. The exhaust temperature is high at the high power operation points; however, its temperature gets lower for the low power operation points. Thus, the heat up of system components takes a significant amount of time to reach at least their light-off temperatures. Here, the most important point is the heat up of the SCR because it is the outermost component. For example, SCR reaches its light-off temperature at almost 1/4 of the WHTC and almost 1/3 of the FTP test. Besides, reaching the most efficient temperature region, 300-400 °C, takes much longer time. In addition, the urea injection, which is significantly important NO_x conversion due to NH_3 deposition in the SCR, can be started when the SCR is in the light-off temperature. To conclude, the thermal management of the SCR has great importance for the cold start performance according to NO_x . Also, even the current standards apply a small amount of contribution cold start test, the upcoming standard most probably will include all cold start emissions. To conclude, the thermal management of EAS components for not only rapid heat up but also keeping the components in the temperature window has great importance. There are many solutions discussed, and electrically heated catalysts are one of the promising solutions because it provides EAS thermal management without relying on the engine operating condition.



3. DIESEL ENGINE AND AFTERTREATMENT ELECTRIFICATION

In this chapter, the electrified components of the diesel powertrain are investigated to present their effect on the engine-out and tailpipe emissions. To show that effect, the emission results of the conventional model, which are given in the previous chapter, are compared with the electrified model results. In addition, the electrified model results are compared with the current and upcoming legislation limits to emphasize the potential of those new technologies. For the compliance of the comparison, engine and aftertreatment combined model with electrified component implementations is used. Also, all model properties and parameters are kept as same with conventional model except for the electrified component-related parameters.

Here one assumption, which is used theoretically and not implemented into the models to avoid model complexity, should be mentioned. The usage of a battery in the systems is assumed to supply required electrical energy to energy-consuming components such as the e-compressor, the EGR pump, and the e-cat; also, to save the produced electrical energy by e-turbo. Even the produced electrical energy is enough for energy-consuming components in total, a battery system is needed to feed the required current to the components instantaneously. The higher power demand of the electrical components brings the usage of 48V electrical system architecture that can supply with higher power demand while avoiding the extra safety concern of the 60V system; also, it gives more flexibility to further improvements like driving the auxiliaries such as water pump, oil pump, etc. by electrically instead of using belt-driven [49]. For example, an average e-cat needs ~5kW power at full performance. The higher power capacity of 48V is shown in figure 3.1.

The hypothesizes of the study can be summarized as follows:

- The usage of an electrical turbocharger provides improvements in fuel consumption and CO₂ reduction.
- The usage of the EGR pump provides improvements in engine-out NO_x reduction.

- The usage of electrically heated catalyst (E-Cat) provides rapid heat-up and better thermal control, so it causes emission reduction in cold phases.

The electrified models and properties of the electrical components are explained in the following sections.

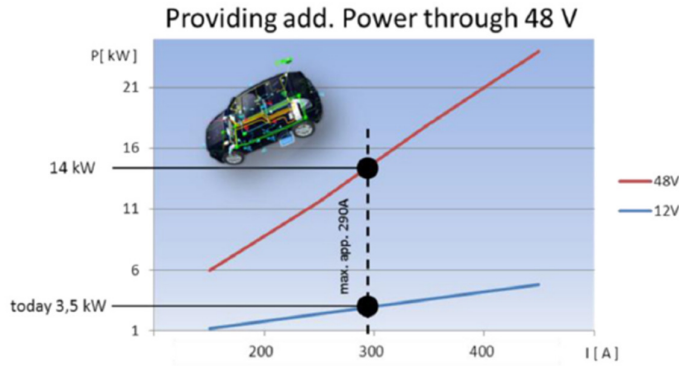


Figure 3.1 : Higher power capacity of 48V [49].

3.1 Electrified 13lt Heavy-Duty Engine and Aftertreatment Models

As mentioned in the previous chapters, the electric turbocharger, EGR pump, electric catalyst, and their layout combinations are investigated. Firstly, the properties and parameters of the components are explained. Then, the system layouts with the corresponding model are introduced.

3.1.1 Electric turbocharger (E-Turbo)

The electric turbochargers are introduced in the first chapter. Separating the turbine shaft and compressor shaft, and joining them via an electric motor/generator is the fundamental perspective of the e-turbo systems. This allows the independent operation of the e-compressor by consuming electrical energy while thermal energy of the exhaust gas is converted to mechanical energy by the turbine, the mechanical energy is converted to the electrical energy by the generator between the turbine and the compressor, and it is stored the battery. The different topologies of e-turbo systems are introduced by Lee, et al [42]. In this study, a common topology which electric motor/generator locates between turbine and compressor and it is connected to their shafts correspondingly. The e-turbo model is shown in the figure below.

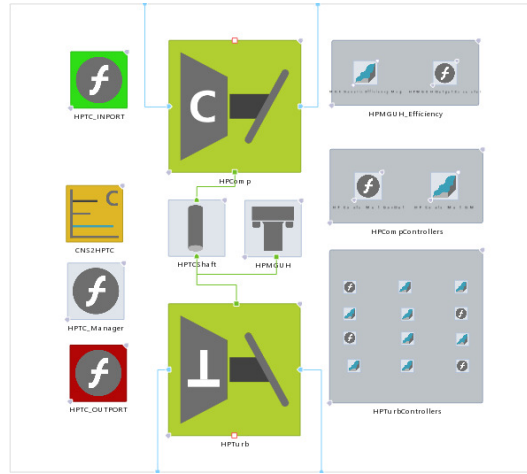


Figure 3.1.1.1 : E-turbo model.

Although the e-turbo system has the opportunity to change the compressor and turbine sizes for better efficiency, for the compliance of the comparison with the conventional turbocharger model, and to show purely electrification effect, the same compressor, and turbine are used for the e-turbo system. Only an electric motor/generator is mounted between the compressor and the turbine. As mentioned earlier, for the model's simplicity, the electric motor/generator and the battery system are not modeled. Instead of that, it is represented via shaft and flange connection and some basic functions are used to control the system because it is assumed that the electric motor can get sufficient current to drive the electric compressor to supply the necessary boost without concerning turbine speed. The working principle of the e-turbo model can be explained that the gained mechanical energy from turbine converted electrical energy by the generator and stored in the battery if the turbine produces more energy than consumed energy by the compressor, then the compressor speed demand is determined according to the boost demand, then the compressor speed demand is compared with turbine speed, then if it is higher than turbine speed, the e-motor is activated and increase the compressor speed up to demand. Therefore, the compressor can operate independently from turbine operating conditions due to the electric motor boost.

3.1.2 EGR pump

The EGR pump model is shown in figure 3.1.2.1.

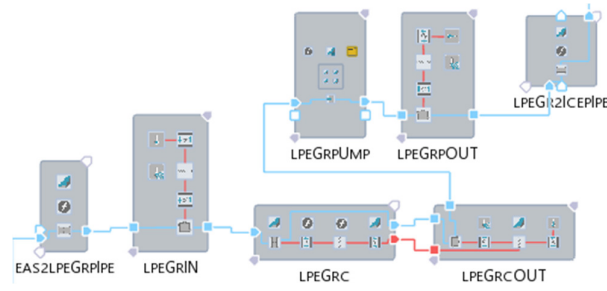


Figure 3.1.2.1 : The LP-EGR model.

The EGR pump system, which is also called low-pressure EGR (LP-EGR) has a similar layout to the high-pressure EGR (HP-EGR) system. The LP-EGR takes the exhaust gas from after ASC, then it is cooled by a cooling system, and then feeds it before the compressor inlet by the pump. Naturally, the pressure difference between compressor inlet and tailpipe is very small, so the exhaust gas cannot flow through that direction. The amount of exhaust gas that is mixed with fresh air is determined by controlling the pump speed. This provides full authority EGR rate control and allows the potential removal of expensive components used to drive external EGR.

Due to the movement of the gas is only needed in one direction, usage of a positive displacement pump is assumed in the study. Fluid is taken from the inlet pipe and pushed through the outlet pipe by a positive displacement pump which is a constant flow machine, and the flow can be controlled by arranging pump speed [50]. A helical lobe type blower, which is a type of positive displacement pump, is modeled as the LP-EGR pump because there is not enough technical information from any EGR pump supplier, and the lobe type blower is similar to EGR pump. The schematic of a lobe type blower and a picture of the cross-section of an EGR pump from EATON, which is an EGR pump supplier, are shown in the figures below.

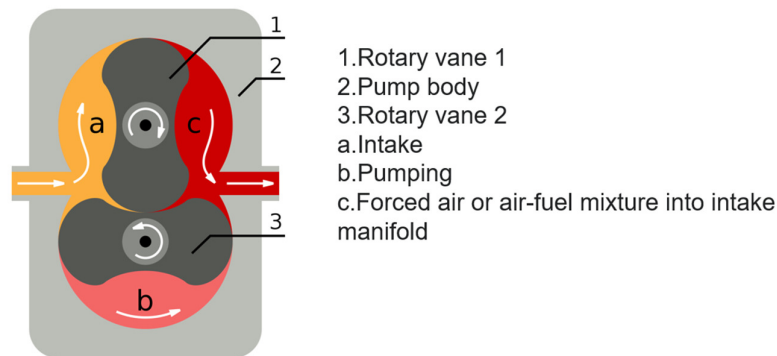


Figure 3.1.2.2 : The schematic of a lobe type blower.



Figure 3.1.2.3 : The picture of the cross-section of EATON's EGR pump [51].

Therefore, the technical specifications of the HLB1614 helical lobe blower of TMM Blower are used to model an EGR pump [52]. The datasheet of the blower is given in appendix A. Finally, the amount of LP-EGR is defined by map-based control. The map takes the pressure differences between the tailpipe and compressor inlet, and the pump speed, then it supplies the required volumetric flow of LP-EGR.

For LP-EGR two cases are concerned and simulated: the usage of LP-EGR alone and the usage of LP-EGR with HP-EGR. The main strategies for the two cases are to supply the same amount of EGR as the conventional model by LP-EGR only and to increase the amount of EGR by using the LP-EGR pump with the HP-EGR system.

3.1.3 Electrically Heated Catalyst (E-Cat)

As mentioned in the modeling of the conventional system, AVL Cruise-M MOBEO EAS is used to model the aftertreatment. Also, a similar approach is used to model the 48V E-Cat with a maximum power of 4.8 kW. In addition, it should be mentioned that even it is called the catalyst, it is used for only thermal management in the simulations and catalytic conversion features are excluded. It behaves like an external electric heater before the catalysts. Therefore, the E-Cat is modeled by implementing it into the MOBEO EAS block as the internal heating value of the corresponding pipe just before the catalyst. For example, the E-Cat is modeled as pipe 12 to locate it on the SCR inlet, and it is shown in figure 3.1.3.1.

The internal heating value is decided by basic E-Cat control functions. It is an on-off control principle. Here, one of the most important parameters is the E-Cat target temperature. For the simulation, the target temperature is defined as 300 °C because it is the temperature that the SCR can work very effectively. First, the temperature of the

target catalyst is taken, then is compared with the target temperature. If the catalyst temperature is higher than the target temperature, the E-Cat is deactivated. On the other hand, if the catalyst temperature is lower than the target temperature, the E-Cat heat the exhaust gas with maximum power until the catalyst temperature reaches the target value. The specific energy to heat the gas is defined by the power consumed by the heater per the exhaust massflow.

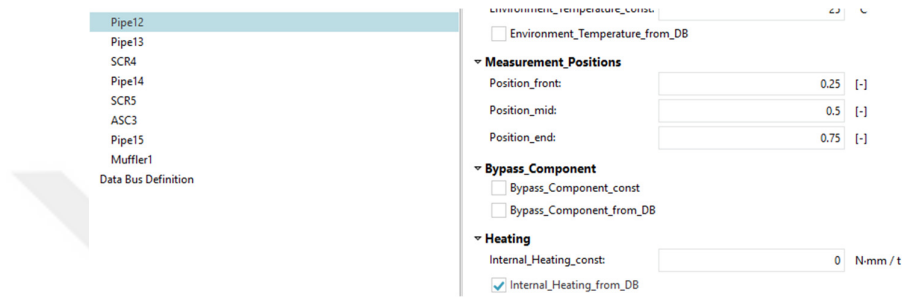


Figure 3.1.3.1 : The E-Cat modeling example before SCR.

Finally, two test cases are considered in the simulations with two E-Cat positions: before DOC inlet and before SCR inlet. The aim of the two positions is to observe the effect of the E-Cat position on SCR performance and the reduction of other emissions.

3.1.4 System layouts and their models

Several system layouts, in which one component is implemented alone and the combinations of components are implemented, are modeled and simulated. The seven layouts can be listed below.

- Only E-Turbo model
- Only EGR pump
- Only E-Cat
- EGR pump and E-Cat
- E-Turbo and EGR pump
- E-Turbo and E-Cat
- E-Turbo, EGR pump, and E-Cat

Each model has similar components, and only related parts are activated and the others are deactivated. Thus, only the model of all components is shown in the following figure not to give very similar models repeatedly. The red box shows the e-turbo model, the blue box shows the LP-EGR system and the green box shows the e-cat.

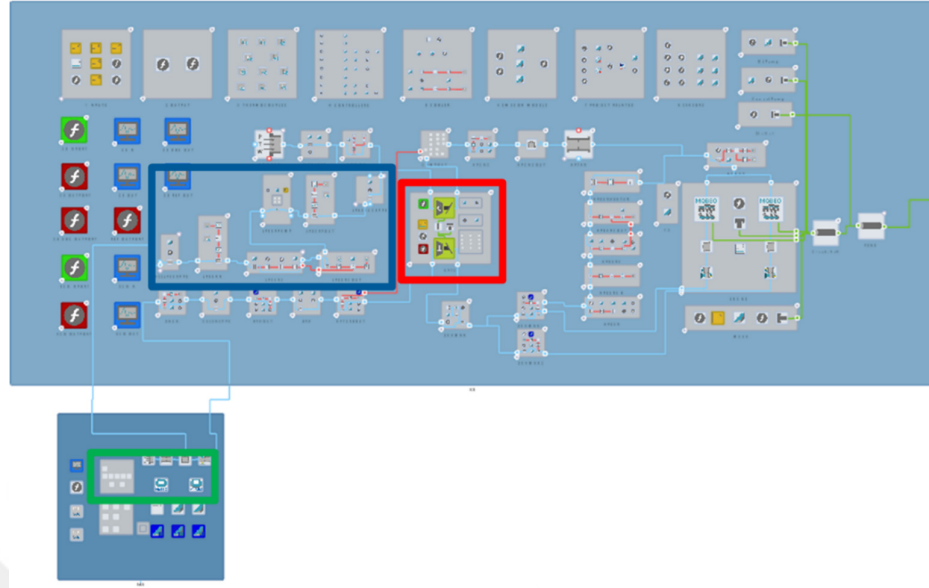


Figure 3.1.4.1 : Cruise-M model of all component implementations.

3.2 Drive Cycles

This thesis focuses on the effect of electrification on greenhouse gasses and pollutant emissions under transient and real-world conditions. Thus, for both comparison compliance with the conventional model and investigating the impact of electrified components under transient conditions, four drive cycles, which are WHTC cold/hot and FTP cold/hot, are used for simulations like doing for the conventional engine and aftertreatment simulations. Also, this provides to judge the results by current and upcoming Europe's and USA's greenhouse gas and pollutant emission regulations.

3.3 Model Inputs

The model inputs are explained deeply in the previous chapter. The same aftertreatment component initial temperatures and the same engine inputs are used for the electrified model simulations for the compliance of comparison. The only exception is here the EGR position because of including LP-EGR in the system. As mentioned in the EGR pump section, two LP-EGR test cases are considered. For the simulations of only the LP-EGR system, the HP-EGR is closed. For the simulations of the LP-EGR with HP-EGR, the EGR valve position is arranged according to the amount of EGR demand from the HP-EGR. The EGR valve positions of the two cases are shown in the figure below. The red shows the valve position for the conventional

model, the black line is for only the LP-EGR case and the blue line shows the valve position of the case LP-EGR with HP-EGR.

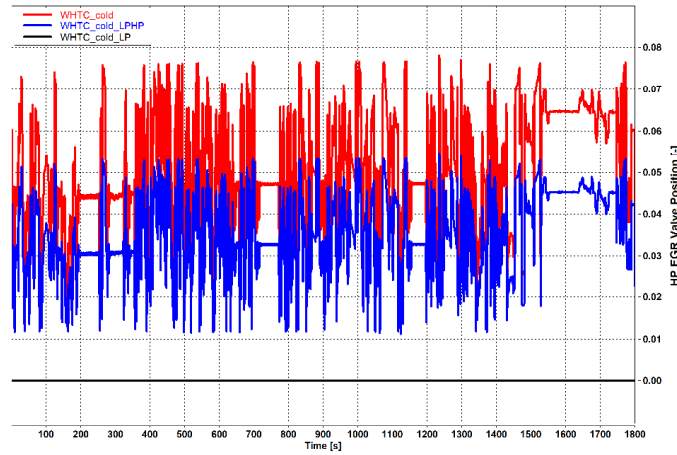


Figure 3.3.1 : HP-EGR valve position inputs.

3.4 Simulation Results

Under this section, the results of each case of each layout are given and interpreted. Also, each of them is compared with the results of the conventional model. Moreover, the system component temperatures are given to see the effect of E-Cat. Then, the results are compared with the current and upcoming regulation limits. Finally, power consumption and energy balance are investigated.

3.4.1 Only E-Turbo model

3.4.1.1 Fuel consumption

The fuel consumption results of WHTC cold and hot simulations are shown in figure 3.4.1.1.1. The black lines represent the e-turbo and the red lines represent the conventional model.

The total fuel consumption, amount of fuel injected, and total work are given in table 3.4.1.1.1.

The fuel consumption results of FTP cold and hot simulations are shown in figure 3.4.1.1.2. The black lines represent the e-turbo and the red lines represent the conventional model.

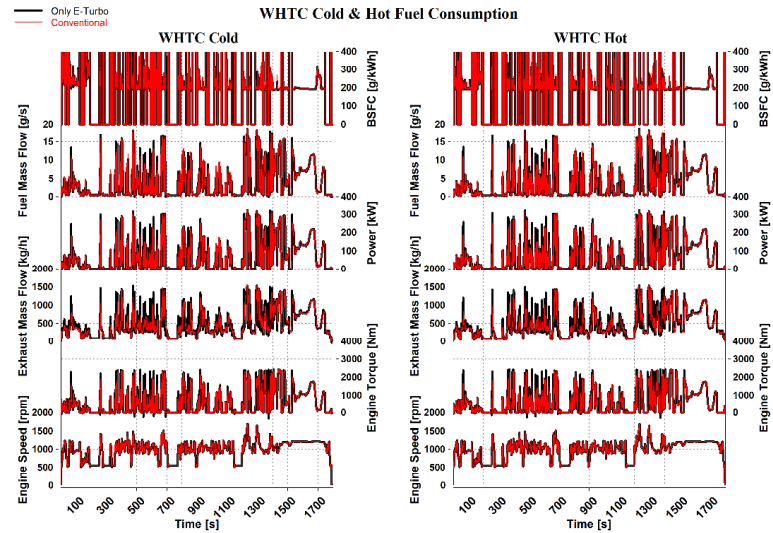


Figure 3.4.1.1.1 : Only E-Turbo WHTC fuel consumption results.

Table 3.4.1.1.1 : Only E-Turbo WHTC fuel consumption results.

Result	E-Turbo WHTC Cold	Conventional WHTC Cold	E-Turbo WHTC Hot	Conventional WHTC Hot
Total Work	33.53 kWh	32.33 kWh	33.55 kWh	32.31 kWh
Total Fuel	6758 g	6833 g	6648 g	6724 g
Total BSFC	202 g/kWh	211 g/kWh	199 g/kWh	208 g/kWh

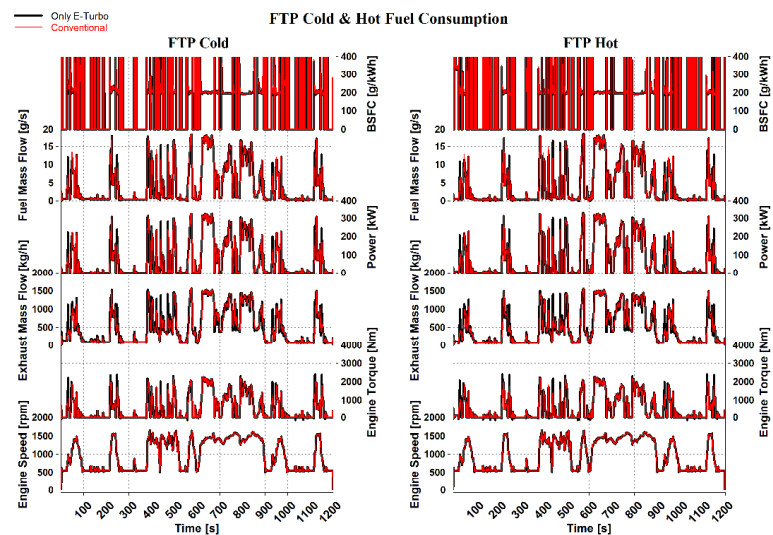


Figure 3.4.1.1.2 : Only E-Turbo FTP fuel consumption results.

The FTP total fuel consumption results are given in the following table.

Table 3.4.1.1.2 : Only E-Turbo FTP fuel consumption results.

Result	E-Turbo	Conventional	E-Turbo	Conventional
	FTP Cold	FTP Cold	FTP Hot	FTP Hot
Total Work	30.84 bhp-hr	29.76 bhp-hr	31 bhp-hr	29.89 bhp-hr
Total Fuel	4800 g	4812 g	4717 g	4725 g
Total BSFC	156 g/bhp-hr	162 g/bhp-hr	152 g/bhp-hr	158 g/bhp-hr

The results show that the implementation of the e-turbo only provides ~4% fuel consumption reduction according to WHTC, and ~3.5% fuel consumption reduction according to FTP. The cycle works and the total amount of fuel consumed indicate that the engine can produce more power output while consuming a similar amount of fuel. Also, it can be seen from the exhaust massflow, e-motor assisted compressor can provide more air into the cylinder than the conventional compressor. This benefit directly comes from the independent control of the e-compressor, so the compressor can operate its efficient point without concerning the turbine condition. In this condition, the e-compressor uses more power than the power generated from the turbine. The additional power requirement is assisted by e-motor. The power consumption/production of the compressor/turbine, the pressure ratio in the compressor outlet, and the charge air massflow in the intake manifold are shown in the figure below as an example in a transient torque peak of the WHTC hot cycle.

