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Methods of Thermal Management of Catalytic Converters in Gasoline-Based Engine Exhaust Systems

[1]Spoorthi HB, [2]Dr. Hemalatha J N.

[1]PG Student, [2]Associate Professor
[1]Department of Electrical and Electronics,
[1]RV College of Engineering, India

Abstract : Controlling exhaust emissions from internal combustion engines has emerged as one of the most pressing issues. Breathing difficulties, headaches, persistently impaired lung function, eye discomfort, lack of appetite, and corroded teeth are all possible side effects. It can have an indirect impact on humans by harming the ecosystems on which they rely in the sea and on land. The Indian government amended European regulations considering environmental concerns and health risks. To fulfil the impending pollution standards, existing engine technology must be modified, and a better system developed. Exhaust temperature management is the most effective approach to controlling emissions. The temperature in the exhaust system has a significant impact on emissions since exhaust gas treatment equipment like catalysts, oxygen sensors, and storage catalysts operate only within a narrow temperature range. Thus, by efficiently managing the exhaust system temperature, we can reduce emissions to a given level. The main criterion for accomplishing all of these requirements is engine torque. Catalytic converters reduce the emissions of carbon monoxide, hydrocarbons, nitrogen oxides, and particulate matter from internal combustion engines, allowing them to satisfy increasingly rigorous emission laws. Catalytic converters, on the other hand, have light-off troubles during cold start and warm-up. This work evaluates the literature on catalyst thermal management, with the goal of drastically reducing light-off time and emission concentrations using optimal heating methods. Methods based on engine parameter control, in particular, are simple to apply since they do not necessitate the use of additional heating equipment. They do well in terms of reducing catalyst light-off time.

***Index Terms* - Light off temperature, Catalytic converter, Thermal management, Internal combustion engines, Spark ignited engines, Catalyst, Exhaust emissions.**

I. INTRODUCTION

This Automobiles are increasingly widely utilized since mobility improves living conditions. The ever-increasing transportation of people and things across numerous locations has a significant impact on economic progress. India, the world's second most populous country, has a diverse economy, with transportation being a key component. According to statistics, the number of automobiles in our nation has increased by more than 240 percent in the last decade. This is predicted to continue increasing at a similar rate over the next 20 years. This high car rate has negative consequences. These include severe environmental risks such as climate change, pollution, global warming, poorer agricultural yields, and threats to living creatures as a result of increased dependency on fossil fuels and increased pollution emissions, which may finally result in total ecological imbalance.

Major automotive emissions from internal combustion engines include traditional pollutants such as carbon monoxide (CO), nitrogen oxides (NOx), particulate matter (PM), and hydrocarbons (HC), as well as greenhouse gases such as carbon dioxide (CO2), methane (CH4), and others. The implementation of Bharat V/VI standards across the country may reduce automotive emissions by 86 percent. It is very advised to create engine control systems in order to attain high performance and minimal exhaust emissions. The engine management system is a mixed-signal embedded system that communicates with the engine via a variety of sensors and actuators. It organizes all of the engine's requirements, prioritizes them, and eventually implements them. The control techniques are designed for air-fuel ratio management, ignition control, electronic throttle control, idle speed control, accelerator pedal position control, and other applications. The control system's successful design and execution results in higher engine output.

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II. Thermal Management

Internal combustion (IC) engines for vehicle propulsion have significant hurdles due to their relatively high emissions and limited efficiency. Nonetheless, popular estimates imply that IC engines will continue to be widely utilized for a relatively long time [1][2], at least as components of hybrid electric powertrains. As a result, the automobile industry is making major efforts to minimize IC engine emissions, such as carbon monoxide (CO), hydrocarbon (HC), nitrogen oxides (NOx), and particulate matter (PM) [3]. After-treatment systems, such as three-way catalysts (TWCs) [4], diesel oxidation catalysts (DOCs) [5], selective catalytic reduction systems [6], and diesel particulate matter filters (DPFs) [7] have been effectively applied in spark ignition (SI) and compression ignition (CI) engines for this purpose.