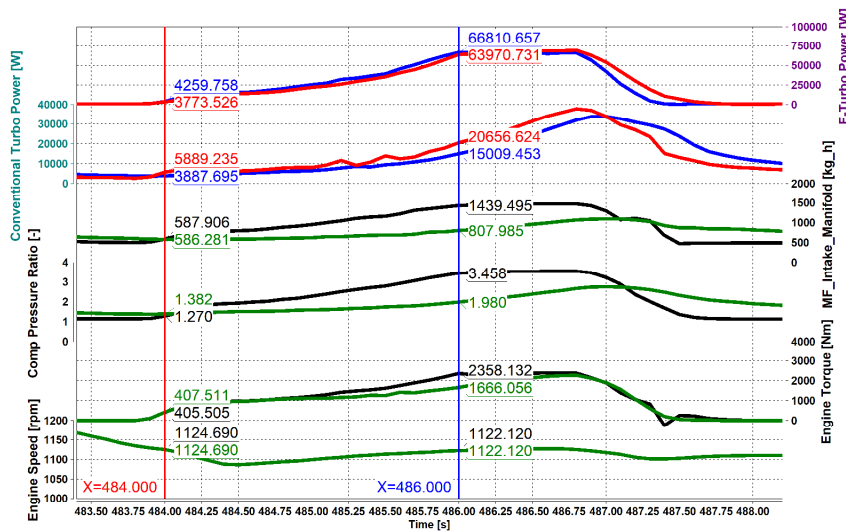


Figure 3.4.1.1.3 : E-Turbo power consumption example.

The e-compressor provides ~1.4 times greater boost than the conventional compressor more rapidly. E-compressor can reach the maximum pressure ratio in 2s while the conventional compressor can reach its maximum pressure ratio in 3s. It shows the more quick response of e-turbo to avoid turbo-lag.

3.4.1.2 CO₂ engine-out and tailpipe

The CO₂ results of WHTC cold and hot simulations are shown in the figure below. The black lines represent the e-turbo and the red lines represent the conventional model.

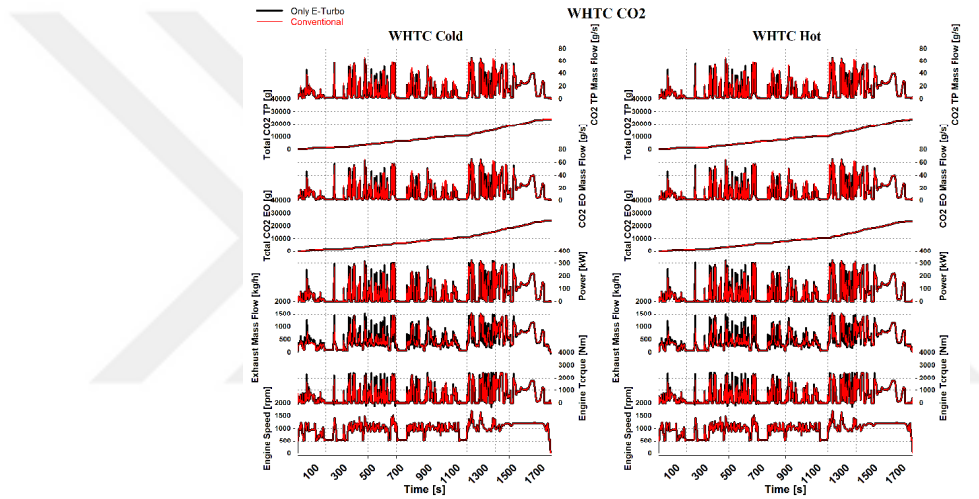


Figure 3.4.1.2.1 : Only E-Turbo WHTC CO₂ results.

The total CO₂ results are given in the following table.

Table 3.4.1.2.1 : Only E-Turbo WHTC CO₂ results.

Result	E-Turbo	Conventional	E-Turbo	Conventional
	Engine-out BSCO ₂	Engine-out BSCO ₂	Tailpipe BSCO ₂	Tailpipe BSCO ₂
WHTC Cold	675 g/kWh	735 g/kWh	678 g/kWh	740 g/kWh
WHTC Hot	664 g/kWh	724 g/kWh	667 g/kWh	730 g/kWh

The CO₂ results of FTP cold and hot simulations are shown in figure 3.4.1.2.2. The black lines represent the e-turbo and the red lines represent the conventional. The FTP total CO₂ results are given in table 3.4.1.2.2.

As expected, the e-turbo provides engine-out CO₂ reduction that leads CO₂ reduction in tailpipe with less fuel consumption.

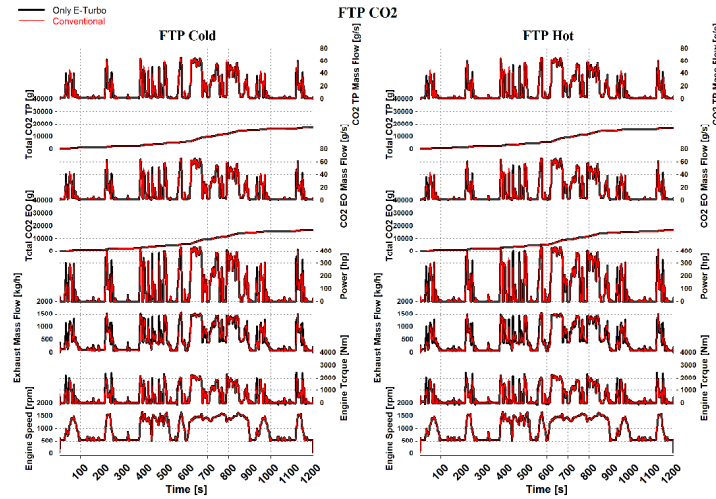


Figure 3.4.1.2.2 : Only E-Turbo FTP CO₂ results.

Table 3.4.1.2.2 : Only E-Turbo FTP CO₂ results.

Result	E-Turbo	Conventional	E-Turbo	Conventional
	Engine-out BSCO ₂	Engine-out BSCO ₂	Tailpipe BSCO ₂	Tailpipe BSCO ₂
FTP Cold	522 g/bhp-hr	561 g/bhp-hr	524 g/bhp-hr	565 g/bhp-hr
FTP Hot	510 g/bhp-hr	549 g/bhp-hr	513 g/bhp-hr	553 g/bhp-hr

3.4.1.3 NO_x engine-out and tailpipe

The NO_x results of WHTC cold and hot simulations are shown in figure 3.4.1.3.1. The black lines represent the e-turbo and the red lines represent the conventional model. The total NO_x results are given in table 3.4.1.3.1.

The NO_x results of FTP cold and hot simulations are shown in figure 3.4.1.3.2. The black lines represent the e-turbo and the red lines represent the conventional model. The FTP total NO_x results are given in table 3.4.1.3.2.

For the NO_x side, the e-turbo implementation itself makes worse the system.

Table 3.4.1.3.1 : Only E-Turbo WHTC NO_x results.

Result	E-Turbo	Conventional	E-Turbo	Conventional
	Engine-out BSNO _x	Engine-out BSNO _x	Tailpipe BSNO _x	Tailpipe BSNO _x
WHTC Cold	3.11 g/kWh	2.86 g/kWh	1.23 g/kWh	0.75 g/kWh
WHTC Hot	3.07 g/kWh	2.85 g/kWh	0.63 g/kWh	0.29 g/kWh

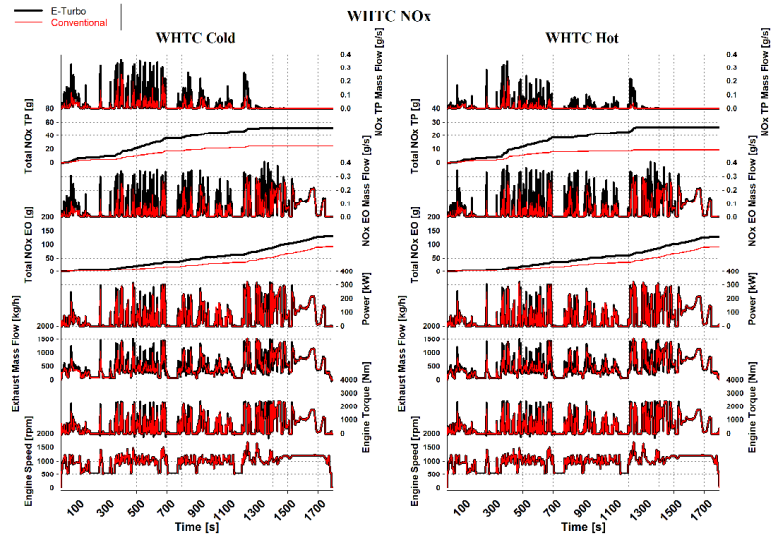


Figure 3.4.1.3.1 : Only E-Turbo WHTC NO_x results.

Table 3.4.1.3.2 : Only E-Turbo FTP NO_x results.

Result	E-Turbo	Conventional	E-Turbo	Conventional
	Engine-out BSNO _x	Engine-out BSNO _x	Tailpipe BSNO _x	Tailpipe BSNO _x
FTP Cold	2.03 g/bhp-hr	1.71 g/bhp-hr	0.57 g/bhp-hr	0.28 g/bhp-hr
FTP Hot	2.00 g/bhp-hr	1.70 g/bhp-hr	0.29 g/bhp-hr	0.11 g/bhp-hr

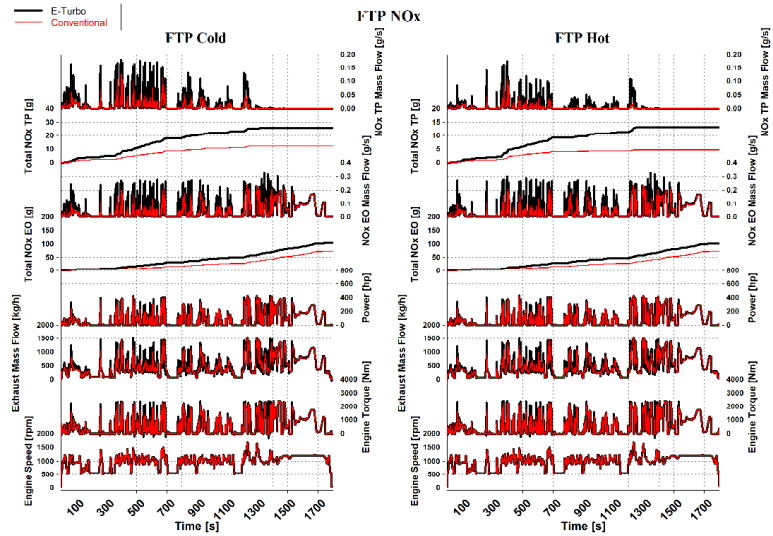


Figure 3.4.1.3.2 : Only E-Turbo FTP NO_x results.

3.4.1.4 Other engine-out and tailpipe emissions

The other emissions evaluated are CO, total hydrocarbon (THC), non-methane hydrocarbon (NMHC), PM, N₂O, and NH₃. The WHTC cold and hot engine-out and

tailpipe results are given in the following figures. Black lines represent the e-turbo and the red lines represent the conventional model.

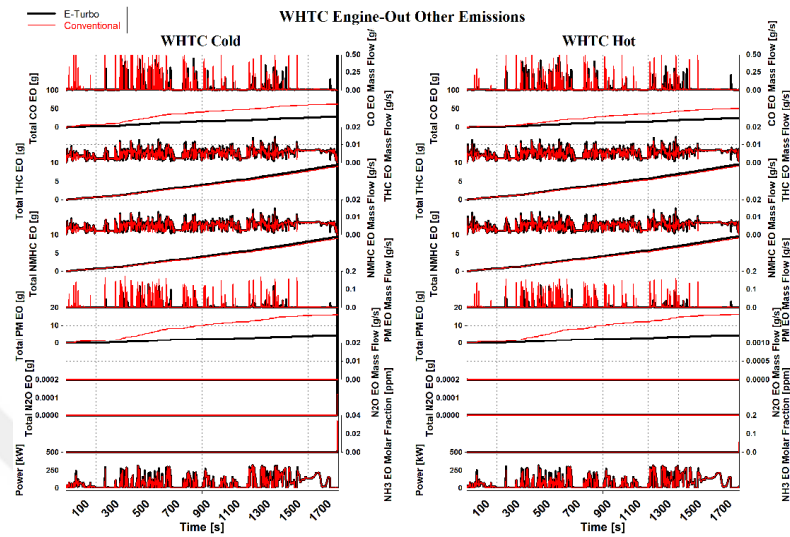


Figure 3.4.1.4.1 : Only E-Turbo WHTC engine-out other emissions.

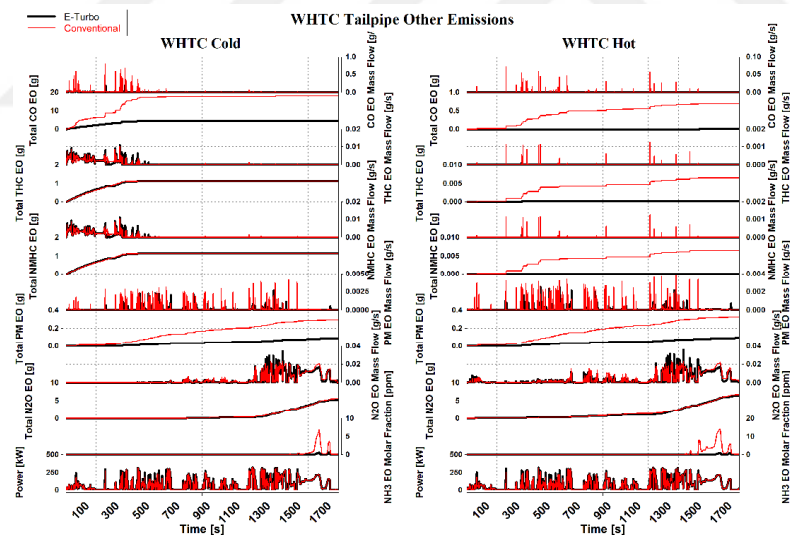


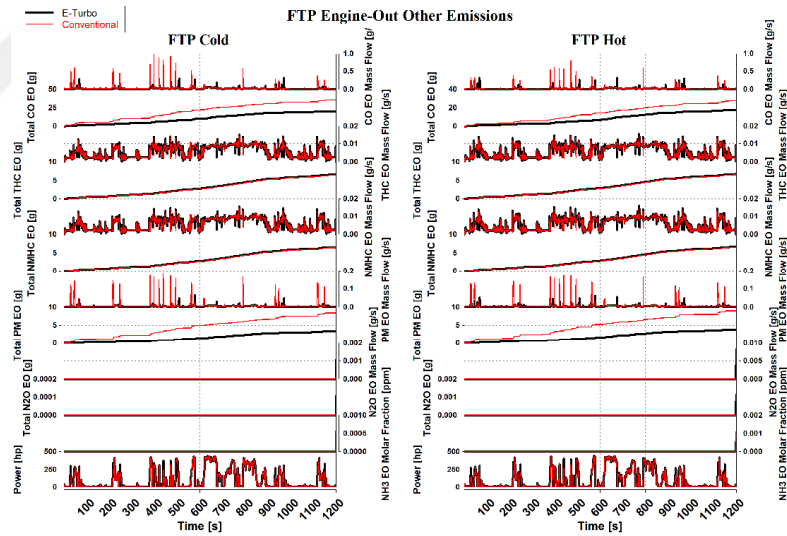
Figure 3.4.1.4.2 : Only E-Turbo WHTC tailpipe other emissions.

The WHTC cycle results of other emissions for hot and cold tests are given in table 3.4.1.4.1. The NH_3 is evaluated according to its average value.

The FTP cold and hot engine-out and tailpipe results are given in the figures 3.4.1.4.3 and 3.4.1.4.4. Black lines represent the e-turbo and the red lines represent the conventional model.

Table 3.4.1.4.1 : Only E-Turbo WHTC other emissions cycles results.

Result	CO	THC	NMHC	PM	N ₂ O	NH ₃
	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	ppm
E-Turbo WHTC Cold EO	0.84	0.28	0.28	0.14	0	0
Conventional WHTC Cold EO	1.93	0.27	0.27	0.49	0	0
E-Turbo WHTC Cold TP	0.13	0.03	0.03	0.003	0.159	0.012
Conventional WHTC Cold TP	0.56	0.04	0.04	0.009	0.172	0.177
E-Turbo WHTC Hot EO	0.73	0.29	0.29	0.14	0	0
Conventional WHTC Hot EO	1.56	0.29	0.29	0.49	0	0
E-Turbo WHTC Hot TP	0.0001	0	0	0.003	0.19	0.021
Conventional WHTC Hot TP	0.021	0	0	0.01	0.21	0.613

**Figure 3.4.1.4.3 : Only E-Turbo FTP engine-out other emissions.**

The FTP cycle results of other emissions for hot and cold tests are given in table 3.4.1.4.2. The NH₃ is evaluated according to its average value.

The result shows that the implementation of e-turbo provides a significant reduction in pollutant emissions of CO and PM for both engine-out and tailpipe. The fundamental reason for that is improved combustion due to e-turbo. As a result of better combustion, the engine-out NO_x increases, and the system can be evaluated worse than conventional for NO_x. However, the increasing NO_x may be tolerated by E-Cat application. This is also investigated.

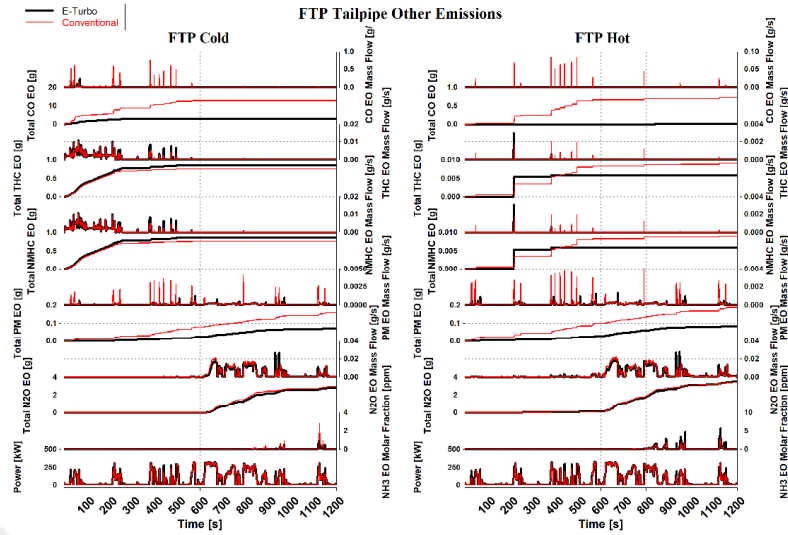


Figure 3.4.1.4.4 : Only E-Turbo FTP tailpipe other emissions.

Table 3.4.1.4.2 : Only E-Turbo FTP other emissions cycles results.

Result	CO	THC	NMHC	PM	N ₂ O	NH ₃
	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr	ppm
E-Turbo FTP Cold EO	0.66	0.21	0.21	0.11	0	0
Conventional FTP Cold EO	1.19	0.21	0.21	0.28	0	0
E-Turbo FTP Cold TP	0.13	0.04	0.04	0.003	0.122	0.01
Conventional FTP Cold TP	0.58	0.03	0.03	0.007	0.132	0.022
E-Turbo FTP Hot EO	0.57	0.22	0.22	0.12	0	0
Conventional FTP Hot EO	0.92	0.22	0.22	0.3	0	0
E-Turbo FTP Hot TP	0.0001	0	0	0.004	0.15	0.1
Conventional FTP Hot TP	0.033	0	0	0.008	0.15	0.06

3.4.1.5 EAS component temperatures

The EAS component temperatures are shown in figure 3.4.1.5.1. Black lines represent the e-turbo and the red lines represent the conventional model.

The e-turbo implementation does not have any significant effect on temperatures.

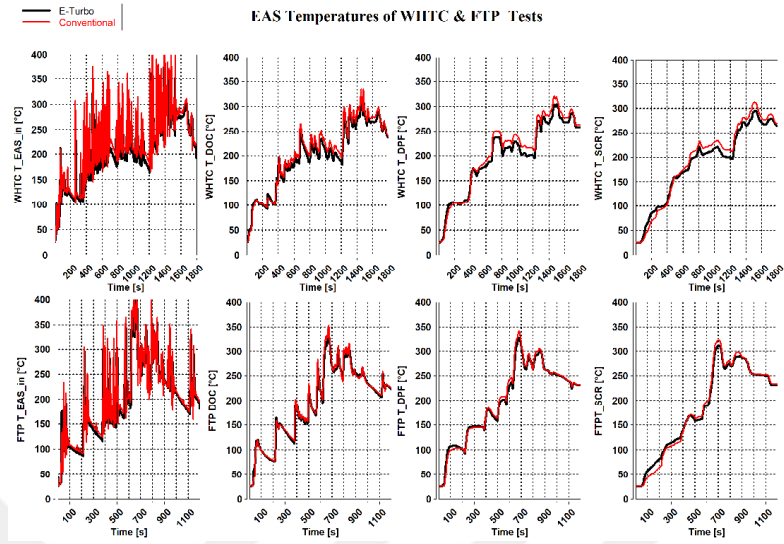


Figure 3.4.1.5.1 : Only E-Turbo EAS component temperatures.

3.4.2 Only E-Cat model

For the E-Cat simulations, two cases are considered. E-Cat is positioned before DOC and before SCR.

3.4.2.1 Fuel consumption

The fuel consumption results of WHTC cold and hot simulations are shown in the following figure. The black and blue lines represent the e-cat and the red lines represent the conventional model.

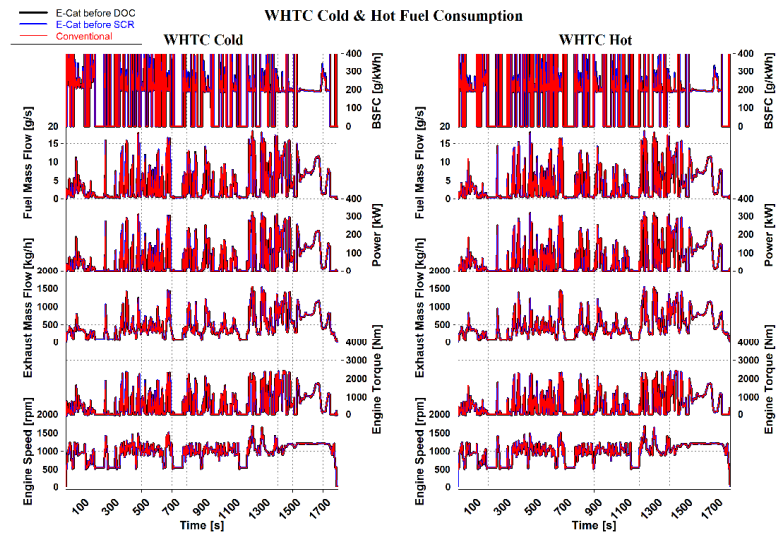


Figure 3.4.2.1.1 : Only E-Cat WHTC fuel consumption results.

The total fuel consumption, amount of fuel injected, and total work are given in the following table.

Table 3.4.2.1.1 : Only E-Cat WHTC fuel consumption results.

Result	E-Cat b.DOC	E-Cat b.SCR	Conventional	E-Cat b.DOC	E-Cat b.SCR	Conventional
	WHTC Cold	WHTC Cold	WHTC Cold	WHTC Hot	WHTC Hot	WHTC Hot
Total Work	33.37 kWh	32.40 kWh	32.33 kWh	33.33 kWh	32.36 kWh	32.31 kWh
Total Fuel	6873 g	6875 g	6833 g	6762 g	6765 g	6724 g
Total BSFC	212 g/kWh	212 g/kWh	211 g/kWh	209 g/kWh	209 g/kWh	208 g/kWh

The fuel consumption results of FTP cold and hot simulations are shown in the figure below. The black and blue lines represent the e-cat and the red lines represent the conventional model.

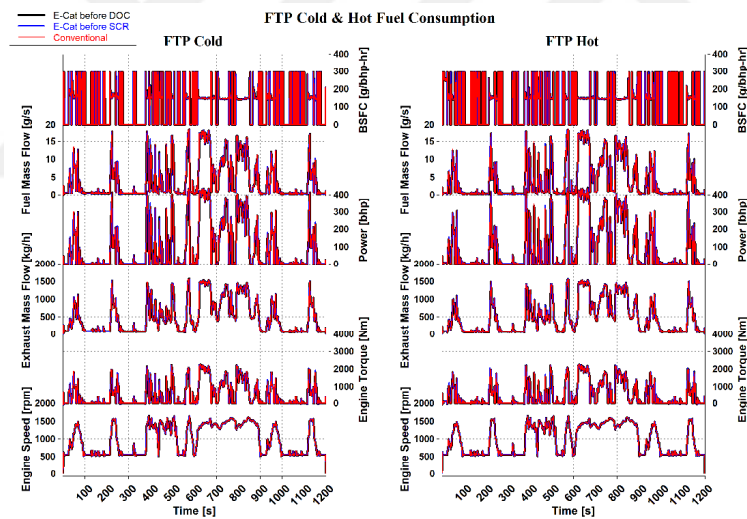


Figure 3.4.2.1.2 : Only E-Cat FTP fuel consumption results.

The FTP total fuel consumption results are given in the following table.

Table 3.4.2.1.2 : Only E-Cat FTP fuel consumption results.

Result	E-Cat b.DOC	E-Cat b.SCR	Conventional	E-Cat b.DOC	E-Cat b.SCR	Conventional
	FTP Cold	FTP Cold	FTP Cold	FTP Hot	FTP Hot	FTP Hot
Total Work	29.79 bhp-hr	29.82 bhp-hr	29.76 bhp-hr	29.91 bhp-hr	29.93 bhp-hr	29.89 bhp-hr
Total Fuel	4831 g	4835 g	4812 g	4743 g	4745 g	4725 g
Total BSFC	162 g/bhp-hr	162 g/bhp-hr	162 g/bhp-hr	158 g/bhp-hr	158 g/bhp-hr	158 g/bhp-hr

The result shows that the implementation of E-Cat with different positions does not have any significant effect on fuel consumption.

3.4.2.2 CO₂ engine-out and tailpipe

The CO₂ results of WHTC cold and hot simulations are shown in the figure below. The black and blue lines represent the e-cat and the red lines represent the conventional model.

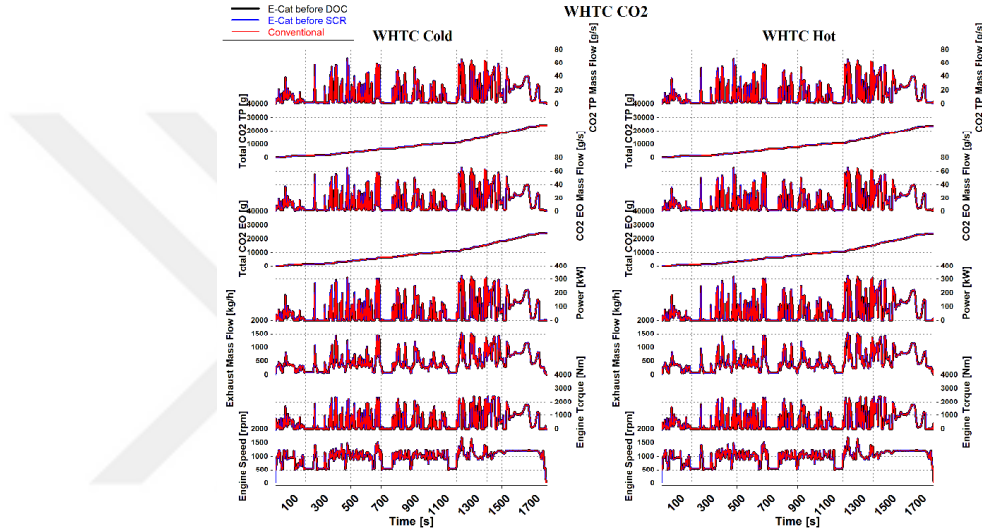


Figure 3.4.2.2.1 : Only E-Cat WHTC CO₂ results.

The total CO₂ results are given in the following table.

Table 3.4.2.2.1 : Only E-Cat WHTC CO₂ results.

Result	E-Cat b.DOC	E-Cat b.SCR	Conventional	E-Cat b.DOC	E-Cat b.SCR	Conventional
	Engine-out	Engine-out	Engine-out	Tailpipe	Tailpipe	Tailpipe
	BSCO ₂	BSCO ₂	BSCO ₂	BSCO ₂	BSCO ₂	BSCO ₂
WHTC Cold	738 g/kWh	738 g/kWh	735 g/kWh	744 g/kWh	744 g/kWh	740 g/kWh
WHTC Hot	728 g/kWh	728 g/kWh	724 g/kWh	734 g/kWh	734 g/kWh	730 g/kWh

The CO₂ results of FTP cold and hot simulations are shown in figure 3.4.2.2.2. The black and blue lines represent the e-cat and the red lines represent the conventional model. The FTP total CO₂ results are given in table 3.4.2.2.2.

The result shows that the implementation of E-Cat with different positions does not have any significant effect on CO₂ reduction like fuel consumption.

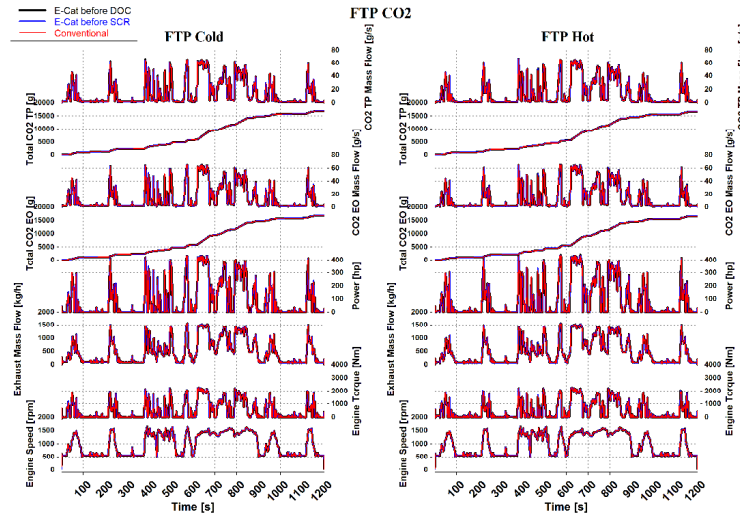


Figure 3.4.2.2.2 : Only E-Cat FTP CO₂ results.

Table 3.4.2.2.2 : Only E-Cat FTP CO₂ results.

	E-Cat b.DOC	E-Cat b.SCR	Conventional	E-Cat b.DOC	E-Cat b.SCR	Conventional
Result	Engine-out BSCO ₂	Engine-out BSCO ₂	Engine-out BSCO ₂	Tailpipe BSCO ₂	Tailpipe BSCO ₂	Tailpipe BSCO ₂
FTP Cold	562 g/bhp-hr	562 g/bhp-hr	561 g/bhp-hr	566 g/bhp-hr	566 g/bhp-hr	565 g/bhp-hr
FTP Hot	551 g/bhp-hr	551 g/bhp-hr	549 g/bhp-hr	555 g/bhp-hr	555 g/bhp-hr	553 g/bhp-hr

3.4.2.3 NO_x engine-out and tailpipe

The NO_x results of WHTC cold and hot are shown in the following figure. The black and blue lines represent the e-cat and the red lines represent the conventional model.

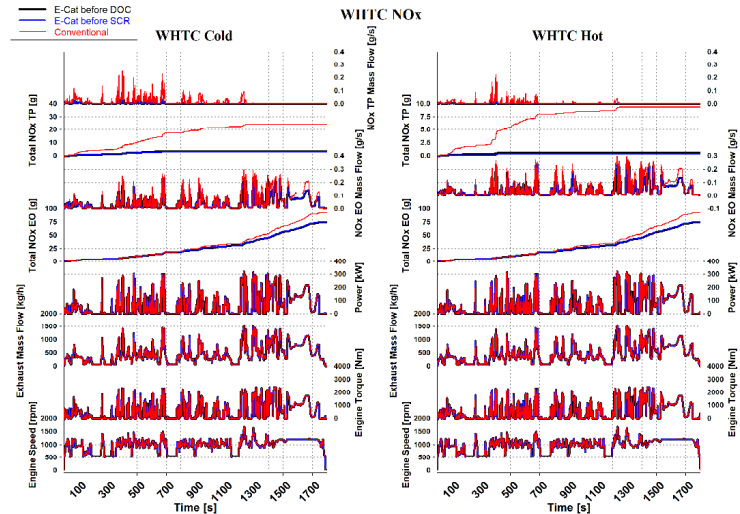


Figure 3.4.2.3.1 : Only E-Cat WHTC NO_x results.

The total NO_x results are given in the following table.

Table 3.4.2.3.1 : Only E-Cat WHTC NO_x results.

Result	E-Cat b.DOC	E-Cat b.SCR	Conventional	E-Cat b.DOC	E-Cat b.SCR	Conventional
	Engine-out	Engine-out	Engine-out	Tailpipe	Tailpipe	Tailpipe
	BSNO _x	BSNO _x	BSNO _x	BSNO _x	BSNO _x	BSNO _x
WHTC Cold	2.31 g/kWh	2.32 g/kWh	2.86 g/kWh	0.106 g/kWh	0.102 g/kWh	0.75 g/kWh
WHTC Hot	2.30 g/kWh	2.31 g/kWh	2.85 g/kWh	0.011 g/kWh	0.007 g/kWh	0.29 g/kWh

The NO_x results of FTP cold and hot simulations are shown in the figure below. The black and blue lines represent the e-cat and the red lines represent the conventional model.

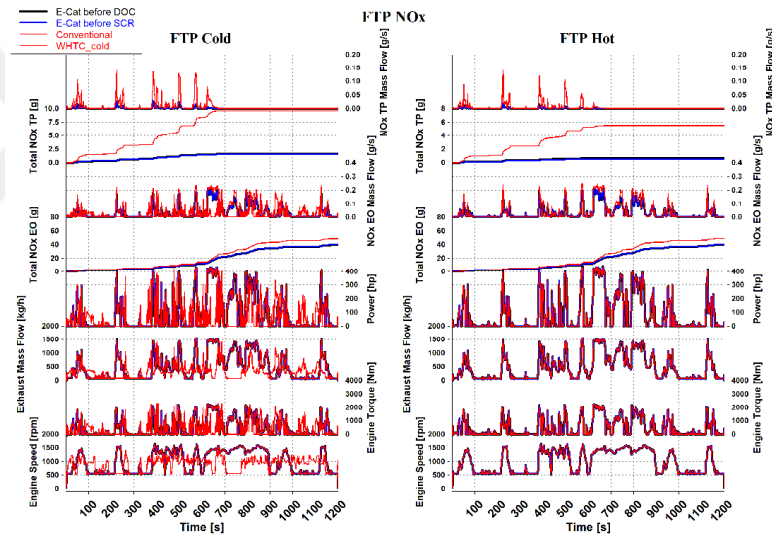


Figure 3.4.2.3.2 : Only E-Cat FTP cold and hot NO_x results.

The FTP total NO_x results are given in the following table.

Table 3.4.2.3.2 : Only E-Cat FTP NO_x results.

Result	E-Cat b.DOC	E-Cat b.SCR	Conventional	E-Cat b.DOC	E-Cat b.SCR	Conventional
	Engine-out	Engine-out	Engine-out	Tailpipe	Tailpipe	Tailpipe
	BSNO _x	BSNO _x	BSNO _x	BSNO _x	BSNO _x	BSNO _x
FTP Cold	1.33 g/bhp-hr	1.33 g/bhp-hr	1.63 g/bhp-hr	0.053 g/bhp-hr	0.051 g/bhp-hr	0.32 g/bhp-hr
FTP Hot	1.32 g/bhp-hr	1.32 g/bhp-hr	1.63 g/bhp-hr	0.023 g/bhp-hr	0.018 g/bhp-hr	0.19 g/bhp-hr

The results show that the E-Cat provides great benefits for NO_x reduction and increase in SCR efficiency. Better thermal management of the aftertreatment systems

demonstrates the higher SCR performance. The following figure shows an example from WHTC cold test.

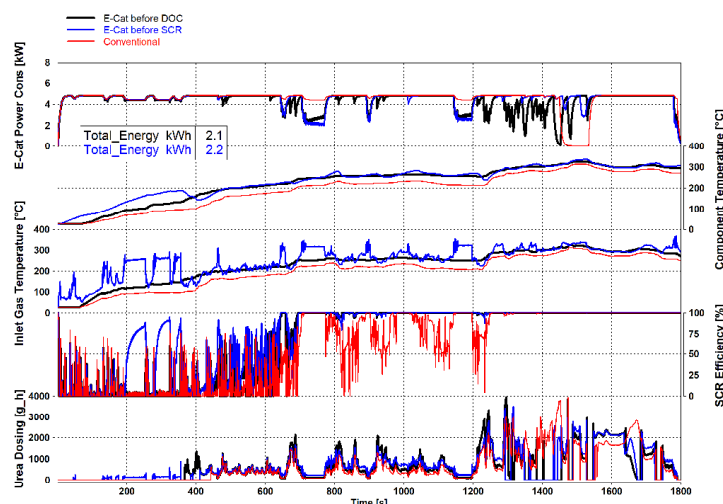


Figure 3.4.2.3.3 : Only E-Cat SCR efficiency and temperature example.

When the E-Cat is positioned before SCR, it causes the temperature to increase in the SCR inlet quickly. That's why the urea dosing begins much earlier than conventional and E-Cat position before DOC. Urea dosing starts at 45 s for the E-Cat position before SCR while it starts at 370 s for the E-Cat position before DOC, and 445 s for conventional. Also, the positioning of E-Cat before SCR results in the average temperature increase of the SCR more than the other cases even the SCR reaches its most effective working temperature region in the same duration whether E-Cat position is before DOC or before SCR. Because of both early urea dosing and higher SCR substrate temperature in the early phase of cold start, the SCR efficiency is much higher than the other two cases. Although the tailpipe NO_x result of E-Cat position before SCR is lower, the tailpipe NO_x difference between before DOC and before SCR is small. Thus, the usage of E-Cat before DOC should be considered because it provides rapid heat-up other components also due to temperature increase of exhaust temperature at the inlet of EAS. This, also, increases the performances of other components like DOC by reaching the light-off temperature earlier. Better DOC performance, also, helps to increase SCR performance by arranging demand NO/NO_2 ratio earlier than the conventional system. Moreover, the power consumption of E-Cat before DOC is slightly lower than the E-Cat before SCR.

3.4.2.4 Other engine-out and tailpipe emissions

The other emissions evaluated are CO, total hydrocarbon (THC), non-methane hydrocarbon (NMHC), PM, N₂O, and NH₃. The WHTC cold and hot engine-out and tailpipe results are given in the following figures. Black and blue lines represent the e-cat and the red lines represent the conventional model.

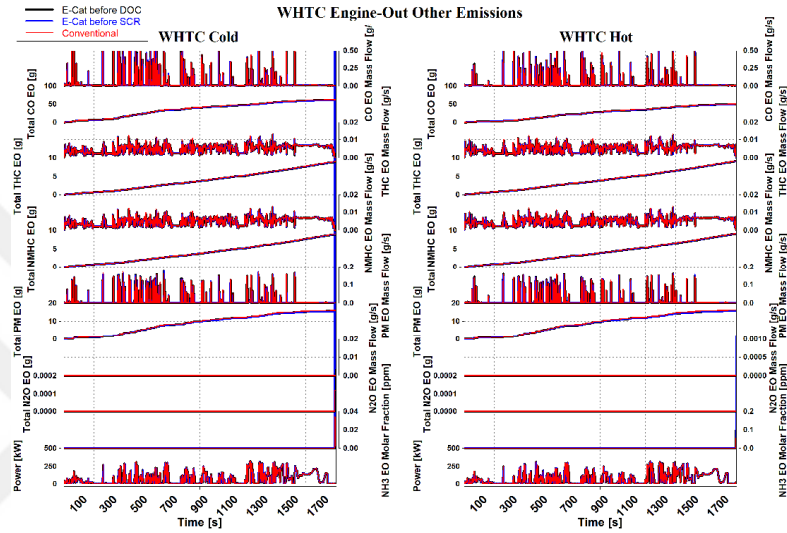


Figure 3.4.2.4.1 : Only E-Cat WHTC engine-out other emissions.

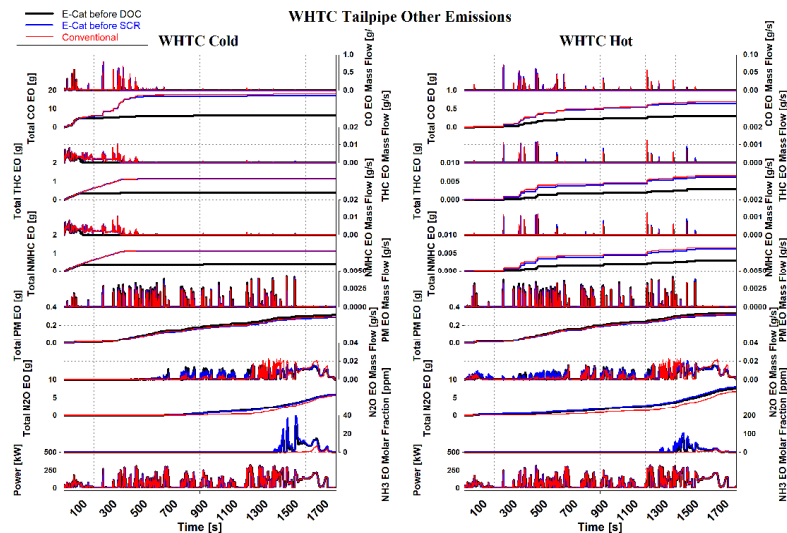


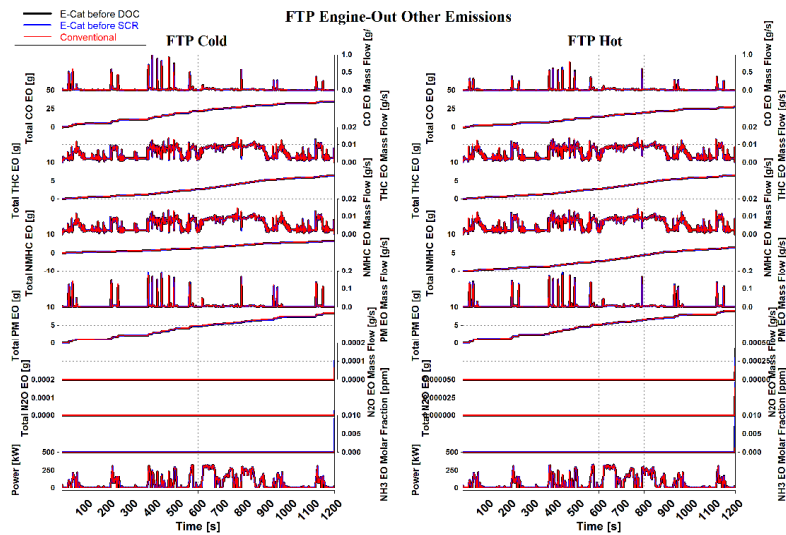
Figure 3.4.2.4.2 : Only E-Cat WHTC tailpipe other emissions.

The WHTC cycle results of other emissions for hot and cold tests are given in the following table. The NH₃ is evaluated according to its average value.