However, as most of the after-treatment systems are catalytic converters, their functionality deteriorates at low temperatures, e.g., during engine cold start and warm-up [8]. In fact, catalysts usually convert harmful emissions only when their temperature reaches certain thresholds, i.e., the so-called light-off temperature, which is normally around 250–300 °C for TWCs [9]. Hence, high levels of exhaust emissions are transferred into the atmosphere while the exhaust temperature is low, during the engine cold start or warm-up phases, in which the catalyst is not fully operational.

In addition, during cold-start, a considerable amount of gas-phase HC condenses on the surface of the tailpipe and catalyst, and partially volatilizes to the atmosphere without catalytic oxidation during the following warm-up phase The thermal management of catalytic converters is a timely topic. In fact, in the current context of the automotive sector, hybrid electric vehicles (HEVs) play an increasingly important role. HEVs allow IC engines to operate more efficiently, and partially recuperate their kinetic energy during braking [10]. However, HEVs still face the challenge of cold-start emissions, as HEV engines are usually switched off at low speed and wheel torque, when the brake specific fuel consumption is particularly high. This may reduce the exhaust temperature, and thus the catalyst efficiency. Therefore, the thermal management of the catalyst is important for both conventional vehicles and HEVs. Therefore, the thermal management of the catalyst is important for both conventional vehicles and HEVs.

A significant amount of study has been conducted to examine catalyst properties and enhance catalyst light-off performance through proper heat management. Nonetheless, the literature lacks a thorough examination of the thermal management of catalytic converters in order to reduce exhaust emissions during engine cold start and warm up.

III. Exhaust Emissions During Cold Start and Warm Up Phases

Reference [11] performed a thorough examination of cold start emissions. Several studies, including Refs. [12] and [13], indicate experimentally observed high CO and HC emissions for both gasoline and diesel engines when started cold. Maximum CO and HC values in the publications studied varied from 950 ppm to 8400 ppm and from 220 ppm to 28,000 ppm, respectively [13][14]. Poor cylinder combustion and catalyst efficiency are to blame for such high emissions. The particle number concentration does not fluctuate considerably during cold start, but it is highly dependent on engine speed and load [15]. Because of the low cylinder temperature, less elemental carbon develops under cold start circumstances, but substantially more gas-phase HC transforms to liquid-phase particles. As a result, the fall in HC content contributes to a decrease in PM under cold start circumstances. High NOx emissions were also recorded in ref. [16], owing mostly to inadequate catalyst efficiency. The exhaust temperature of some vehicles, such as airport shuttle buses, sightseeing buses, and urban buses, can be permanently below the catalyst light-off threshold.

According to Gong et al. [17], in ultra-low emission vehicles (ULEVs), 80-90 percent of tailpipe HC emission occurred during the first test cycle in the federal test procedure (FTP), and these numbers can increase in super ULEVs. Given these facts, actions were taken or considered to minimize emissions during warm-up by enhancing I combustion and/or (ii) catalyst efficiency. For example, in relation to an adequate heat storage or supplementary heat source can boost the temperature of the lubricant [18] or coolant [19] before the engine begins, thus raising the cylinder temperature and reducing CO and HC generation. Intake air heating [20] and fuel heating [21] can also help with combustion. In terms of (ii), standard procedures alter the operating engine parameters, such as adjusting the valve timing, enriching the air/fuel mixture, and adjusting the commencement of combustion. Although such solutions can significantly reduce the catalyst light-off time, IC engine emissions continue to worsen prior to the catalyst light-off. As a result, a pre-catalyst device might heat the exhaust to expedite light-off. Among the several strategies for efficiently reducing cold start and warm up emissions, this paper mainly shows overview about thermal management of the catalytic converters.

When the engine is started with the catalyst temperature too low to reach the light-off temperature, this functionality will ask for catalyst heating. Catalyst heating will be accelerated as much as possible by the FC. The catalyst heating is computed during the start phase in dependency on the engine temperature, intake air temperature, shut off time, and altitude because the measured catalyst temperature is unavailable and the modelled temperature is erroneous.

The ambient temperature, intake air temperature, and engine start temperature are approximately equal when the engine is first chilly. When the cold start heating request is set, the catalyst's light-off temperature is then gradually attained based on the catalyst ageing factor. In the meantime, a ratio between the required value for integrated air mass and the integrated air mass quality at engine start is determined. The catalyst heating is started once this ratio exceeds a predetermined threshold, failing which the catalyst heating for cold start scenarios is stopped.