Table 3.4.2.4.1 : Only E-Cat WHTC other emissions cycles results.

Result	CO	THC	NMHC	PM	N ₂ O	NH ₃
	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	ppm
E-Cat b.DOC WHTC Cold EO	1.91	0.28	0.28	0.48	0	0
E-Cat b.SCR WHTC Cold EO	1.88	0.28	0.28	0.48	0	0
Conventional WHTC Cold EO	1.93	0.27	0.27	0.49	0	0
E-Cat b.DOC WHTC Cold TP	0.19	0.012	0.012	0.01	0.18	1.48
E-Cat b.SCR WHTC Cold TP	0.53	0.034	0.034	0.009	0.18	1.86
Conventional WHTC Cold TP	0.56	0.035	0.035	0.009	0.17	0.18
E-Cat b.DOC WHTC Hot EO	1.54	0.28	0.28	0.49	0	0
E-Cat b.SCR WHTC Hot EO	1.52	0.28	0.28	0.48	0	0
Conventional WHTC Hot EO	1.56	0.28	0.28	0.50	0	0
E-Cat b.DOC WHTC Hot TP	0.009	0	0	0.01	0.23	3.74
E-Cat b.SCR WHTC Hot TP	0.02	0	0	0.01	0.25	5.81
Conventional WHTC Hot TP	0.02	0	0	0.01	0.21	0.61

The FTP cold and hot engine-out and tailpipe results are given in the following figures. Black and blue lines represent the e-cat and the red lines represent the conventional model.

**Figure 3.4.2.4.3 : Only E-Cat FTP engine-out other emissions.**

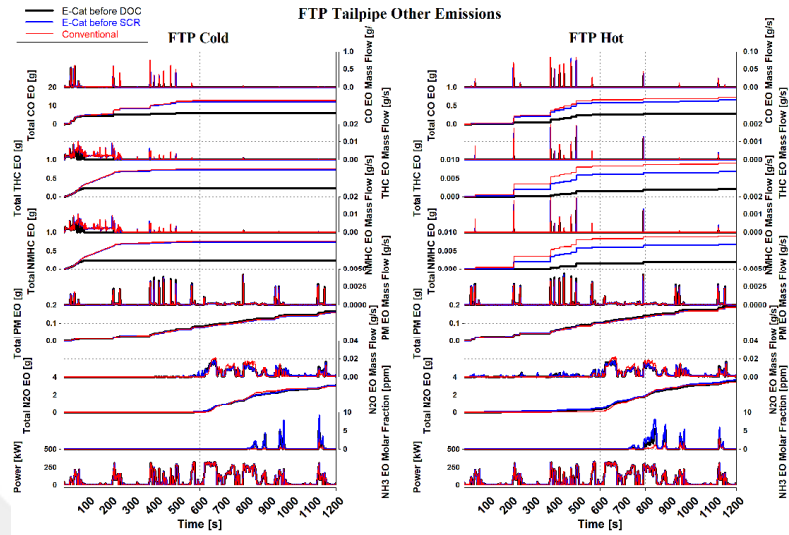


Figure 3.4.2.4.4 : Only E-Cat FTP tailpipe other emissions.

The FTP cycle results of other emissions for hot and cold tests are given in the following table. The NH_3 is evaluated according to its average value.

Table 3.4.2.4.2 : Only E-Cat FTP other emissions cycles results.

Result	CO	THC	NMHC	PM	N ₂ O	NH ₃
	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr	ppm
E-Cat b.DOC FTP Cold EO	1.56	0.29	0.29	0.37	0	0
E-Cat b.SCR FTP Cold EO	1.56	0.29	0.29	0.37	0	0
Conventional FTP Cold EO	1.60	0.29	0.29	0.38	0	0
E-Cat b.DOC FTP Cold TP	0.23	0.011	0.011	0.007	0.138	0.132
E-Cat b.SCR FTP Cold TP	0.54	0.033	0.033	0.007	0.139	0.168
Conventional FTP Cold TP	0.58	0.034	0.034	0.007	0.132	0.022
E-Cat b.DOC FTP Hot EO	1.23	0.29	0.29	0.398	0	0
E-Cat b.SCR FTP Hot EO	1.22	0.29	0.29	0.400	0	0
Conventional FTP Hot EO	1.23	0.29	0.29	0.403	0	0
E-Cat b.DOC FTP Hot TP	0.013	0	0	0.009	0.158	0.221
E-Cat b.SCR FTP Hot TP	0.029	0	0	0.008	0.165	0.349
Conventional FTP Hot TP	0.033	0	0	0.008	0.154	0.061

As stated in the comments of NO_x result, the position of E-Cat before DOC increases the DOC and DPF performance which can be seen from especially CO and PM results. Also, the E-Cat position before DOC gives better results for N₂O and NH₃ slip due to less aggressive temperature characteristics than other E-Cat positions.

3.4.2.5 EAS component temperatures

The EAS component temperatures are shown in the following figure. Black and blue lines represent the e-cat and the red lines represent the conventional model.

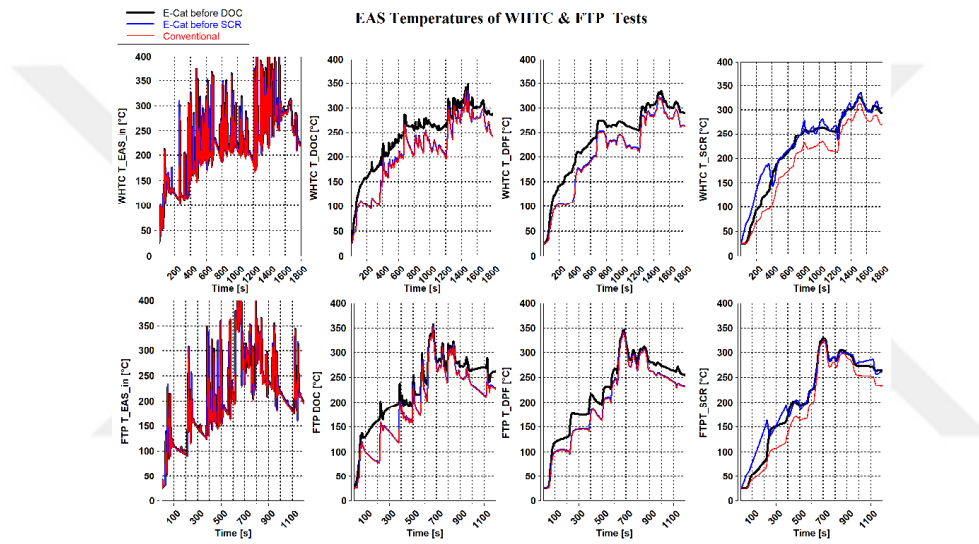


Figure 3.4.2.5.1 : Only E-Cat EAS component temperatures.

While the engine-out exhaust temperatures are the same with both cases, positioning of E-Cat before DOC allows temperature management for all components and the E-Cat before SCR provides better SCR thermal management only.

3.4.3 Only EGR pump model

For the EGR pump simulations, two cases are considered. The first one is the usage of LP-EGR only and the second one usage of LP-EGR with HP-EGR.

3.4.3.1 Fuel consumption

The fuel consumption results of WHTC cold and hot simulations are shown in the following figure. The black and blue lines represent the EGR pump and the red lines represent the conventional model.

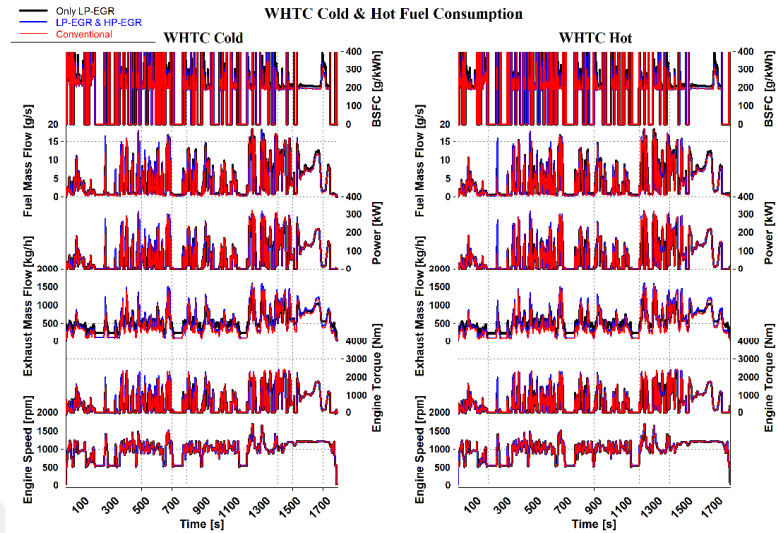


Figure 3.4.3.1.1 : Only EGR pump WHTC fuel consumption results.

The total fuel consumption, amount of fuel injected, and total work are given in the following table.

Table 3.4.3.1.1 : Only EGR pump WHTC fuel consumption results.

Result	Only LP	LP & HP	Conventional	Only LP	LP & HP	Conventional
	WHTC Cold	WHTC Cold	WHTC Cold	WHTC Hot	WHTC Hot	WHTC Hot
Total Work	32.08 kWh	32.73 kWh	32.33 kWh	32.15 kWh	32.71 kWh	32.31 kWh
Total Fuel	7372 g	6932 g	6833 g	7304 g	6825 g	6724 g
Total BSFC	230 g/kWh	211 g/kWh	211 g/kWh	227 g/kWh	208 g/kWh	208 g/kWh

The fuel consumption results of FTP cold and hot are shown in figure 3.4.3.1.2. The black and blue lines represent the EGR pump and the red lines represent the conventional. The FTP total fuel consumption results are given in the table 3.4.3.1.2.

Table 3.4.3.1.2 : Only EGR pump FTP fuel consumption results.

Result	Only LP	LP & HP	Conventional	Only LP	LP & HP	Conventional
	FTP Cold	FTP Cold	FTP Cold	FTP Hot	FTP Hot	FTP Hot
Total Work	29.84 bhp-hr	30.08 bhp-hr	29.76 bhp-hr	29.94 bhp-hr	30.20 bhp-hr	29.89 bhp-hr
Total Fuel	5316 g	4909 g	4812 g	5247 g	4821 g	4725 g
Total BSFC	178 g/bhp-hr	163 g/bhp-hr	162 g/bhp-hr	175 g/bhp-hr	159 g/bhp-hr	158 g/bhp-hr

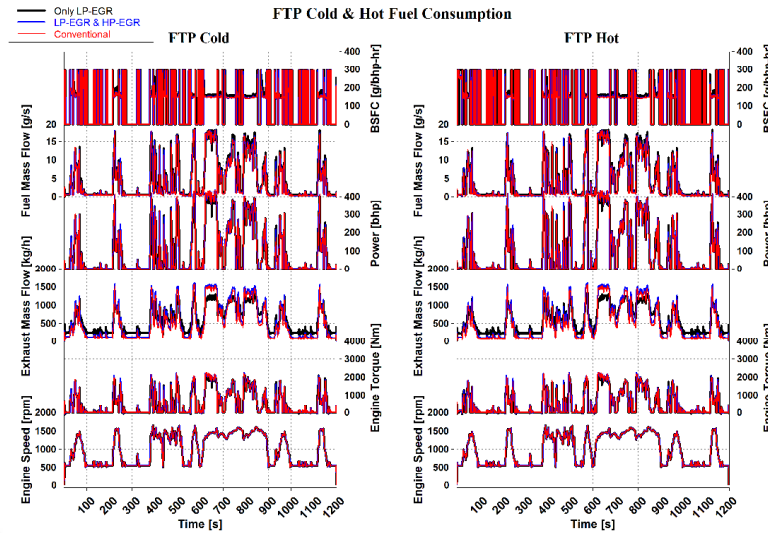


Figure 3.4.3.1.2 : Only EGR pump FTP fuel consumption results.

The results indicate that the application of LP-EGR alone makes the system worse than conventional whereas the application of LP-EGR with HP-EGR gives almost the same as the conventional model. Though it is mentioned in the model description section, it is beneficial to repeat here that the strategy to define EGR rate is supplying the same amount of EGR to the system with LP-EGR only and LP-EGR with HP-EGR to compare the applications with conventional model fairly. The EGR conditions of the models are shown in the figure below with an example from WHTC warm test.

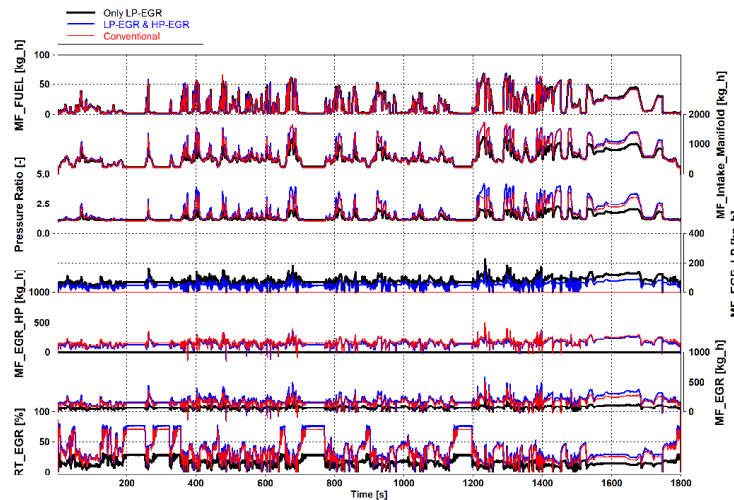


Figure 3.4.3.1.3 : The EGR of three models from WHTC hot simulation.

While the LP-EGR with HP-EGR system can feed a slightly higher amount of EGR than the conventional system, only LP-EGR can feed much less amount of EGR than

the conventional system. The main reason for this phenomenon is that the compressor is selected to operate without exhaust gas at the inlet. Because enough amount of EGR cannot be supplied by LP-EGR in idle conditions, there is much fresh air in the intake manifold. The engine injected more fuel due to more fresh air and produces more unuseful power. This problem can be solved by proper compressor/turbine selection and calibration, and the system can be made much more efficient for fuel consumption. An example from idle between 1150 s and 1190 s is shown in the figure below.

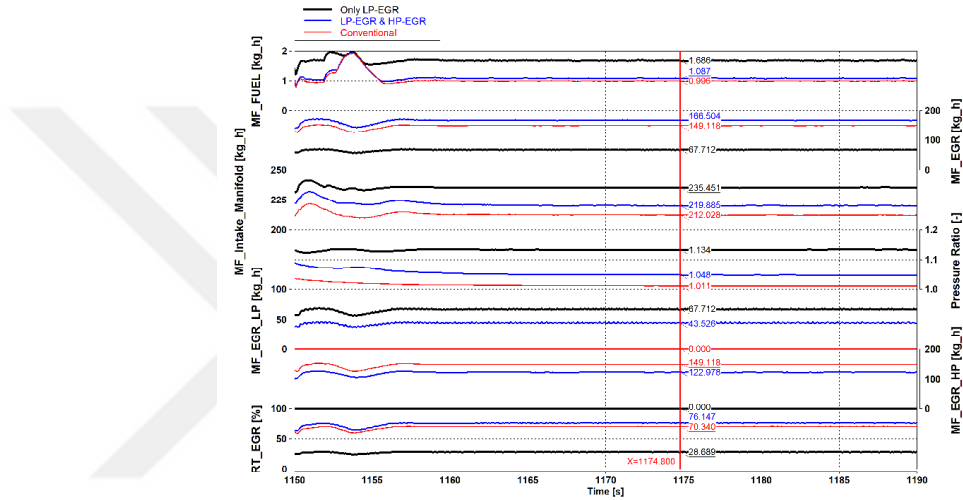


Figure 3.4.3.1.4 : LP-EGR idle problem example.

3.4.3.2 CO₂ engine-out and tailpipe

The CO₂ results of WHTC cold and hot simulations are shown in figure 3.4.3.2.1. The black and blue lines represent the EGR pump and the red lines represent the conventional model. The total CO₂ results are given in table 3.4.3.2.1.

Table 3.4.3.2.1 : Only EGR pump WHTC CO₂ results.

Result	Only LP	LP & HP	Conventional	Only LP	LP & HP	Conventional
	Engine-out BSCO ₂	Engine-out BSCO ₂	Engine-out BSCO ₂	Tailpipe BSCO ₂	Tailpipe BSCO ₂	Tailpipe BSCO ₂
WHTC Cold	916 g/kWh	801 g/kWh	735 g/kWh	921 g/kWh	807 g/kWh	740 g/kWh
WHTC Hot	904 g/kWh	790 g/kWh	724 g/kWh	910 g/kWh	796 g/kWh	730 g/kWh

The CO₂ results of FTP cold and hot simulations are shown in figure 3.4.3.2.2. The black and blue lines represent the EGR pump and the red lines represent the conventional model. The FTP total CO₂ results are given in table 3.4.3.2.2.

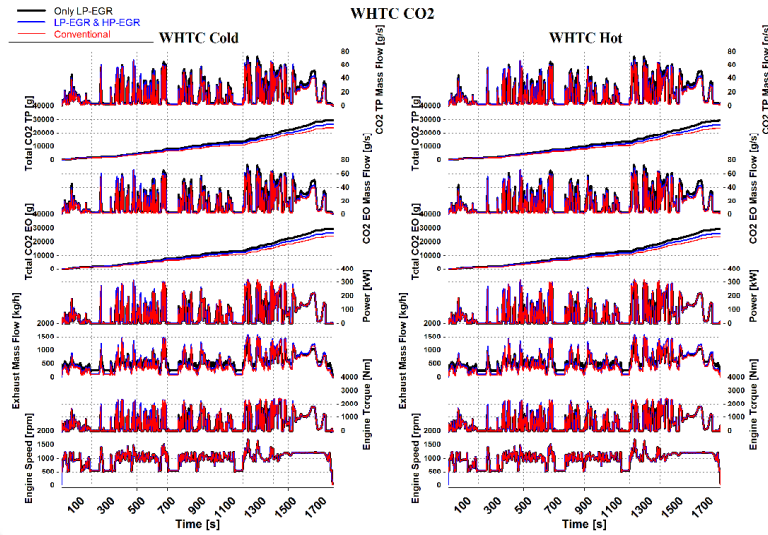


Figure 3.4.3.2.1 : Only EGR pump WHTC CO₂ results.

Table 3.4.3.2.2 : Only EGR pump FTP CO₂ results.

	Only LP	LP & HP	Conventional	Only LP	LP & HP	Conventional
Result	Engine-out	Engine-out	Engine-out	Tailpipe	Tailpipe	Tailpipe
	BSCO ₂	BSCO ₂	BSCO ₂	BSCO ₂	BSCO ₂	BSCO ₂
FTP Cold	682 g/bhp-hr	624 g/bhp-hr	561 g/bhp-hr	687 g/bhp-hr	626 g/bhp-hr	565 g/bhp-hr
FTP Hot	670 g/bhp-hr	610 g/bhp-hr	549 g/bhp-hr	675 g/bhp-hr	613 g/bhp-hr	553 g/bhp-hr

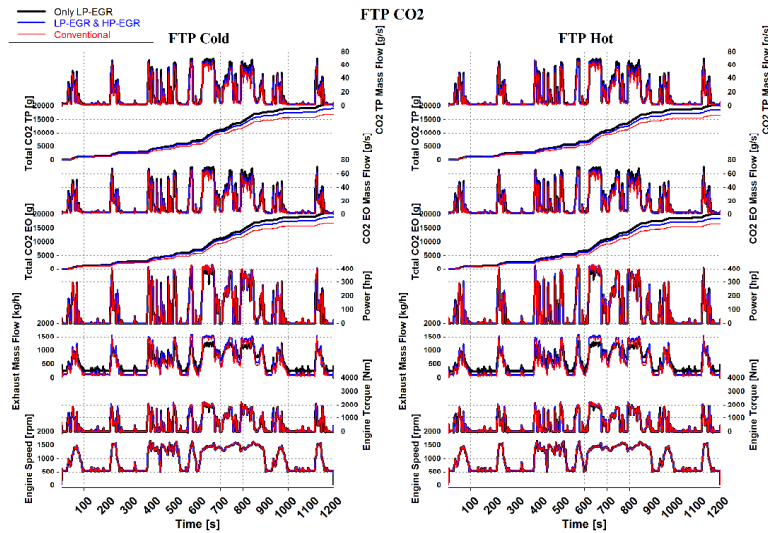


Figure 3.4.3.2.2 : Only EGR pump FTP CO₂ results.

The result shows that the implementation of the EGR pump with different applications makes the system worse for CO₂ reduction like fuel consumption.

3.4.3.3 NO_x engine-out and tailpipe

The NO_x results of WHTC cold and hot simulations are shown in figure 3.4.3.3.1. The black and blue lines represent the EGR pump and the red lines represent the conventional model. The total NO_x results are given in table 3.4.3.3.1.

Table 3.4.3.3.1 : Only EGR pump WHTC NO_x results.

Result	Only LP	LP & HP	Conventional	Only LP	LP & HP	Conventional
	Engine-out	Engine-out	Engine-out	Tailpipe	Tailpipe	Tailpipe
	BSNO _x	BSNO _x	BSNO _x	BSNO _x	BSNO _x	BSNO _x
WHTC Cold	3.99 g/kWh	2.16 g/kWh	2.86 g/kWh	0.87 g/kWh	0.68 g/kWh	0.75 g/kWh
WHTC Hot	3.97 g/kWh	2.16 g/kWh	2.85 g/kWh	0.29 g/kWh	0.30 g/kWh	0.29 g/kWh

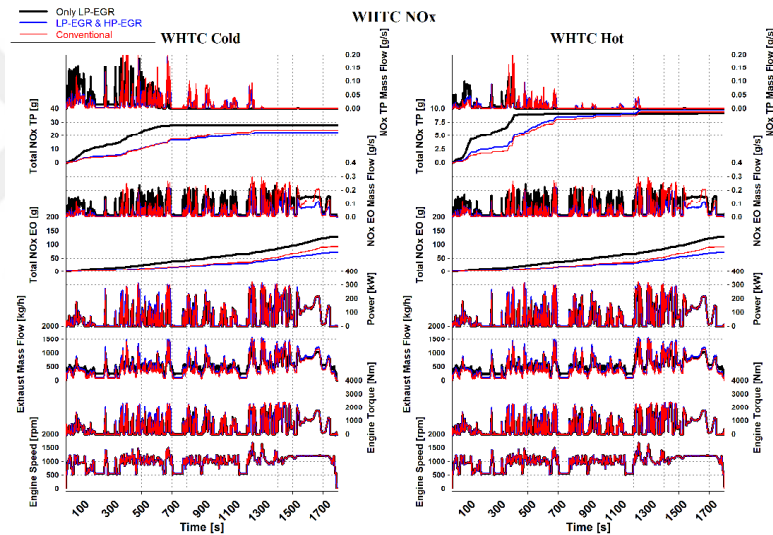


Figure 3.4.3.3.1 : Only EGR pump WHTC NO_x results.