In order to heat up the catalyst during long coasting phases, GPF regeneration requests, and when dew point end is not reached, catalyst heating is necessary. Figure 1 illustrates the algorithm for the controller's operation for catalyst heating owing to cold start and catalyst warming.

Long coasting conditions could be challenging for a vehicle to handle. Therefore, using an engine dyno, which can replicate a very long coasting phase, is advised. Here, we must check to make sure there are no defects caused by engine temperature. The catalyst is warmed as soon as the catalyst heating request is set to true and all necessary operating parameters are satisfied. Time should be provided to the car in the event that the dew point is high enough to soak, as a cold start is necessary and there shouldn't be any engine temperature or air pressure-related issues.

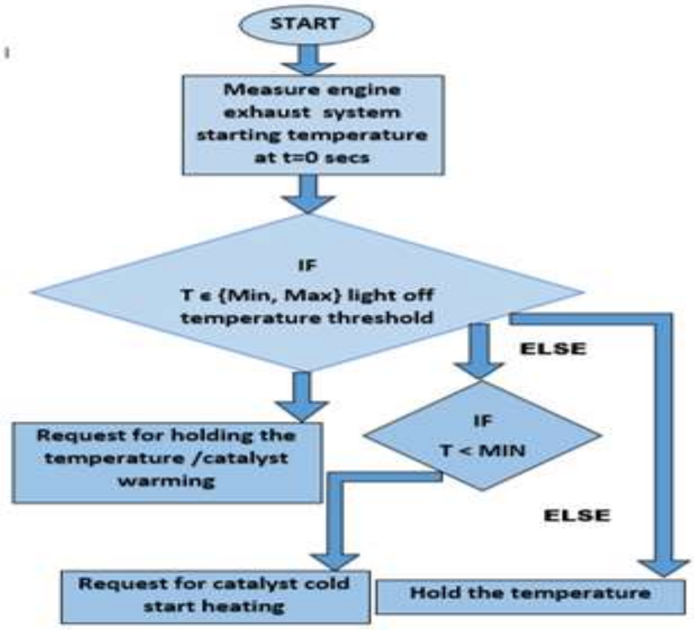

Fig.1 Algorithm for operation of controller for catalyst heating due to cold start and catalyst heating

IV. Methods of Thermal Management in Gasoline Based Engine Vehicles

The purpose of thermal management is to reach a sufficiently high temperature of the catalysts as fast as possible and maintain in order to assure an optimal conversion of exhaust emissions.

Depending on the specific system configuration, boundary conditions/restrictions and specific calibration of the heat up strategy a number of different heat up measures are possible. Some main heat up measures are described below:

- Late ignition timing to increase the exhaust temperature and exhaust mass flow
- Request heat up operation mode with adapted injection pattern
- Increased idle speed to increase the exhaust mass flow over the catalyst
- Rich combustion lambda set point in combination with secondary air to enable exotherm reaction on catalyst
- Request cylinder lambda split strategy (e.g. 2 cylinder rich / 2 cylinder lean) to enable exotherm reaction on catalyst
- Disable fuel cut–off in case of low temperatures to avoid further cooling down.

The heating strategy determines the heating demand and takes into account technical/physical restrictions as well as optimization criteria among different emission components. In case of insufficient catalyst temperatures e.g. cooling out or interrupted heating, a reactivation of the heat up measures has to be assured. The thermal state of the exhaust catalysts directly influences exhaust emissions and indirectly fuel consumption/ CO_2 emission.

Adjusting the operational engine settings can quickly reach high exhaust temperatures, but it causes the engine to diverge from ideal operating conditions. The subsections explains the each of the strategies for thermal management.

4.1 Ignition Retardation

Retarded ignition time is a typical and successful way to raise exhaust temperature without the need of additional technologies [63]. However, it limits constant volume combustion and results in more unburned fuel in the exhaust pipe, resulting in decreased engine power and efficiency. When ignition occurs earlier in the cycle, more amount of heat is released around the top dead center. Thus, advanced ignition timings will result in higher peak cylinder pressure and temperature. With increase in combustion temperature NOx formation will also increase. Thus, results higher NO emissions with advanced ignition timing. Knock and engine damage problem can also occur. Whereas if the ignition timing is retarded more burning takes place during the expansion stroke that results in lower peak combustion pressure. But the exhaust gas temperature increases which reduces the engine efficiency. Also, higher oxidation rate of HC and CO are obtained with higher exhaust temperature through retarded ignition timing. Thus, low HC emissions are obtained with retarded ignition timings. Figure 2 depicts the algorithm for the controller's work flow for the worsening of engine efficiency and ignition retardation.