The NO_x results of FTP cold and hot simulations are shown in figure 3.4.3.3.2. The black and blue lines represent the EGR pump and the red lines represent the conventional model. The FTP total NO_x results are given in table 3.4.3.3.2.

Table 3.4.3.3.2 : Only EGR pump FTP NO_x results.

Result	Only LP	LP & HP	Conventional	Only LP	LP & HP	Conventional
	Engine-out	Engine-out	Engine-out	Tailpipe	Tailpipe	Tailpipe
	BSNO _x	BSNO _x	BSNO _x	BSNO _x	BSNO _x	BSNO _x
FTP Cold	2.58 g/bhp-hr	1.26 g/bhp-hr	1.63 g/bhp-hr	0.4 g/bhp-hr	0.27 g/bhp-hr	0.32 g/bhp-hr
FTP Hot	2.56 g/bhp-hr	1.26 g/bhp-hr	1.63 g/bhp-hr	0.18 g/bhp-hr	0.16 g/bhp-hr	0.19 g/bhp-hr

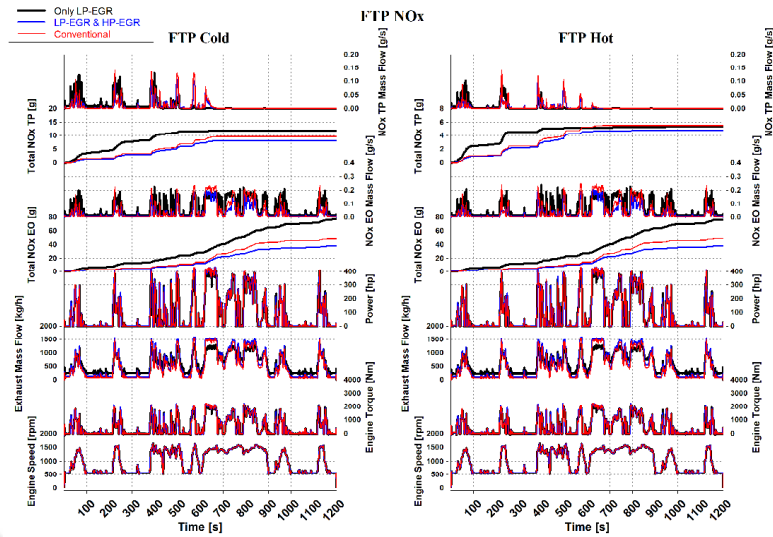


Figure 3.4.3.3.2 : Only EGR pump FTP cold and hot NO_x results.

The results show that the alone application of the EGR pump makes the system worse than the conventional system for NO_x reduction due to less amount of EGR. On the other hand, the application of LP-EGR with HP-EGR gives a small advantage.

3.4.3.4 Other engine-out and tailpipe emissions

The other emissions evaluated are CO, total hydrocarbon (THC), non-methane hydrocarbon (NMHC), PM, N₂O, and NH₃. The WHTC cold and hot engine-out and tailpipe results are given in the following figures. Black and blue lines represent the EGR pump and the red lines represent the conventional model.

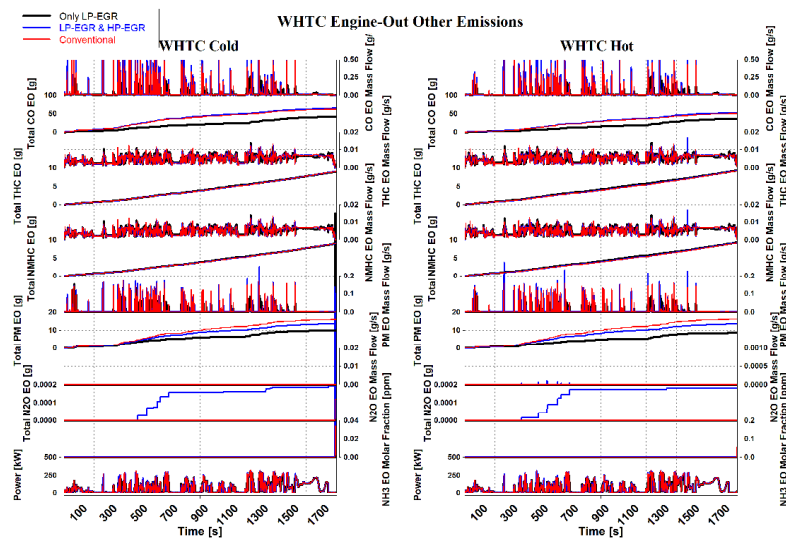


Figure 3.4.3.4.1 : Only EGR pump WHTC engine-out other emissions.

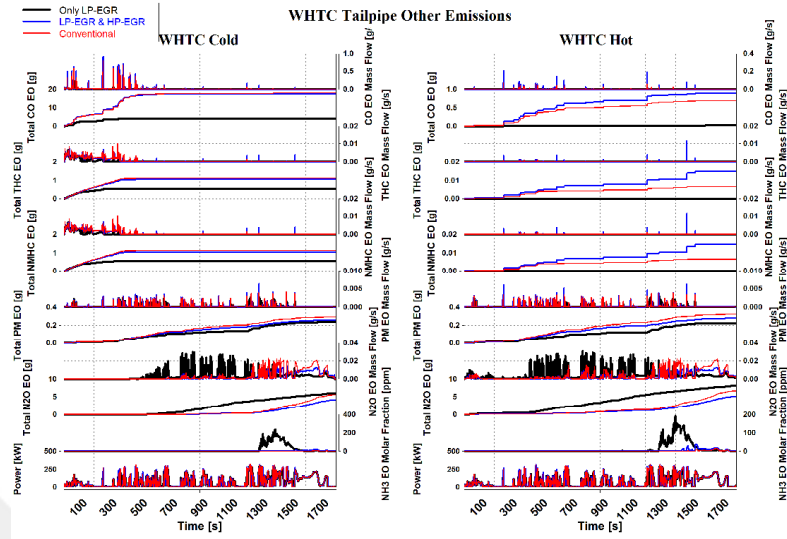


Figure 3.4.3.4.2 : Only EGR pump WHTC tailpipe other emissions.

The WHTC cycle results of other emissions for hot and cold tests are given in the following table. The NH_3 is evaluated according to its average value.

Table 3.4.3.4.1 : Only EGR pump WHTC other emissions cycles results.

Result	CO	THC	NMHC	PM	N_2O	NH_3
	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	ppm
Only LP WHTC Cold EO	1.32	0.28	0.28	0.309	0	0
LP & HP WHTC Cold EO	1.99	0.27	0.27	0.415	0	0
Conventional WHTC Cold EO	1.93	0.27	0.27	0.493	0	0
Only LP WHTC Cold TP	0.13	0.017	0.017	0.007	0.19	15
LP & HP WHTC Cold TP	0.54	0.032	0.032	0.008	0.13	1.11
Conventional WHTC Cold TP	0.56	0.035	0.035	0.009	0.17	0.18
Only LP WHTC Hot EO	1.15	0.29	0.29	0.270	0	0
LP & HP WHTC Hot EO	1.61	0.28	0.28	0.413	0	0
Conventional WHTC Hot EO	1.56	0.28	0.28	0.499	0	0
Only LP WHTC Hot TP	0.001	0	0	0.007	0.25	11.6
LP & HP WHTC Hot TP	0.03	0	0	0.009	0.16	1.86
Conventional WHTC Hot TP	0.02	0	0	0.01	0.21	0.61

The FTP cold and hot engine-out and tailpipe results are given in the following figures. Black and blue lines represent the EGR pump and the red lines represent the conventional model.

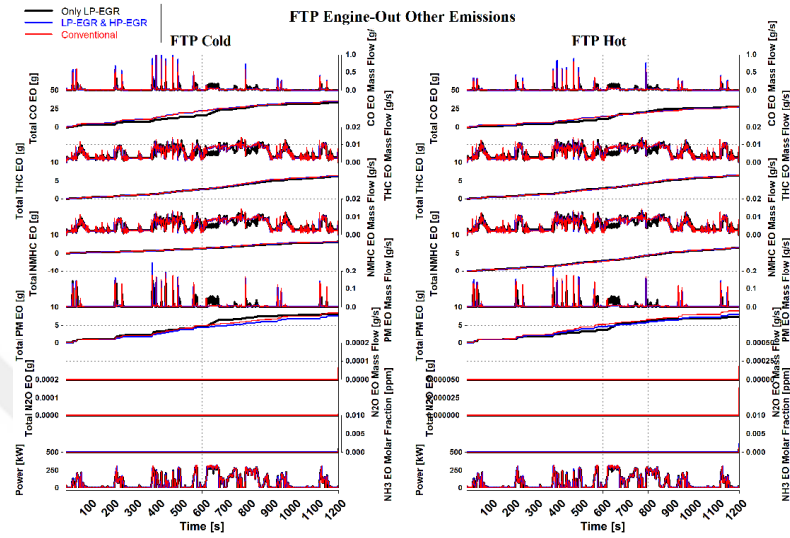


Figure 3.4.3.4.3 : Only EGR pump FTP engine-out other emissions.

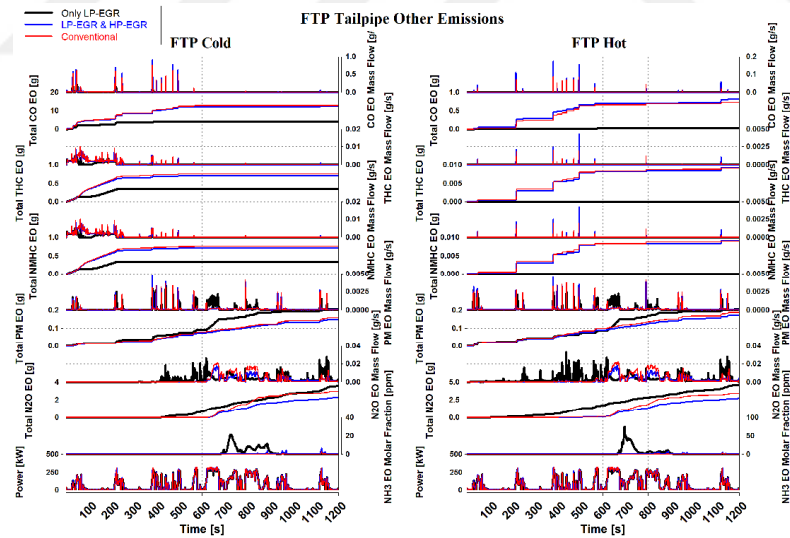


Figure 3.4.3.4.4 : Only EGR pump FTP tailpipe other emissions.

The FTP cycle results of other emissions for hot and cold tests are given in table 3.4.3.4.2. The NH_3 is evaluated according to its average value.

The implementation of the EGR pump makes the system better for CO and PM. However, the NH_3 slip and N_2O formation increase too much as a result of high engine-out NO_x formation.

Table 3.4.3.4.2 : Only EGR pump FTP other emissions cycles results.

Result	CO	THC	NMHC	PM	N ₂ O	NH ₃
	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr	ppm
Only LP FTP Cold EO	1.50	0.28	0.28	0.37	0	0
LP & HP FTP Cold EO	1.59	0.28	0.28	0.34	0	0
Conventional FTP Cold EO	1.60	0.29	0.29	0.38	0	0
Only LP FTP Cold TP	0.17	0.015	0.015	0.009	0.160	0.365
LP & HP FTP Cold TP	0.54	0.032	0.032	0.007	0.101	0.104
Conventional FTP Cold TP	0.58	0.034	0.034	0.007	0.132	0.022
Only LP FTP Hot EO	1.25	0.29	0.29	0.328	0	0
LP & HP FTP Hot EO	1.22	0.29	0.29	0.352	0	0
Conventional FTP Hot EO	1.23	0.29	0.29	0.403	0	0
Only LP FTP Hot TP	0.001	0	0	0.009	0.205	2.758
LP & HP FTP Hot TP	0.036	0	0	0.008	0.121	0.261
Only LP FTP Cold EO	0.033	0	0	0.008	0.154	0.061

3.4.3.5 EAS component temperatures

The EAS component temperatures are shown in the following figure. Black and blue lines represent the EGR pump and the red lines represent the conventional model.

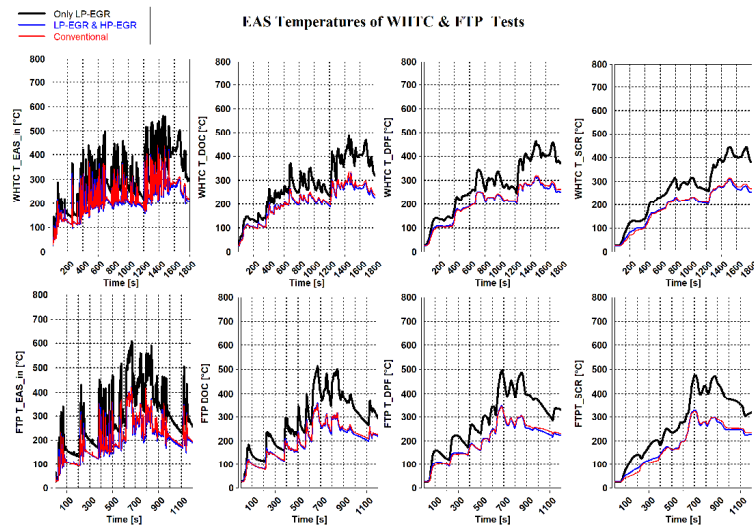


Figure 3.4.3.5.1 : Only EGR pump EAS component temperatures.

As a result of higher fuel injection, the exhaust gas temperature becomes higher for only the LP-EGR system. Thus, it provides more heat sources for EAS components.

3.4.4 EGR pump and E-Cat model

Until this section, the impact of the application of one component was given with their graphs and cycle results. Now, the results of combinations of components models are given. There are four cases for the implementation of EGR pump with E-Cat: only LP-EGR with E-Cat before DOC, only LP-EGR with E-Cat before SCR, LP&HP-EGR with E-Cat before DOC, and LP&HP-EGR with E-Cat before SCR. Because both showing many lines in one graph is not understandable and giving every case takes too much space, only cycle results of system combinations are shared.

3.4.4.1 Fuel consumption

The total fuel consumption and related features are given in the following table.

Table 3.4.4.1.1 : LP-EGR with E-Cat b. DOC and b. SCR WHTC bsfc results.

Result	Only LP E-Cat b. DOC WHTC Cold	Only LP E-Cat b. SCR WHTC Cold	Conventional WHTC Cold	Only LP E-Cat b. DOC WHTC Hot	Only LP E-Cat b. SCR WHTC Hot	Conventional WHTC Hot
Total Work	32.07 kWh	32.08 kWh	32.33 kWh	32.13 kWh	32.15 kWh	32.31 kWh
Total Fuel	7372 g	7373 g	6833 g	7302 g	7305 g	6724 g
Total BSFC	230 g/kWh	230 g/kWh	211 g/kWh	227 g/kWh	227 g/kWh	208 g/kWh

Table 3.4.4.1.2 : LP&HP-EGR with E-Cat b. DOC and b. SCR WHTC bsfc results.

Result	LP & HP E-Cat b. DOC WHTC Cold	LP & HP E-Cat b. SCR WHTC Cold	Conventional WHTC Cold	LP & HP E-Cat b. DOC WHTC Hot	LP & HP E-Cat b. SCR WHTC Hot	Conventional WHTC Hot
Total Work	32.71 kWh	32.73 kWh	32.33 kWh	32.68 kWh	32.71 kWh	32.31 kWh
Total Fuel	6930 g	6933 g	6833 g	6822 g	6825 g	6724 g
Total BSFC	211 g/kWh	211 g/kWh	211 g/kWh	208 g/kWh	208 g/kWh	208 g/kWh

The FTP total fuel consumption results are given in the following table.

Table 3.4.4.1.3 : LP-EGR with E-Cat b. DOC and b. SCR FTP bsfc results.

Result	Only LP E-Cat b. DOC FTP Cold	Only LP E-Cat b. SCR FTP Cold	Conventional FTP Cold	Only LP E-Cat b. DOC FTP Hot	Only LP E-Cat b. SCR FTP Hot	Conventional FTP Hot
Total Work	29.83 bhp-hr	29.84 bhp-hr	29.76 bhp-hr	29.93 bhp-hr	29.93 bhp-hr	29.89 bhp-hr
Total Fuel	5314 g	5315 g	4812 g	5247 g	5246 g	4725 g
Total BSFC	178 g/bhp-hr	178 g/bhp-hr	162 g/bhp-hr	175 g/bhp-hr	175 g/bhp-hr	158 g/bhp-hr

Table 3.4.4.1.4 : LP&HP-EGR with E-Cat b. DOC and b. SCR FTP bsfc results.

Result	LP & HP E-Cat b. DOC FTP Cold	LP & HP E-Cat b. SCR FTP Cold	Conventional FTP Cold	LP & HP E-Cat b. DOC FTP Hot	LP & HP E-Cat b. SCR FTP Hot	Conventional FTP Hot
Total Work	30.07 bhp-hr	30.07 bhp-hr	29.76 bhp-hr	30.19 bhp-hr	30.20 bhp-hr	29.89 bhp-hr
Total Fuel	4909 g	4909 g	4812 g	4820 g	4821 g	4725 g
Total BSFC	163 g/bhp-hr	163 g/bhp-hr	162 g/bhp-hr	159 g/bhp-hr	159 g/bhp-hr	158 g/bhp-hr

Only LP-EGR makes the system worse than conventional even with E-Cat.

3.4.4.2 CO₂ engine-out and tailpipe

The total CO₂ results are given in the following table.

Table 3.4.4.2.1 : LP-EGR with E-Cat b. DOC and b. SCR WHTC CO₂ results.

Result	Only LP E-Cat b. DOC Engine-out BSCO ₂	Only LP E-Cat b. SCR Engine-out BSCO ₂	Conventional Engine-out BSCO ₂	Only LP E-Cat b. DOC Tailpipe BSCO ₂	Only LP E-Cat b. SCR Tailpipe BSCO ₂	Conventional Tailpipe BSCO ₂
WHTC Cold	916 g/kWh	916 g/kWh	735 g/kWh	922 g/kWh	921 g/kWh	740 g/kWh
WHTC Hot	905 g/kWh	904 g/kWh	724 g/kWh	911 g/kWh	911 g/kWh	730 g/kWh

Table 3.4.4.2.2 : LP&HP-EGR with E-Cat b. DOC and b. SCR WHTC CO₂ results.

Result	LP & HP E-Cat b. DOC Engine-out BSCO ₂	LP & HP E-Cat b. SCR Engine-out BSCO ₂	Conventional Engine-out BSCO ₂	LP & HP E-Cat b. DOC Tailpipe BSCO ₂	LP & HP E-Cat b. SCR Tailpipe BSCO ₂	Conventional Tailpipe BSCO ₂
WHTC Cold	802 g/kWh	802 g/kWh	735 g/kWh	808 g/kWh	807 g/kWh	740 g/kWh
WHTC Hot	791 g/kWh	791 g/kWh	724 g/kWh	797 g/kWh	797 g/kWh	730 g/kWh

The FTP total CO₂ results are given in the following table.

Table 3.4.4.2.3 : LP-EGR with E-Cat b. DOC and b. SCR FTP CO₂ results.

Result	Only LP E-Cat b. DOC Engine-out BSCO ₂	Only LP E-Cat b. SCR Engine-out BSCO ₂	Conventional Engine-out BSCO ₂	Only LP E-Cat b. DOC Tailpipe BSCO ₂	Only LP E-Cat b. SCR Tailpipe BSCO ₂	Conventional Tailpipe BSCO ₂
FTP Cold	681 g/bhp-hr	682 g/bhp-hr	561 g/bhp-hr	687 g/bhp-hr	687 g/bhp-hr	565 g/bhp-hr
FTP Hot	670 g/bhp-hr	671 g/bhp-hr	549 g/bhp-hr	675 g/bhp-hr	675 g/bhp-hr	553 g/bhp-hr

Table 3.4.4.2.4 : LP&HP-EGR with E-Cat b. DOC and b. SCR FTP CO₂ results.

Result	LP & HP E-Cat b. DOC Engine-out BSCO ₂	LP & HP E-Cat b. SCR Engine-out BSCO ₂	Conventional Engine-out BSCO ₂	LP & HP E-Cat b. DOC Tailpipe BSCO ₂	LP & HP E-Cat b. SCR Tailpipe BSCO ₂	Conventional Tailpipe BSCO ₂
FTP Cold	624 g/kWh	624 g/kWh	562 g/kWh	628 g/kWh	627 g/kWh	565 g/kWh
FTP Hot	610 g/kWh	610 g/kWh	550 g/kWh	614 g/kWh	613 g/kWh	553 g/kWh

The result shows that the implementation of the EGR pump and E-Cat with different combinations makes the system worse for CO₂ reduction like fuel consumption.

3.4.4.3 NO_x engine-out and tailpipe

The total NO_x results are given in the following table.

Table 3.4.4.3.1 : LP-EGR with E-Cat b. DOC and b. SCR WHTC NO_x results.