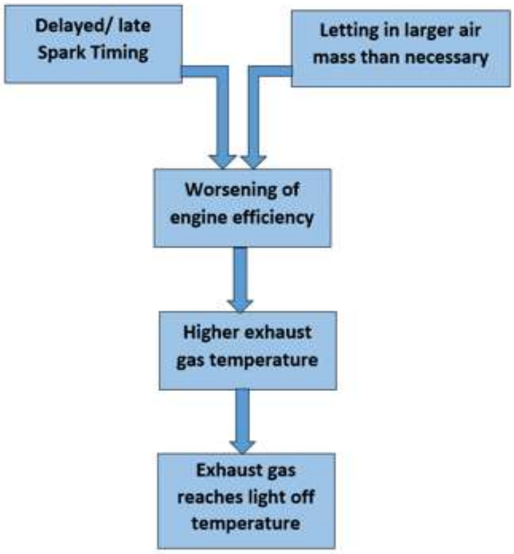

Fig 2. Algorithm for work flow for controller for worsening of engine efficiency and ignition retardation.

4.2 Multiple Injection

The multiple injection approach is used in another way for boosting the exhaust gas temperature. The combustion properties of successive injection operations raise the temperature of the exhaust gas, resulting in a totally homogenous operation. The split injection system also improves ignition stability and allows for a certain late ignition angle to heat the catalytic converter.

A complete fuel quantity that is to be given to the cylinder throughout an operating cycle is provided to the combustion chamber in at least two injection phases in multiple injection operation. Initially, a homogeneous injection occurs during the intake stroke of the cylinder, resulting in virtually homogenous distribution of the injected fuel quantity in the combustion chamber at a later ignition time. Then, during a subsequent combustion stroke, a second late injection called stratified injection is done, resulting in the so-called stratified charge, in which the injected fuel is concentrated in the cylinder in the region near the spark plug.

A multiple injection operation is a hybrid of stratified charging and homogeneous charge. The combustion properties of these operations cause an increase in exhaust gas temperature as compared to a strictly homogeneous operation, allowing for a later ignition angle. Because of the rich mixture around the spark plug, a reliable ignition for lean lambda summing is possible. As a result, both ignition retardation and multiple injection can be usefully coupled.

4.3 Lambda Split

Another heating method is to alter the air-fuel ratio of different cylinders in opposing directions, a technique known as lambda split. Several cylinders in this approach are run with a mixture richer than the total lambda, while others are operated with a leaner mixture. In comparison to lean mode, combustion in the cylinder operating in rich mode is incomplete. The non-combusted components are subsequently exothermally transformed in the downstream catalytic converter with the leftover oxygen fraction of the lean operating cylinder, heating the catalytic converter.

With this lambda split method, a large amount of chemical energy can be introduced into the catalytic converter system, heating up the catalytic converter through exothermal catalytic conversion of the exhaust gas components that were not converted during the engine's non-stoichiometric combustion process. As a result, during the heat up phase, the lambda value should preferably be controlled to at least a stoichiometric value of =1. If a catalytic converter positioned far from the engine has to be heated fast, this approach of lambda detuning is useful.

4.4 Torque Reserve

Torque loss due by thermal heating may be compensated for by increasing the amount of air and fuel. Increasing the air charge while changing the ignition to retard to compensate for the extra air can compensate for torque loss. Torque control is separated into two categories: air system torque and ignition system torque. Torque reserve is a feature that ensures a torque range that may be modified by ignition timing without affecting real torque. As a result, the torque reserve is applied to the air system necessary torque rather than the ignition system required torque.