Result	Only LP E-Cat b. DOC Engine-out BSNO _x	Only LP E-Cat b. SCR Engine-out BSNO _x	Conventional Engine-out BSNO _x	Only LP E-Cat b. DOC Tailpipe BSNO _x	Only LP E-Cat b. SCR Tailpipe BSNO _x	Conventional Tailpipe BSNO _x
WHTC Cold	3.99 g/kWh	3.99 g/kWh	2.86 g/kWh	0.172 g/kWh	0.155 g/kWh	0.75 g/kWh
WHTC Hot	3.97 g/kWh	3.97 g/kWh	2.85 g/kWh	0.033 g/kWh	0.017 g/kWh	0.29 g/kWh

Table 3.4.4.3.2 : LP&HP-EGR with E-Cat b. DOC and b. SCR WHTC NO_x results.

Result	LP & HP E-Cat b. DOC Engine-out BSNO _x	LP & HP E-Cat b. SCR Engine-out BSNO _x	Conventional Engine-out BSNO _x	LP & HP E-Cat b. DOC Tailpipe BSNO _x	LP & HP E-Cat b. SCR Tailpipe BSNO _x	Conventional Tailpipe BSNO _x
WHTC Cold	2.15 g/kWh	2.16 g/kWh	2.86 g/kWh	0.111 g/kWh	0.108 g/kWh	0.75 g/kWh
WHTC Hot	2.14 g/kWh	2.16 g/kWh	2.85 g/kWh	0.020 g/kWh	0.013 g/kWh	0.29 g/kWh

The FTP total NO_x results are given in the following table.

Table 3.4.4.3.3 : LP-EGR with E-Cat b. DOC and b. SCR FTP NO_x results.

Result	Only LP E-Cat b. DOC Engine-out BSNO _x	Only LP E-Cat b. SCR Engine-out BSNO _x	Conventional Engine-out BSNO _x	Only LP E-Cat b. DOC Tailpipe BSNO _x	Only LP E-Cat b. SCR Tailpipe BSNO _x	Conventional Tailpipe BSNO _x
FTP Cold	2.58 g/bhp-hr	2.58 g/bhp-hr	1.63 g/bhp-hr	0.077 g/bhp-hr	0.073 g/bhp-hr	0.32 g/bhp-hr
FTP Hot	2.55 g/bhp-hr	2.56 g/bhp-hr	1.63 g/bhp-hr	0.029 g/bhp-hr	0.023 g/bhp-hr	0.19 g/bhp-hr

Table 3.4.4.3.4 : LP&HP-EGR with E-Cat b. DOC and b. SCR FTP NO_x results.

Result	LP & HP E-Cat b. DOC Engine-out BSNO _x	LP & HP E-Cat b. SCR Engine-out BSNO _x	Conventional Engine-out BSNO _x	LP & HP E-Cat b. DOC Tailpipe BSNO _x	LP & HP E-Cat b. SCR Tailpipe BSNO _x	Conventional Tailpipe BSNO _x
FTP Cold	1.26 g/bhp-hr	1.26 g/bhp-hr	1.63 g/bhp-hr	0.051 g/bhp-hr	0.051 g/bhp-hr	0.32 g/bhp-hr
FTP Hot	1.26 g/bhp-hr	1.26 g/bhp-hr	1.63 g/bhp-hr	0.021 g/bhp-hr	0.018 g/bhp-hr	0.19 g/bhp-hr

Although only LP-EGR usage makes worse the system for engine-out NO_x, the presence of E-Cat in the system provides better tailpipe NO_x result than conventional.

3.4.4.4 Other engine-out and tailpipe emissions

The WHTC cycle results of other emissions for hot and cold tests are given in table 3.4.4.4.1. The NH₃ is evaluated according to its average value.

The FTP cycle results of other emissions for hot and cold tests are given in table 3.4.4.4.2. The NH₃ is evaluated according to its average value.

There is the no different impact of EGR-pump and E-Cat combinations on the system. The engine-out results are similar with only EGR pump results, and the effect of E-Cat is similar with only E-Cat usage. Only it can be mentioned that the E-Cat usage with the EGR pump reduced the NH₃ slip at the tailpipe within current regulation limits.

Table 3.4.4.4.1 : EGR pump with E-Cat b. DOC and b. SCR WHTC other emissions cycles results.

Result	CO g/kWh	THC g/kWh	NMHC g/kWh	PM g/kWh	N ₂ O g/kWh	NH ₃ ppm
Only LP E-Cat b. DOC WHTC Cold EO	1.32	0.28	0.28	0.311	0	0
Only LP E-Cat b. SCR WHTC Cold EO	1.32	0.28	0.28	0.309	0	0
LP & HP E-Cat b. DOC WHTC Cold EO	2.02	0.27	0.27	0.421	0	0
LP & HP E-Cat b. SCR WHTC Cold EO	1.99	0.27	0.27	0.415	0	0
Conventional WHTC Cold EO	1.93	0.27	0.27	0.493	0	0
Only LP E-Cat b. DOC WHTC Cold TP	0.06	0.008	0.008	0.008	0.22	10.8
Only LP E-Cat b. SCR WHTC Cold TP	0.13	0.017	0.017	0.007	0.22	12.4
LP & HP E-Cat b. DOC WHTC Cold TP	0.22	0.011	0.011	0.009	0.162	2.2
LP & HP E-Cat b. SCR WHTC Cold TP	0.54	0.032	0.032	0.008	0.162	2.8
Conventional WHTC Cold TP	0.56	0.035	0.035	0.009	0.172	0.18
Only LP E-Cat b. DOC WHTC Hot EO	1.15	0.29	0.29	0.272	0	0
Only LP E-Cat b. SCR WHTC Hot EO	1.15	0.29	0.29	0.270	0	0
LP & HP E-Cat b. DOC WHTC Hot EO	1.64	0.28	0.28	0.418	0	0
LP & HP E-Cat b. SCR WHTC Hot EO	1.61	0.28	0.28	0.413	0	0
Conventional WHTC Hot EO	1.56	0.28	0.28	0.499	0	0
Only LP E-Cat b. DOC WHTC Hot TP	0	0	0	0.007	0.29	9.8
Only LP E-Cat b. SCR WHTC Hot TP	0.001	0	0	0.007	0.31	12
LP & HP E-Cat b. DOC WHTC Hot TP	0.013	0	0	0.009	0.21	5.6
LP & HP E-Cat b. SCR WHTC Hot TP	0.027	0	0	0.009	0.22	8.3
Conventional WHTC Hot TP	0.021	0	0	0.01	0.21	0.61

Table 3.4.4.2 : EGR pump with E-Cat b. DOC and b. SCR FTP other emissions cycles results.

Result	CO g/bhp-hr	THC g/bhp-hr	NMHC g/bhp-hr	PM g/bhp-hr	N ₂ O g/bhp-hr	NH ₃ ppm
Only LP E-Cat b. DOC FTP Cold EO	1.50	0.28	0.28	0.367	0	0
Only LP E-Cat b. SCR FTP Cold EO	1.50	0.28	0.28	0.368	0	0
LP & HP E-Cat b. DOC FTP Cold EO	1.59	0.28	0.28	0.338	0	0
LP & HP E-Cat b. SCR FTP Cold EO	1.59	0.28	0.28	0.336	0	0
Conventional FTP Cold EO	1.59	0.29	0.29	0.379	0	0
Only LP E-Cat b. DOC FTP Cold TP	0.10	0.006	0.006	0.009	0.172	1.61
Only LP E-Cat b. SCR FTP Cold TP	0.17	0.015	0.015	0.009	0.181	1.84
LP & HP E-Cat b. DOC FTP Cold TP	0.29	0.010	0.010	0.007	0.127	0.26
LP & HP E-Cat b. SCR FTP Cold TP	0.55	0.032	0.032	0.007	0.127	0.32
Conventional FTP Cold TP	0.58	0.034	0.034	0.007	0.132	0.02
Only LP E-Cat b. DOC FTP Hot EO	1.25	0.29	0.29	0.331	0	0
Only LP E-Cat b. SCR FTP Hot EO	1.25	0.29	0.29	0.329	0	0
LP & HP E-Cat b. DOC FTP Hot EO	1.23	0.29	0.29	0.357	0	0
LP & HP E-Cat b. SCR FTP Hot EO	1.22	0.29	0.29	0.353	0	0
Conventional FTP Hot EO	1.23	0.29	0.29	0.403	0	0
Only LP E-Cat b. DOC FTP Hot TP	0	0	0	0.009	0.22	5.9
Only LP E-Cat b. SCR FTP Hot TP	0.001	0	0	0.009	0.23	7.1
LP & HP E-Cat b. DOC FTP Hot TP	0.016	0	0	0.008	0.15	0.54
LP & HP E-Cat b. SCR FTP Hot TP	0.036	0	0	0.008	0.16	0.85
Conventional FTP Hot TP	0.033	0	0	0.008	0.15	0.06

3.4.4.5 EAS component temperatures

Because of the effect of components alone on EAS components shown before, only LP-EGR and LP-EGR with E-Cat are compared to observe the impact of the combination on thermal management. Black and blue lines represent the LP-EGR and E-Cat with before DOC and before SCR, the red lines represent the only LP-EGR and green lines show the conventional system in the following figure.

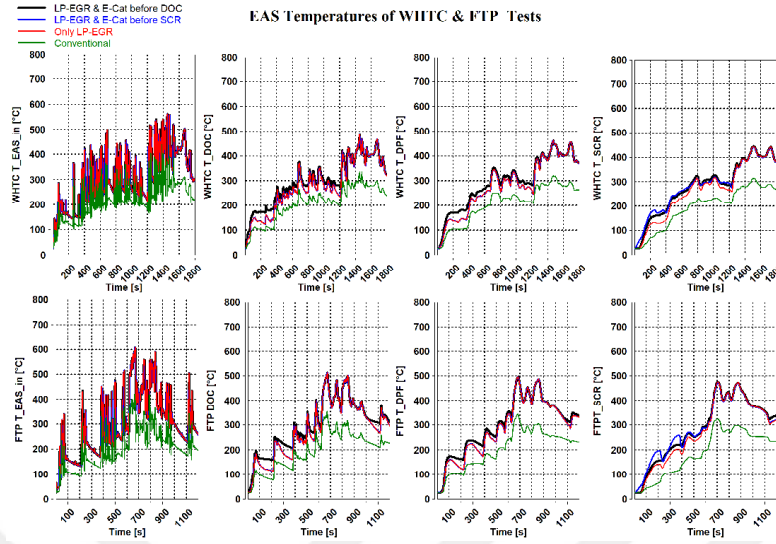


Figure 3.4.4.5.1 : EGR pump and E-Cat EAS component temperatures.

In addition to temperature increases of the LP-EGR in exhaust gas and E-Cat before components, the combinations of those two electrified components provide the system much more heat source. Also, the temperature range is still under the dangerous temperature level for components. For example, the DPF temperature does not reach up to 650 °C which can cause DPF crack. Finally, this higher temperature range obviously increases the catalyst aging; however, it can be tolerated by new catalyst materials, and more efficient catalyst operation can be enabled.

3.4.5 E-Turbo and EGR pump model

Here again, only the cycle results of the simulations are given. There are two cases for this combination: E-Turbo with LP-EGR and E-Turbo with LP&HP-EGR.

3.4.5.1 Fuel consumption

The total bsfc, amount of fuel injected, and total work are given in the following table.

Table 3.4.5.1.1 : E-Turbo with EGR pump WHTC bsfc results.

Result	E-Turbo & LP WHTC Cold	E-Turbo & LP-HP WHTC Cold	Conventional WHTC Cold	E-Turbo & LP WHTC Hot	E-Turbo & LP-HP WHTC Hot	Conventional WHTC Hot
Total Work	33.41 kWh	33.52 kWh	32.33 kWh	33.44 kWh	33.52 kWh	32.31 kWh
Total Fuel	7195 g	6785 g	6833 g	7105 g	6674 g	6724 g
Total BSFC	215 g/kWh	202 g/kWh	211 g/kWh	212 g/kWh	199 g/kWh	208 g/kWh

The FTP total fuel consumption results are given in the following table.

Table 3.4.5.1.2 : E-Turbo with EGR pump FTP bsfc results.

Result	E-Turbo & LP FTP Cold	E-Turbo & LP-HP FTP Cold	Conventional FTP Cold	E-Turbo & LP FTP Hot	E-Turbo & LP-HP FTP Hot	Conventional FTP Hot
Total Work	30.69 bhp-hr	30.81 bhp-hr	29.76 bhp-hr	30.80 bhp-hr	30.96 bhp-hr	29.89 bhp-hr
Total Fuel	5193 g	4847 g	4812 g	5114 g	4763 g	4725 g
Total BSFC	169 g/bhp-hr	157 g/bhp-hr	162 g/bhp-hr	166 g/bhp-hr	153 g/bhp-hr	158 g/bhp-hr

When these results are compared with the only LP-EGR case, it is clear that E-Turbo is much compatible to use with LP-EGR than the conventional turbocharger. However, the system needs proper compressor/turbine selection for better results. On the contrary, E-Turbo with LP&HP EGR combination provides ~4% for WHTC and ~3% for FTP bsfc gain.

3.4.5.2 CO₂ engine-out and tailpipe

The total CO₂ results are given in the following table.

Table 3.4.5.2.1 : E-Turbo with EGR pump WHTC CO₂ results.

Result	E-Turbo & LP Engine-out BSCO ₂	E-Turbo & LP-HP Engine-out BSCO ₂	Conventional Engine-out BSCO ₂	E-Turbo & LP Tailpipe BSCO ₂	E-Turbo & LP-HP Tailpipe BSCO ₂	Conventional Tailpipe BSCO ₂
WHTC Cold	793 g/kWh	738 g/kWh	735 g/kWh	797 g/kWh	741 g/kWh	740 g/kWh
WHTC Hot	782 g/kWh	720 g/kWh	724 g/kWh	786 g/kWh	724 g/kWh	730 g/kWh

The FTP total CO₂ results are given in the following table.

Table 3.4.5.2.2 : E-Turbo with EGR pump FTP CO₂ results.

Result	E-Turbo & LP Engine-out BSCO ₂	E-Turbo & LP-HP Engine-out BSCO ₂	Conventional Engine-out BSCO ₂	E-Turbo & LP Tailpipe BSCO ₂	E-Turbo & LP-HP Tailpipe BSCO ₂	Conventional Tailpipe BSCO ₂
FTP Cold	594 g/bhp-hr	553 g/bhp-hr	561 g/bhp-hr	598 g/bhp-hr	555 g/bhp-hr	565 g/bhp-hr
FTP Hot	583 g/bhp-hr	541 g/bhp-hr	549 g/bhp-hr	587 g/bhp-hr	544 g/bhp-hr	553 g/bhp-hr

Like fuel consumption, LP-EGR makes the system worse than the conventional model. However, the combination of E-Turbo with LP&HP-EGR provides CO₂ reduction.

3.4.5.3 NO_x engine-out and tailpipe

The total NO_x results are given in the following table.

Table 3.4.5.3.1 : E-Turbo with EGR pump WHTC NO_x results.

Result	E-Turbo & LP Engine-out BSNO _x	E-Turbo & LP-HP Engine-out BSNO _x	Conventional Engine-out BSNO _x	E-Turbo & LP Tailpipe BSNO _x	E-Turbo & LP- HP Tailpipe BSNO _x	Conventional Tailpipe BSNO _x
WHTC Cold	6.82 g/kWh	3.25 g/kWh	2.86 g/kWh	1.50 g/kWh	1.30 g/kWh	0.75 g/kWh
WHTC Hot	6.72 g/kWh	3.29 g/kWh	2.85 g/kWh	0.99 g/kWh	1.15 g/kWh	0.29 g/kWh

The FTP total NO_x results are given in the following table.

Table 3.4.5.3.2 : E-Turbo with EGR pump FTP NO_x results.

Result	E-Turbo & LP Engine-out BSNO _x	E-Turbo & LP-HP Engine-out BSNO _x	Conventional Engine-out BSNO _x	E-Turbo & LP Tailpipe BSNO _x	E-Turbo & LP- HP Tailpipe BSNO _x	Conventional Tailpipe BSNO _x
FTP Cold	4.70 g/bhp-hr	1.98 g/bhp-hr	1.63 g/bhp-hr	0.71 g/bhp-hr	0.46 g/bhp-hr	0.32 g/bhp-hr
FTP Hot	4.63 g/bhp-hr	1.96 g/bhp-hr	1.63 g/bhp-hr	0.55 g/bhp-hr	0.41 g/bhp-hr	0.19 g/bhp-hr

The application of the E-Turbo and EGR pump with different combinations makes the system the worst case for engine-out and tailpipe NO_x among all cases.

3.4.5.4 Other engine-out and tailpipe emissions

The WHTC cycle results of other emissions for hot and cold tests are given in table 3.4.5.4.1. The NH₃ is evaluated according to its average value.

The FTP cycle results of other emissions for hot and cold tests are given in table 3.4.5.4.2. The NH₃ is evaluated according to its average value.

Not only E-Turbo and LP-EGR combination but also E-Turbo and LP&HP-EGR combination give better results than the conventional system for other pollutant emissions. As expected, the E-Turbo and LP-EGR combination provides the best result due to the lower EGR rate in the system.

Table 3.4.5.4.1 : E-Turbo with EGR pump WHTC other emissions cycles results.

Result	CO	THC	NMHC	PM	N ₂ O	NH ₃
	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	ppm
E-Turbo & LP WHTC Cold EO	0.49	0.30	0.30	0.074	0	0
E-Turbo & LP-HP WHTC Cold EO	0.88	0.29	0.29	0.149	0	0
Conventional WHTC Cold EO	1.93	0.27	0.27	0.493	0	0
E-Turbo & LP WHTC Cold TP	0.06	0.018	0.018	0.002	0.38	0.93
E-Turbo & LP-HP WHTC Cold TP	0.12	0.031	0.031	0.003	0.14	0.20
Conventional WHTC Cold TP	0.56	0.035	0.035	0.009	0.17	0.18
E-Turbo & LP WHTC Hot EO	0.40	0.31	0.31	0.06	0	0
E-Turbo & LP-HP WHTC Hot EO	0.746	0.29	0.29	0.147	0	0
Conventional WHTC Hot EO	1.56	0.28	0.28	0.499	0	0
E-Turbo & LP WHTC Hot TP	0.01	0.006	0.06	0.001	0.42	1.29
E-Turbo & LP-HP WHTC Hot TP	0.023	0.011	0.011	0.003	0.15	0.16
Conventional WHTC Hot TP	0.021	0	0	0.01	0.21	0.61

Table 3.4.5.4.2 : E-Turbo with EGR pump FTP other emissions cycles results.

Result	CO	THC	NMHC	PM	N ₂ O	NH ₃
	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr	ppm
E-Turbo & LP FTP Cold EO	0.57	0.31	0.31	0.086	0	0
E-Turbo & LP-HP FTP Cold EO	0.85	0.28	0.28	0.143	0	0
Conventional FTP Cold EO	1.59	0.29	0.29	0.379	0	0
E-Turbo & LP FTP Cold TP	0.04	0.017	0.017	0.002	0.355	0.72
E-Turbo & LP-HP FTP Cold TP	0.12	0.034	0.034	0.003	0.147	0.06
Conventional FTP Cold TP	0.58	0.034	0.034	0.007	0.132	0.02
E-Turbo & LP FTP Hot EO	0.46	0.32	0.32	0.070	0	0
E-Turbo & LP-HP FTP Hot EO	0.73	0.29	0.29	0.163	0	0
Conventional FTP Hot EO	1.23	0.29	0.29	0.403	0	0
E-Turbo & LP FTP Hot TP	0.008	0.006	0.006	0.002	0.37	0.81
E-Turbo & LP-HP FTP Hot TP	0.032	0.015	0.015	0.003	0.15	0.07
Conventional FTP Hot TP	0.033	0	0	0.008	0.15	0.06

3.4.5.5 EAS component temperatures

The EAS component temperatures of the E-Turbo and EGR pump combination model are shown in the figure below.

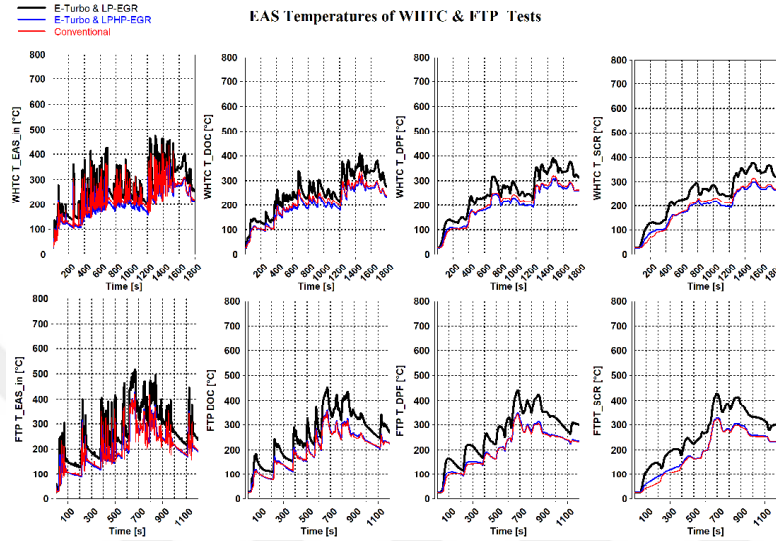


Figure 3.4.5.5.1 : E-Turbo and EGR pump EAS component temperatures.

The thermal result of the only EGR pump model repeats for this case as expected because there is not any other heating source in the system.

3.4.6 E-Turbo and E-Cat model

Here again, only the cycle results of the simulations are given. There are two cases for this combination: E-Turbo with E-Cat before DOC and E-Turbo with E-Cat before SCR.

3.4.6.1 Fuel consumption

The WHTC total fuel consumption, amount of fuel injected, and total work are given in the table 3.4.6.1.1.

The FTP total fuel consumption results are given in table 3.4.6.1.2.

As expected, there is almost no effect of E-Cat on fuel consumption. Thus, the results are better than the conventional model and they are very similar to only the E-Turbo result.

Table 3.4.6.1.1 : E-Turbo with E-Cat WHTC bsfc results.