4.5 Increase in Idle Speed for Catalyst Heating

Idle functioning of an automobile engine necessitates particular care. In idle mode, there is no throttle input from the driver via the accelerator pedal. To maintain a constant idle angular speed, the engine must provide exactly the torque necessary to balance all applied load torques from the gearbox and any accessories, as well as internal friction and pumping torques. Certain load torques are caused by driver activity. Certain additional load torques, however, occur in the absence of a direct driving order. The mass flow rate of intake air determines the torque generated by the engine at idle, as it does in all engine operating phases. While the engine is completely warmed, the electronic fuel control regulates fuel flow to maintain stoichiometry and may momentarily regulate fuel to slightly richer than stoichiometry during cold starts. Normally, when the engine is idle, the ECU is designed to keep the engine running at a constant RPM regardless of load. This is accomplished by modulating mass air flow in response to the driver's throttle order. The air flow necessary to maintain the correct idle RPM must enter the engine through the throttle assembly at a slight but non-zero angle.

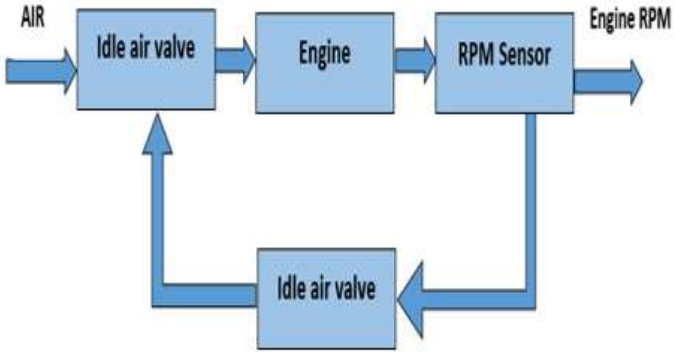

Fig.3 Algorithm for controller for idle speed and camshaft adjustment

Alternatively, some engines have an air tunnel that bypasses the throttle plate. An actuator is necessary for either way to allow the electronic engine control system to manage the idle mass air flow.

4.6 Exhaust Camshaft Adjustment

Exhaust camshaft modification can contribute to increased heat flow even further. The procedure of opening the exhaust valve as soon as feasible pauses the delayed combustion and thereby reduces the mechanical effort created even further. The corresponding amount of energy is accessible as heat in the exhaust gas.

The automobile industry has commonly used variable valve timing (VVT) to increase engine performance. VVT is another option for increasing exhaust temperature during cold start. In reality, late intake valve opening (IVO) allows less new air into the cylinders, resulting in a richer air/fuel combination in combustion engines, whereas early exhaust valve opening (EVO) limits exhaust expansion and raises exhaust temperature. These two actions result in post-oxidation and rapid catalyst light-off. Figure 3 depicts the controller's algorithm for controlling idle speed and camshaft adjustment.

Thus, executing this technique while taking these parameters into account can increase the catalyst heating characteristics efficiently, resulting in a reduction in exhaust emissions.

V. WORK ENVIRONMENT

Advanced Simulation and Control Engineering Tool is referred to as ASCET. It is a multifaceted and adaptable product family that offers an original approach to the functional and software design of contemporary automotive embedded systems. With a fresh take on modelling, code generation, and simulation, ASCET supports each step of the development process, enabling improved quality, quicker innovation cycles, and lower costs. Working of ASCET is depicted in Figure 4.

A tool for creating software for embedded systems that uses both graphical models and textual programming notations is called ETAS ASCET. The proposed function models will be converted into extremely efficient and secure embedded C-Code for AUTOSAR (Automotive Open System Architecture) applications by the ASCET Code Generator. The ASCET has been created primarily to handle the difficulties in software development for sectors where goods must be produced in large quantities, at a low cost, in compliance with industry standards, and without any flaws.