Result	E-Turbo E-Cat b. DOC WHTC Cold	E-Turbo E-Cat b. SCR WHTC Cold	Conventional WHTC Cold	E-Turbo E-Cat b. DOC WHTC Hot	E-Turbo E-Cat b. SCR WHTC Hot	Conventional WHTC Hot
Total Work	33.53 kWh	33.3 kWh	32.33 kWh	33.55 kWh	33.55 kWh	32.31 kWh
Total Fuel	6757 g	6757 g	6833 g	6648 g	6648 g	6724 g
Total BSFC	201 g/kWh	201 g/kWh	211 g/kWh	198 g/kWh	198 g/kWh	208 g/kWh

Table 3.4.6.1.2 : E-Turbo with E-Cat FTP bsfc results.

Result	E-Turbo E-Cat b. DOC FTP Cold	E-Turbo E-Cat b. SCR FTP Cold	Conventional FTP Cold	E-Turbo E-Cat b. DOC FTP Hot	E-Turbo E-Cat b. SCR FTP Hot	Conventional FTP Hot
Total Work	30.85 bhp-hr	30.85 bhp-hr	29.76 bhp-hr	31.01 bhp-hr	31.01 bhp-hr	29.89 bhp-hr
Total Fuel	4800 g	4800 g	4812 g	4716 g	4716 g	4725 g
Total BSFC	155 g/bhp-hr	155 g/bhp-hr	162 g/bhp-hr	152 g/bhp-hr	152 g/bhp-hr	158 g/bhp-hr

3.4.6.2 CO₂ engine-out and tailpipe

The total CO₂ results are given in the following table.

Table 3.4.6.2.1 : E-Turbo with E-Cat WHTC CO₂ results.

Result	E-Turbo E-Cat b. DOC Engine-out BSCO ₂	E-Turbo E-Cat b. SCR Engine-out BSCO ₂	Conventional Engine-out BSCO ₂	E-Turbo E-Cat b. DOC Tailpipe BSCO ₂	E-Turbo E-Cat b. SCR Tailpipe BSCO ₂	Conventional Tailpipe BSCO ₂
WHTC Cold	674 g/kWh	674 g/kWh	735 g/kWh	678 g/kWh	678 g/kWh	740 g/kWh
WHTC Hot	663 g/kWh	663 g/kWh	724 g/kWh	667 g/kWh	667 g/kWh	730 g/kWh

The FTP total CO₂ results are given in the following table.

Table 3.4.6.2.2 : E-Turbo with E-Cat FTP CO₂ results.

Result	E-Turbo E-Cat b. DOC Engine-out BSCO ₂	E-Turbo E-Cat b. SCR Engine-out BSCO ₂	Conventional Engine-out BSCO ₂	E-Turbo E-Cat b. DOC Tailpipe BSCO ₂	E-Turbo E-Cat b. SCR Tailpipe BSCO ₂	Conventional Tailpipe BSCO ₂
FTP Cold	521 g/bhp-hr	521 g/bhp-hr	561 g/bhp-hr	524 g/bhp-hr	524 g/bhp-hr	565 g/bhp-hr
FTP Hot	510 g/bhp-hr	510 g/bhp-hr	549 g/bhp-hr	513 g/bhp-hr	513 g/bhp-hr	553 g/bhp-hr

The system is better than the conventional model for CO₂ reduction like only E-Turbo.

3.4.6.3 NO_x engine-out and tailpipe

The total NO_x results of WHTC and FTP are given in the following tables.

Table 3.4.6.3.1 : E-Turbo with E-Cat WHTC NO_x results.

Result	E-Turbo	E-Turbo	Conventional	E-Turbo	E-Turbo	Conventional
	E-Cat b. DOC	E-Cat b. SCR	Engine-out	E-Cat b. DOC	E-Cat b. SCR	Tailpipe
	Engine-out BSNO _x	Engine-out BSNO _x	BSNO _x	Tailpipe BSNO _x	Tailpipe BSNO _x	BSNO _x
WHTC Cold	3.84 g/kWh	3.85 g/kWh	2.86 g/kWh	0.191 g/kWh	0.189 g/kWh	0.75 g/kWh
WHTC Hot	3.79 g/kWh	3.80 g/kWh	2.85 g/kWh	0.145 g/kWh	0.133 g/kWh	0.29 g/kWh

Table 3.4.6.3.2 : E-Turbo with E-Cat FTP NO_x results.

Result	E-Turbo	E-Turbo	Conventional	E-Turbo	E-Turbo	Conventional
	E-Cat b. DOC	E-Cat b. SCR	Engine-out	E-Cat b. DOC	E-Cat b. SCR	Tailpipe BSNO _x
	Engine-out BSNO _x	Engine-out BSNO _x	BSNO _x	Tailpipe BSNO _x	Tailpipe BSNO _x	Tailpipe BSNO _x
FTP Cold	1.94 g/bhp-hr	1.94 g/bhp-hr	1.63 g/bhp-hr	0.095 g/bhp-hr	0.092 g/bhp-hr	0.32 g/bhp-hr
FTP Hot	1.94 g/bhp-hr	1.94 g/bhp-hr	1.63 g/bhp-hr	0.083 g/bhp-hr	0.081 g/bhp-hr	0.19 g/bhp-hr

Although the E-Turbo results in higher engine-out NO_x, the E-Cat can compensate for it and provide better NO_x reduction than the conventional model. The E-Cat position before SCR gives a slightly better result.

3.4.6.4 Other engine-out and tailpipe emissions

The WHTC cycle results of other emissions for hot and cold tests are given in table 3.4.6.4.1. The NH₃ is evaluated according to its average value.

The FTP cycle results of other emissions for hot and cold tests are given in table 3.4.6.4.2. The NH₃ is evaluated according to its average value.

For all pollutant emissions, the E-Turbo and E-Cat combination gives lower results than the conventional model. Here, one exception is the NH₃ slip. The NH₃ slip increases because more urea is injected into the system to convert a higher amount of engine-out NO_x.

Table 3.4.6.4.1 : E-Turbo with E-Cat WHTC other emissions cycles results.

Result	CO	THC	NMHC	PM	N ₂ O	NH ₃
	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	ppm
E-Turbo E-Cat b. DOC WHTC Cold EO	0.85	0.28	0.28	0.138	0	0
E-Turbo E-Cat b. SCR WHTC Cold EO	0.85	0.28	0.28	0.138	0	0
Conventional WHTC Cold EO	1.93	0.27	0.27	0.493	0	0
E-Turbo E-Cat b. DOC WHTC Cold TP	0.04	0.013	0.013	0.003	0.232	15.2
E-Turbo E-Cat b. SCR WHTC Cold TP	0.13	0.033	0.033	0.003	0.215	17.6
Conventional WHTC Cold TP	0.56	0.035	0.035	0.009	0.172	0.18
E-Turbo E-Cat b. DOC WHTC Hot EO	0.73	0.29	0.29	0.138	0	0
E-Turbo E-Cat b. SCR WHTC Hot EO	0.73	0.29	0.29	0.138	0	0
Conventional WHTC Hot EO	1.56	0.28	0.28	0.499	0	0
E-Turbo E-Cat b. DOC WHTC Hot TP	0.006	0.004	0.004	0.003	0.253	16.1
E-Turbo E-Cat b. SCR WHTC Hot TP	0.024	0.012	0.012	0.003	0.234	19.5
Conventional WHTC Hot TP	0.021	0	0	0.01	0.21	0.61

Table 3.4.6.4.2 : E-Turbo with E-Cat FTP other emissions cycles results.

Result	CO	THC	NMHC	PM	N ₂ O	NH ₃
	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr	ppm
E-Turbo E-Cat b. DOC FTP Cold EO	0.89	0.29	0.29	0.147	0	0
E-Turbo E-Cat b. SCR FTP Cold EO	0.89	0.29	0.29	0.147	0	0
Conventional FTP Cold EO	1.59	0.28	0.28	0.379	0	0
E-Turbo E-Cat b. DOC FTP Cold TP	0.06	0.012	0.012	0.003	0.174	8.9
E-Turbo E-Cat b. SCR FTP Cold TP	0.13	0.036	0.036	0.003	0.168	9.6
Conventional FTP Cold TP	0.58	0.034	0.034	0.007	0.132	0.02
E-Turbo E-Cat b. DOC FTP Hot EO	0.76	0.29	0.29	0.165	0	0
E-Turbo E-Cat b. SCR FTP Hot EO	0.76	0.29	0.29	0.164	0	0
Conventional FTP Hot EO	1.23	0.29	0.29	0.403	0	0
E-Turbo E-Cat b. DOC FTP Hot TP	0.016	0.005	0.005	0.004	0.18	9.4
E-Turbo E-Cat b. SCR FTP Hot TP	0.031	0.015	0.015	0.004	0.17	10.8
Conventional FTP Hot TP	0.033	0	0	0.008	0.15	0.06

3.4.6.5 EAS component temperatures

The EAS component temperatures of the E-Turbo and EGR pump combination model are shown in the following figure.

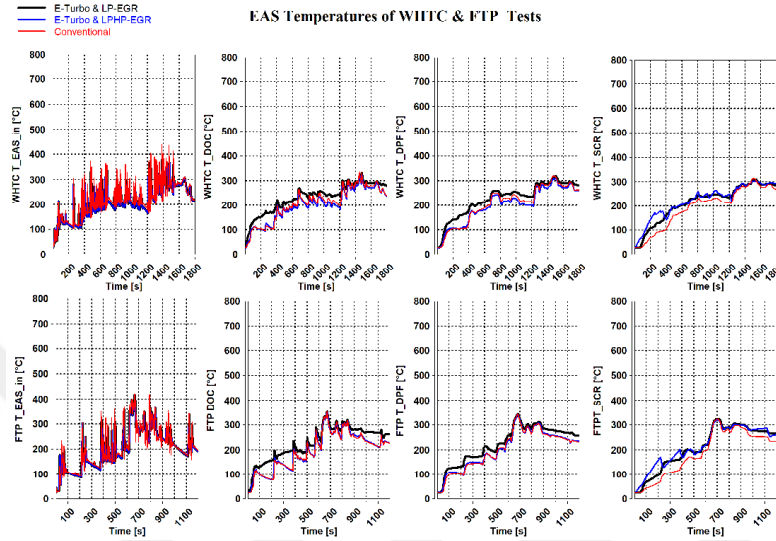


Figure 3.4.6.5.1 : E-Turbo with E-Cat EAS component temperatures.

The thermal characteristics of the E-Turbo and E-Cat combination model are the same as the E-Cat only model because E-Turbo does not have an impact on exhaust temperature.

3.4.7 E-Turbo, EGR pump and E-Cat model

Here, the cycle results of all electrified component combinations are given. There are four different cases: E-Turbo, LP-EGR, and E-Cat before DOC, E-Turbo, LP-EGR, and E-Cat before SCR, E-Turbo, LP&HP-EGR, and E-Cat before DOC, and LP&HP-EGR, and E-Cat before SCR.

3.4.7.1 Fuel consumption

The WHTC total fuel consumption, amount of fuel injected, and total work are given in tables 3.4.7.1.1 and 3.4.7.1.2.

The FTP total fuel consumption results are given in tables 3.4.7.1.3 and 3.4.7.1.4.

The impact of LP-EGR is shown here. It makes all combinations worse than the conventional system. However, the system with LP&HP-EGR gives better results.

Table 3.4.7.1.1 : E-Turbo, LP-EGR, and E-Cat b. DOC and b. SCR WHTC bsfc results.

Result	Only LP E-Cat b. DOC WHTC Cold	Only LP E-Cat b. SCR WHTC Cold	Conventional WHTC Cold	Only LP E-Cat b. DOC WHTC Hot	Only LP E-Cat b. SCR WHTC Hot	Conventional WHTC Hot
Total Work	33.41 kWh	33.41 kWh	32.33 kWh	33.44 kWh	33.44 kWh	32.31 kWh
Total Fuel	7195 g	7195 g	6833 g	7105 g	7105 g	6724 g
Total BSFC	215 g/kWh	215 g/kWh	211 g/kWh	212 g/kWh	212 g/kWh	208 g/kWh

Table 3.4.7.1.2 : E-Turbo, LP&HP-EGR, and E-Cat b. DOC and b. SCR WHTC bsfc results.

Result	LP & HP E-Cat b. DOC WHTC Cold	LP & HP E-Cat b. SCR WHTC Cold	Conventional WHTC Cold	LP & HP E-Cat b. DOC WHTC Hot	LP & HP E-Cat b. SCR WHTC Hot	Conventional WHTC Hot
Total Work	33.52 kWh	33.52 kWh	32.33 kWh	33.52 kWh	33.52 kWh	32.31 kWh
Total Fuel	6785 g	6785 g	6833 g	6674 g	6674 g	6724 g
Total BSFC	202 g/kWh	202 g/kWh	211 g/kWh	199 g/kWh	199 g/kWh	208 g/kWh

Table 3.4.7.1.3 : E-Turbo, LP-EGR, and E-Cat b. DOC and b. SCR FTP bsfc results.

Result	Only LP E-Cat b. DOC FTP Cold	Only LP E-Cat b. SCR FTP Cold	Conventional FTP Cold	Only LP E-Cat b. DOC FTP Hot	Only LP E-Cat b. SCR FTP Hot	Conventional FTP Hot
Total Work	30.69 bhp-hr	30.69 bhp-hr	29.76 bhp-hr	30.80 bhp-hr	30.80 bhp-hr	29.89 bhp-hr
Total Fuel	5193 g	5193 g	4812 g	5114 g	5114 g	4725 g
Total BSFC	169 g/bhp-hr	169 g/bhp-hr	162 g/bhp-hr	166 g/bhp-hr	166 g/bhp-hr	158 g/bhp-hr

Table 3.4.7.1.4 : E-Turbo, LP&HP-EGR, and E-Cat b. DOC and b. SCR FTP bsfc results.

Result	LP & HP E-Cat b. DOC FTP Cold	LP & HP E-Cat b. SCR FTP Cold	Conventional FTP Cold	LP & HP E-Cat b. DOC FTP Hot	LP & HP E-Cat b. SCR FTP Hot	Conventional FTP Hot
Total Work	30.81 bhp-hr	30.81 bhp-hr	29.76 bhp-hr	30.96 bhp-hr	30.96 bhp-hr	29.89 bhp-hr
Total Fuel	4847 g	4847 g	4812 g	4762 g	4762 g	4725 g
Total BSFC	157 g/bhp-hr	157 g/bhp-hr	162 g/bhp-hr	153 g/bhp-hr	153 g/bhp-hr	158 g/bhp-hr

3.4.7.2 CO₂ engine-out and tailpipe

The total CO₂ results are given in the following tables.

Table 3.4.7.2.1 : E-Turbo, LP-EGR, and E-Cat b. DOC and b. SCR WHTC CO₂ results.

Result	Only LP	Only LP	Conventional	Only LP	Only LP	Conventional
	E-Cat b. DOC	E-Cat b. SCR	Engine-out	E-Cat b. DOC	E-Cat b. SCR	Tailpipe
	Engine-out BSCO ₂	Engine-out BSCO ₂	BSCO ₂	Tailpipe BSCO ₂	Tailpipe BSCO ₂	BSCO ₂
WHTC Cold	792 g/kWh	792 g/kWh	735 g/kWh	797 g/kWh	797 g/kWh	740 g/kWh
WHTC Hot	781 g/kWh	781 g/kWh	724 g/kWh	786 g/kWh	786 g/kWh	730 g/kWh

Table 3.4.7.2.2 : E-Turbo, LP&HP-EGR, and E-Cat b. DOC and b. SCR WHTC CO₂ results.

Result	LP & HP	LP & HP	Conventional	LP & HP	LP & HP	Conventional
	E-Cat b. DOC	E-Cat b. SCR	Engine-out	E-Cat b. DOC	E-Cat b. SCR	Tailpipe
	Engine-out BSCO ₂	Engine-out BSCO ₂	BSCO ₂	Tailpipe BSCO ₂	Tailpipe BSCO ₂	BSCO ₂
WHTC Cold	738 g/kWh	738 g/kWh	735 g/kWh	742 g/kWh	742 g/kWh	740 g/kWh
WHTC Hot	720 g/kWh	720 g/kWh	724 g/kWh	724 g/kWh	724 g/kWh	730 g/kWh

The FTP total CO₂ results are given in the following tables.

Table 3.4.7.2.3 : E-Turbo, LP-EGR, and E-Cat b. DOC and b. SCR FTP CO₂ results.

Result	Only LP	Only LP	Conventional	Only LP	Only LP	Conventional
	E-Cat b. DOC	E-Cat b. SCR	Engine-out	E-Cat b. DOC	E-Cat b. SCR	Tailpipe
	Engine-out BSCO ₂	Engine-out BSCO ₂	BSCO ₂	Tailpipe BSCO ₂	Tailpipe BSCO ₂	BSCO ₂
FTP Cold	594 g/bhp-hr	594 g/bhp-hr	561 g/bhp-hr	598 g/bhp-hr	598 g/bhp-hr	565 g/bhp-hr
FTP Hot	582 g/bhp-hr	582 g/bhp-hr	549 g/bhp-hr	587 g/bhp-hr	587 g/bhp-hr	553 g/bhp-hr

Table 3.4.7.2.4 : E-Turbo, LP&HP-EGR, and E-Cat b. DOC and b. SCR FTP CO₂ results.

Result	LP & HP	LP & HP	Conventional	LP & HP	LP & HP	Conventional
	E-Cat b. DOC	E-Cat b. SCR	Engine-out	E-Cat b. DOC	E-Cat b. SCR	Tailpipe
	Engine-out BSCO ₂	Engine-out BSCO ₂	BSCO ₂	Tailpipe BSCO ₂	Tailpipe BSCO ₂	BSCO ₂
FTP Cold	553 g/kWh	553 g/kWh	562 g/kWh	556 g/kWh	556 g/kWh	565 g/kWh
FTP Hot	541 g/kWh	541 g/kWh	550 g/kWh	544 g/kWh	544 g/kWh	553 g/kWh

Similar results with fuel consumption are achieved.

3.4.7.3 NO_x engine-out and tailpipe

The total NO_x results are given in the following tables.

Table 3.4.7.3.1 : E-Turbo, LP-EGR, and E-Cat b. DOC and b. SCR WHTC NO_x results.

Result	Only LP	Only LP	Conventional	Only LP	Only LP	Conventional
	E-Cat b. DOC	E-Cat b. SCR	Engine-out	E-Cat b. DOC	E-Cat b. SCR	Tailpipe
	Engine-out BSNO _x	Engine-out BSNO _x	BSNO _x	Tailpipe BSNO _x	Tailpipe BSNO _x	BSNO _x
WHTC Cold	6.82 g/kWh	6.82 g/kWh	2.86 g/kWh	0.195 g/kWh	0.213 g/kWh	0.75 g/kWh
WHTC Hot	6.71 g/kWh	6.71 g/kWh	2.85 g/kWh	0.132 g/kWh	0.137 g/kWh	0.29 g/kWh

Table 3.4.7.3.2 : E-Turbo, LP&HP-EGR, and E-Cat b. DOC and b. SCR WHTC NO_x results.

Result	LP & HP	LP & HP	Conventional	LP & HP	LP & HP	Conventional
	E-Cat b. DOC	E-Cat b. SCR	Engine-out	E-Cat b. DOC	E-Cat b. SCR	Tailpipe
	Engine-out BSNO _x	Engine-out BSNO _x	BSNO _x	Tailpipe BSNO _x	Tailpipe BSNO _x	BSNO _x
WHTC Cold	3.24 g/kWh	3.24 g/kWh	2.86 g/kWh	0.167 g/kWh	0.166 g/kWh	0.75 g/kWh
WHTC Hot	3.24 g/kWh	3.24 g/kWh	2.85 g/kWh	0.115 g/kWh	0.123 g/kWh	0.29 g/kWh

The FTP total NO_x results are given in the following tables.

Table 3.4.7.3.3 : E-Turbo, LP-EGR, and E-Cat b. DOC and b. SCR FTP NO_x results.

Result	Only LP	Only LP	Conventional	Only LP	Only LP	Conventional
	E-Cat b. DOC	E-Cat b. SCR	Engine-out	E-Cat b. DOC	E-Cat b. SCR	Tailpipe BSNO _x
	Engine-out BSNO _x	Engine-out BSNO _x	BSNO _x	Tailpipe BSNO _x	Tailpipe BSNO _x	
FTP Cold	4.69 g/bhp-hr	4.69 g/bhp-hr	1.63 g/bhp-hr	0.135 g/bhp-hr	0.134 g/bhp-hr	0.32 g/bhp-hr
FTP Hot	4.62 g/bhp-hr	4.62 g/bhp-hr	1.63 g/bhp-hr	0.100 g/bhp-hr	0.105 g/bhp-hr	0.19 g/bhp-hr

Table 3.4.7.3.4 : E-Turbo, LP&HP-EGR, and E-Cat b. DOC and b. SCR FTP NO_x results.

Result	LP & HP	LP & HP	Conventional	LP & HP	LP & HP	Conventional
	E-Cat b. DOC	E-Cat b. SCR	Engine-out	E-Cat b. DOC	E-Cat b. SCR	Tailpipe BSNO _x
	Engine-out BSNO _x	Engine-out BSNO _x	BSNO _x	Tailpipe BSNO _x	Tailpipe BSNO _x	
FTP Cold	1.96 g/bhp-hr	1.96 g/bhp-hr	1.63 g/bhp-hr	0.078 g/bhp-hr	0.081 g/bhp-hr	0.32 g/bhp-hr
FTP Hot	1.96 g/bhp-hr	1.96 g/bhp-hr	1.63 g/bhp-hr	0.054 g/bhp-hr	0.055 g/bhp-hr	0.19 g/bhp-hr

All combinations result better than the conventional system. However, they are not the best results due to the high engine-out NO_x level.

3.4.7.4 Other engine-out and tailpipe emissions

The WHTC cycle results of other emissions for hot and cold tests are given in the following table. The NH₃ is evaluated according to its average value.

Table 3.4.7.4.1 : E-Turbo, EGR pump, and E-Cat b. DOC and b. SCR WHTC other emissions cycles results.

Result	CO g/kWh	THC g/kWh	NMHC g/kWh	PM g/kWh	N ₂ O g/kWh	NH ₃ ppm
Only LP E-Cat b. DOC WHTC Cold EO	0.49	0.29	0.29	0.074	0	0
Only LP E-Cat b. SCR WHTC Cold EO	0.49	0.29	0.29	0.074	0	0
LP & HP E-Cat b. DOC WHTC Cold EO	0.88	0.28	0.28	0.149	0	0
LP & HP E-Cat b. SCR WHTC Cold EO	0.88	0.28	0.28	0.149	0	0
Conventional WHTC Cold EO	1.93	0.28	0.28	0.493	0	0
Only LP E-Cat b. DOC WHTC Cold TP	0.06	0.018	0.018	0.002	0.446	18.1
Only LP E-Cat b. SCR WHTC Cold TP	0.02	0.009	0.009	0.002	0.459	19.4
LP & HP E-Cat b. DOC WHTC Cold TP	0.12	0.031	0.031	0.003	0.18	15.2
LP & HP E-Cat b. SCR WHTC Cold TP	0.04	0.012	0.012	0.003	0.192	16.5
Conventional WHTC Cold TP	0.56	0.035	0.035	0.009	0.172	0.18
Only LP E-Cat b. DOC WHTC Hot EO	0.40	0.31	0.31	0.06	0	0
Only LP E-Cat b. SCR WHTC Hot EO	0.40	0.31	0.31	0.06	0	0
LP & HP E-Cat b. DOC WHTC Hot EO	0.75	0.29	0.29	0.148	0	0
LP & HP E-Cat b. SCR WHTC Hot EO	0.75	0.29	0.29	0.149	0	0
Conventional WHTC Hot EO	1.56	0.28	0.28	0.499	0	0
Only LP E-Cat b. DOC WHTC Hot TP	0.01	0.006	0.006	0.001	0.488	18.3
Only LP E-Cat b. SCR WHTC Hot TP	0.004	0.003	0.003	0.001	0.505	19.8
LP & HP E-Cat b. DOC WHTC Hot TP	0.023	0.011	0.011	0.003	0.203	16.2
LP & HP E-Cat b. SCR WHTC Hot TP	0.005	0.003	0.003	0.003	0.219	17.4
Conventional WHTC Hot TP	0.021	0	0	0.01	0.21	0.61

The FTP cycle results of other emissions for hot and cold tests are given in the following table. The NH₃ is evaluated according to its average value.

Table 3.4.7.4.2 : E-Turbo, EGR pump, and E-Cat b. DOC and b. SCR FTP other emissions cycles results.

Result	CO g/bhp-hr	THC g/bhp-hr	NMHC g/bhp-hr	PM g/bhp-hr	N ₂ O g/bhp-hr	NH ₃ ppm
Only LP E-Cat b. DOC FTP Cold EO	0.57	0.31	0.31	0.086	0	0
Only LP E-Cat b. SCR FTP Cold EO	0.57	0.31	0.31	0.086	0	0
LP & HP E-Cat b. DOC FTP Cold EO	0.85	0.28	0.28	0.143	0	0
LP & HP E-Cat b. SCR FTP Cold EO	0.85	0.28	0.28	0.143	0	0
Conventional FTP Cold EO	1.59	0.29	0.29	0.379	0	0
Only LP E-Cat b. DOC FTP Cold TP	0.04	0.017	0.017	0.002	0.386	9.0
Only LP E-Cat b. SCR FTP Cold TP	0.02	0.007	0.007	0.002	0.389	9.9
LP & HP E-Cat b. DOC FTP Cold TP	0.12	0.034	0.034	0.003	0.170	5.2
LP & HP E-Cat b. SCR FTP Cold TP	0.05	0.012	0.012	0.003	0.178	6.8
Conventional FTP Cold TP	0.58	0.034	0.034	0.007	0.132	0.02
Only LP E-Cat b. DOC FTP Hot EO	0.46	0.32	0.32	0.07	0	0
Only LP E-Cat b. SCR FTP Hot EO	0.46	0.32	0.32	0.07	0	0
LP & HP E-Cat b. DOC FTP Hot EO	0.73	0.29	0.29	0.163	0	0
LP & HP E-Cat b. SCR FTP Hot EO	0.73	0.29	0.29	0.164	0	0
Conventional FTP Hot EO	1.23	0.29	0.29	0.403	0	0
Only LP E-Cat b. DOC FTP Hot TP	0.008	0.006	0.006	0.002	0.409	9.3
Only LP E-Cat b. SCR FTP Hot TP	0.005	0.005	0.005	0.002	0.411	10.6
LP & HP E-Cat b. DOC FTP Hot TP	0.032	0.015	0.015	0.003	0.178	7.5
LP & HP E-Cat b. SCR FTP Hot TP	0.015	0.005	0.005	0.004	0.184	8.7
Conventional FTP Hot TP	0.033	0	0	0.008	0.15	0.06

For all pollutant emissions, the all-component combination gives lower results than the conventional model. Here, one exception is the NH₃ slip. The NH₃ slip increases because more urea is injected into the system to convert a higher amount of engine-out NO_x.

3.4.7.5 EAS component temperatures

The EAS component temperatures of the E-Turbo, EGR pump, and E-Cat combination model are shown in the following figure.

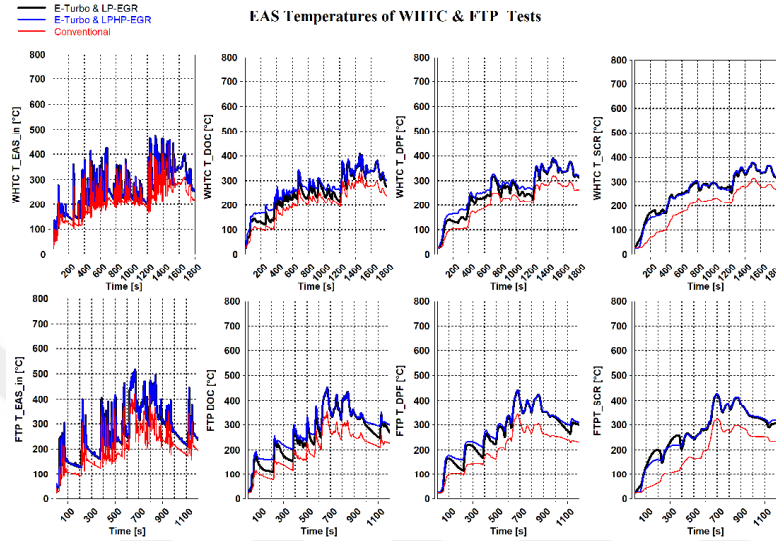


Figure 3.4.7.5.1 : E-Turbo, EGR pump, and E-Cat EAS component temperatures.

The temperature characteristics of the all-component combination are similar to LP-EGR and E-Cat combination because there is not any contribution of E-Turbo to the exhaust gas.

3.4.8 Upcoming legislation comparison

The conventional system is a standard EURO VI benchmark system in which their emission results are below regulation limits. Because the electrified system models generally result in lower emission levels than the conventional system, it is clear that they satisfy the current legislation. Also, the aim of the application of those new technologies is to satisfy upcoming regulations. Therefore, the result of each test case is compared with the next regulations.

3.4.8.1 Europe

The WHTC results of each simulation and two proposals for the next EURO VII limits are given in the following table.

Table 3.4.8.1.1 : Simulation results comparison with EURO VII regulation.

	NO _x	CO	NMOG	PM	N ₂ O	NH ₃
	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	ppm
EU VII HD2 proposal	0.15	1.25	0.075	0.01	0.14	65
EU VII HD2 proposal	0.10	1.25	0.075	0.01	0.14	65
Only E-Turbo	0.716	0.019	0.006	0.004	0.146	0.087
Only E-Cat before DOC	0.025	0.035	0.002	0.010	0.223	3.417
Only E-Cat before SCR	0.021	0.093	0.005	0.010	0.240	5.246
Only LP-EGR	0.373	0.019	0.002	0.007	0.241	12.086
Only LP&HP-EGR	0.354	0.103	0.005	0.009	0.156	1.753
LP-EGR with E-Cat before DOC	0.053	0.009	0.001	0.007	0.280	9.943
LP-EGR with E-Cat before SCR	0.037	0.019	0.002	0.007	0.297	12.057
LP&HP-EGR with E-Cat before DOC	0.033	0.043	0.002	0.009	0.203	5.114
LP&HP-EGR with E-Cat before SCR	0.027	0.100	0.005	0.009	0.212	7.514
E-Turbo with LP-EGR	1.063	0.017	0.008	0.001	0.414	1.239
E-Turbo with LP&HP-EGR	1.171	0.037	0.014	0.003	0.149	0.166
E-Turbo with E-Cat before DOC	0.152	0.011	0.005	0.003	0.250	15.971
E-Turbo with E-Cat before SCR	0.141	0.039	0.015	0.003	0.231	19.229
E-Turbo, LP-EGR with E-Cat before DOC	0.141	0.017	0.008	0.001	0.482	18.271
E-Turbo, LP-EGR with E-Cat before SCR	0.148	0.006	0.004	0.001	0.498	19.743
E-Turbo, LP&HP-EGR with E-Cat before DOC	0.122	0.037	0.014	0.003	0.200	16.057
E-Turbo, LP&HP-EGR with E-Cat before SCR	0.129	0.010	0.004	0.003	0.215	17.271

All cases can satisfy the next European regulation. Another outcome is that new system designs must consider the new N₂O limit. All cases fail for N₂O criteria. The increasing NH₃ limit allows to inject more urea into the system to increase SCR performance, so all cases can satisfy this limit. The most critical part of the systems NO_x control, so the selection of the optimum system is made according to this approach. Combining all components in one layout is not a suitable choice due to the high NO_x tailpipe result caused by the incompatibility of LP-EGR with compressor/turbine couple. E-Cat before SCR with E-Turbo is optimal system selection because it helps both better CO₂

reduction and NO_x reduction despite higher engine-out NO_x level. To sum up, the application of E-Turbo and E-Cat located before SCR steps forth as the optimal system layout for upcoming EURO VII legislation.

3.4.8.2 USA

The FTP results of simulations and upcoming US limits are given in the table below.

Table 3.4.8.2.1 : Simulation results comparison with new US regulation.

	NO _x	CO ₂
	g/bhp-hr	g/bhp-hr
CARB 2021-2023	0.2	513
CARB 2024-2026	0.05	506
CARB 2027 and later	0.02	503
Only E-Turbo	0.330	515
Only E-Cat before DOC	0.027	557
Only E-Cat before SCR	0.023	557
Only LP-EGR	0.211	677
Only LP&HP-EGR	0.176	615
LP-EGR with E-Cat before DOC	0.036	677
LP-EGR with E-Cat before SCR	0.030	677
LP&HP-EGR with E-Cat before DOC	0.025	627
LP&HP-EGR with E-Cat before SCR	0.023	615
E-Turbo with LP-EGR	0.573	589
E-Turbo with LP&HP-EGR	0.417	546
E-Turbo with E-Cat before DOC	0.085	515
E-Turbo with E-Cat before SCR	0.083	515
E-Turbo, LP-EGR with E-Cat before DOC	0.105	589
E-Turbo, LP-EGR with E-Cat before SCR	0.109	589
E-Turbo, LP&HP-EGR with E-Cat before DOC	0.081	546
E-Turbo, LP&HP-EGR with E-Cat before SCR	0.059	546

Because there is information only about the next CO₂ and NO_x limits for upcoming US legislation, the simulations are compared according to CO₂ and NO_x. The important impact of the E-Cat is seen from the comparison. Only E-Cat alone application can satisfy the CARB 2024 limit, but further improvements are necessary to meet the 2027 limit.

As a similar result, the combination of E-Turbo with E-Cat located before SCR becomes the optimal system layout in the consideration of both CO₂ and NO_x. Moreover, it should be discussed that the US regulation is much stricter than Europe. Thus, the same layout cannot satisfy both CO₂ and NO_x limits at the same time; also none of the layouts can satisfy the 2024 CO₂ limit even some of them are very close to the limit while that layout can satisfy European regulation even it is not clear that there will be a CO₂ limit for heavy-duty engine certification. To sum up, the system of E-Turbo and E-Cat located before SCR combination steps forward as an optimum powertrain and aftertreatment layout. It shows its potential to meet upcoming US legislation with further improvements.

3.4.9 Power consumption and energy balance

To investigate whether the generated power over the turbine is sufficient to run other power-consuming components is sufficient or not, power generation and consumption of electric components in layout combinations are evaluated. The evaluation is done only for WHTC cold test. The energy balance is shown in the following table.

Table 3.4.9.1 : Energy balance of different system layouts.

Simulation	Turbine Work kWh	Compressor Work kWh	E-Cat Work kWh	EGR Pump Work kWh	Work Balance kWh
Only E-Turbo	6247	6078	0	0	170
E-Turbo with LP-EGR	4768	6897	0	10.899	-2139
E-Turbo with LP&HP-EGR	6326	6170	0	10.899	145
E-Turbo with E-Cat before DOC	5994	6070	1.9746	0	-77
E-Turbo with E-Cat before SCR	6161	6070	1.9833	0	89
E-Turbo, LP-EGR with E-Cat before DOC	4768	6896	1.3882	10.899	-2140
E-Turbo, LP-EGR with E-Cat before SCR	4763	6897	1.4986	10.899	-2146

The system layouts, except for only the E-Turbo system and E-Turbo with E-Cat position before SCR, are not capable to work without an external power source. The source of this power request will be a crankshaft. The simulations are done without concerning this condition. If it is included, the fuel consumption and CO₂ emission will be higher for those systems. When two layouts which are E-Turbo with E-Cat position before DOC and before SCR, the turbine works much less effective in the case of E-Cat before DOC because it heats up the exhaust gas not only at the inlet of EAS but also at the outlet of the turbine. This temperature increase causes also pressure increase at the outlet of the turbine which results in turbine efficiency decrease. The most significant output of this investigation is that the E-Turbo and E-Cat before SCR layout, which is the optimum design for CO₂ and NO_x control, is a self-sufficient system.

4. CONCLUSION

This thesis studies the impact of electrification on diesel greenhouse gasses and pollutant emissions for a 13lt heavy-duty long-haul truck. The aim of the study both demonstrating the effectiveness of electrification by comparing the EURO VI conventional system layout with different electrified system layouts and investigating different layouts whether they can satisfy upcoming European and US legislation.

The study is done in a simulation environment. For the modeling and simulation, the AVL Cruise-M, which is a simulation environment that specialized in the automotive industry, is used. For the post-process of data and evaluation of results, the AVL Concerto is used.

In the literature research, it is found that the studies for new electric power-based technologies, which are investigated in this thesis, are generally separated into categories as engine-related and aftertreatment system-related. Also, the simulation-based investigations are done separately on standalone engine models and standalone aftertreatment models. In this thesis, an engine and aftertreatment combined model is formed to demonstrate a real engine test bench more closely and to test the system layouts for regulatory engine test bench cycles.

Firstly, a EURO VI conventional system composed of the turbocharger, high pressure EGR, DOC, DPF, SCR, and ASC is modeled and simulated. The WHTC and FTP cycle results prove that the system can be used as a EURO VI benchmark because it satisfies both EURO VI and US10 limits. Then, 7 different systems, which are the application of electrified components alone and some combinations, are modeled and each of them simulated with respect to WHTC cold/hot and FTP cold/hot cycles. Their cycle results are compared with the conventional system and upcoming legislation.

Finally, the layout which includes both E-Turbo and E-Cat located before SCR is founded as the optimum system for NO_x and CO₂ control. The advantage of CO₂ control comes from the independence of an electrically assisted compressor from turbine operating conditions. Also, much better thermal management of EAS by E-Cat

provides a significant SCR efficiency increase. Moreover, the optimum system proves itself by meeting upcoming EURO VII emission limits.

4.1 Future Work

First of all, one of the outcomes of this study is that the direct implementation of the EGR pump without changing the turbine compressor couple makes the system much worse. The reason for this problem is explained in the thesis. To use a low-pressure EGR pump in the system, the turbocharger, electric or conventional, must be selected by concerning EGR pump. Here, there is an optimization problem on which can be worked in the future. The EGR pump studies have big potential due to both the capability of the EGR pump to control EGR rate without relying on engine operating conditions and relatively fewer amount works in the literature.

Secondly, although the optimum system indicates lower cycle emission results than new European emission standards, it fails to meet upcoming US standards for not only NO_x but also CO₂ limits. It is hard and not rational to find a system that satisfies both European and US standards. Thus, more effort is needed to demonstrate a system that gives cycle emissions and greenhouse gas results under the new US limits. For this purpose, the study cannot be limited by the only electrification; also, it can be expanded through engine design for better combustion, reduction of parasitic losses, close-coupled SCR with and without dual urea dosing, and hybridization, etc.

Although diesel systems will probably lose their shares in the automotive market, they, especially the long-haul trucks, will continue to keep their importance in the transportation options. Thus, research and development effort is required to achieve more clean trucks in the future for the environment and people.

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APPENDICES

APPENDIX A: HLB1614 helical lobe blower datasheet



APPENDIX A

Δp (mbar)	Tip	DN100							
	rpm	1500	1800	2200	2600	3000	3600	4000	4400
300	Q m ³ /h	268	336	428	524	616	752	849	941
	DT °C	32	31	30	29	28	27	27	27
	P _s kW	3,0	3,7	4,7	5,7	6,8	8,7	10,2	11,8
	P _{motor} kW	4	5,5	7,5	7,5	11	11	15	15
	Lp(A) _{inlet} dB	72	75	79	83	85	89	91	93
	Lp(A) _{inlet} dB	<70	<70	<70	<70	<70	<70	<70	<70
400	Q m ³ /h	257	325	416	507	604	741	838	929
	DT °C	45	43	41	39	38	37	37	36
	P _s kW	4,0	4,8	6,1	7,4	8,7	11,1	12,7	14,6
	P _{motor} kW	5,5	7,5	7,5	11	11	15	15	18,5
	Lp(A) _{inlet} dB	73	77	81	84	87	91	93	94
	Lp(A) _{inlet} dB	<70	<70	<70	<70	<70	<70	<70	<70
500	Q m ³ /h	245	314	405	502	593	730	827	918
	DT °C	59	55	52	50	49	39	47	47
	P _s kW	4,9	6,1	7,5	9,0	10,7	13,4	15,4	17,5
	P _{motor} kW	7,5	7,5	11	11	15	18,5	18,5	22
	Lp(A) _{inlet} dB	75	78	82	86	88	92	94	96
	Lp(A) _{inlet} dB	<70	<70	<70	<70	<70	<70	<70	<70
600	Q m ³ /h	234	302	393	490	581	724	815	906
	DT °C	74	69	64	61	59	58	57	56
	P _s kW	6,0	7,2	8,9	10,7	12,6	15,8	18,0	20,3
	P _{motor} kW	7,5	11	11	15	15	18,5	22	30
	Lp(A) _{inlet} dB	76	80	84	87	90	93	95	97
	Lp(A) _{inlet} dB	<70	<70	<70	<70	<70	<70	<70	<70
700	Q m ³ /h	222	291	388	479	570	713	804	901
	DT °C	90	83	77	73	71	68	67	66
	P _s kW	6,9	8,4	10,4	12,4	14,6	18,1	20,5	23,2
	P _{motor} kW	11	11	15	15	18,5	22	30	30
	Lp(A) _{inlet} dB	77	81	85	88	91	95	97	98
	Lp(A) _{inlet} dB	<70	<70	<70	<70	<70	<70	<70	<70
800	Q m ³ /h	217	285	376	473	564	701	798	889
	DT °C	107	97	90	85	82	79	77	76
	P _s kW	7,9	9,5	11,8	15,0	16,5	20,4	23,1	25,9
	P _{motor} kW	11	15	15	18,5	22	30	30	30
	Lp(A) _{inlet} dB	79	82	86	89	92	996	98	100
	Lp(A) _{inlet} dB	<70	<70	<70	<70	<70	<70	<70	<70
900	Q m ³ /h			371	462	553	695	787	884
	DT °C			103	97	93	90	88	86
	P _s kW			13,2	15,8	18,4	22,7	25,7	28,8
	P _{motor} kW			18,5	22	22	30	30	37
	Lp(A) _{inlet} dB			87	90	93	97	99	101
	Lp(A) _{inlet} dB			<70	<70	<70	<70	<70	<70
1000	Q m ³ /h				456	547	690	781	872
	DT °C				110	105	101	98	97
	P _s kW				17,5	20,4	25,0	28,3	31,6
	P _{motor} kW				22	30	30	37	37
	Lp(A) _{inlet} dB				92	94	98	100	102
	Lp(A) _{inlet} dB				<70	<70	<70	<70	<70



HLB 1614

Basınç

rpm: blower devri

Q [m³/h]: Hava debisi

DT [°C]: Hava sıcaklık farkı

P_s [kW]: Blower güç tüketimi

P_{motor} [kW]: Önerilen motor gücü

Lp(A)_{inlet} [dB]: Akustik kabinsiz
gürültü seviyesi

Lp(A)_{inlet} [dB]: Akustik kabin ile gürültü
seviyesi

Gürültü seviyeleri (Lp(A)) açık
ortamda, blower setinden 1m
mesafeden, yalıtımlı borular
kullanılırken (± 3 dB tolerans ile)
ölçülmüştür.

Referans koşullar:

Giriş basıncı: 1.013 bar(a)

Giriş sıcaklığı: 20 °C

Kuru hava - 1.2 kg/m³

Sunulan performans verileri bağlayıcı
olmayan örneklerdir.

Figure A.1 : HLB1614 helical lobe blower datasheet [52].

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- **B.Sc.:** 2018, Istanbul Technical University, Faculty of Mechanical Engineering, Mechanical Engineering Department (graduated as the 3rd in the department)
- **B.Sc.:** 2017, Istanbul Technical University, Faculty of Mechanical Engineering, Manufacturing Engineering Department

PROFESSIONAL EXPERIENCE:

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