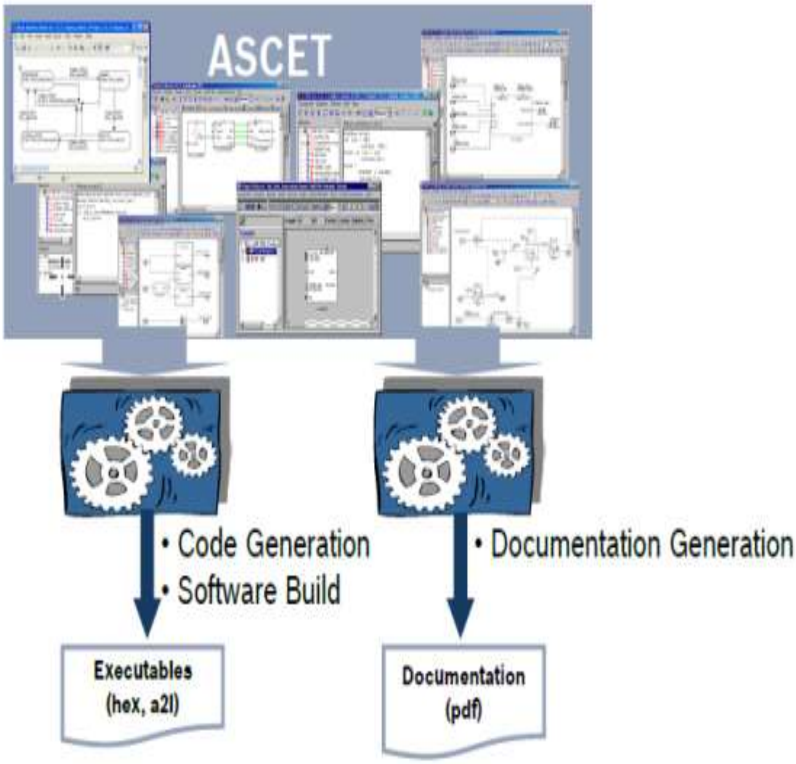

Fig.4 Working of ASCET tool

The ASCET tool enables software developers to create embedded software that is high performing, low overhead, simple to maintain, secure, and safe. High levels of automation enable productive and safe workplaces.

The ASCET tool for Automotive Software Development has the following features:

- Safe - Automatic introduction of defensive code, TUV-certified code generation using ISO26262 and IEC61508, and MISRA-C:2012 compliance
- Used for powertrain, driver assistance, battery management, brake systems (such ABS, ESP), ASCET-generated code powers the 450+ million ECUs in use today.
- The 450+ million ECUs in use today are powered by ASCET-generated code, which is used for brake systems (such as ABS, ESP), driver assistance, battery management, and powertrain.
- Quick and effective - Real-time static analysis for immediate feedback, quicker code generation
- A variety of testing alternatives, including unit testing, PC-based open-loop simulation, closed-loop simulation, and rapid prototyping
- Embedded Software Development Language (ESDL), which has an abstract data type, easy-to-understand syntax, and object-oriented encapsulation

Testing is an examination that aims to reveal details regarding a software product's quality. Executing a software system or component is part of testing. Depending on the level of code knowledge, or when the code is known and when it is unknown, there are many forms of testing.

In addition, there are many types of testing based on the complexity of the testing code, including system testing, which involves testing multiple functional components, and integrity testing, which is done whenever a new component is added to the system. When a hardware component is incorporated in the testing process, we use hardware testing. When we test software components, we use software testing. TPT is a tool for model-based testing that is used for automated embedded system testing, particularly for testing control systems. Applications include:

- PC based testing
- Open and closed loop tests
- Test in vehicle

TPT is certified to do automated tests in vehicles in accordance with ISO 26262 standards. Signal time intervals are used by TPT. The following four test activities are covered by TPT:

- Case modelling
- Execution in different environments
- Result analysis
- Documentation

Test cases for TPT are built independent of how it runs. Due to the so-called Virtual Machine concept, the test cases can be run in nearly any environment. TPT is a comprehensive tool that may be used for all testing phases of development, including system testing, regression testing, integration testing, and unit test.

The exhaust system was initially designed as a simple duct system with the intention to safe route the toxic exhaust gas emissions from our car into harmless gases to the environment at the same time providing attenuation of noise made by the engine during combustion. Today, over the years the responsibility of exhaust system has grown. Modern exhaust systems are an integral part of combustion and pollution control thereby reducing noise, minimize harmful emissions and even give assistance in increasing fuel economy, power and hence the overall drivability. The primary components of the exhaust system work together to expel exhaust, reduce noise and assist smoother running of the operating parts. Although the emission control systems may vary based on the manufacturers and the vehicles, they all are designed to meet the same goal and they work on the same principle. The primary design consideration of an exhaust system include:

- Minimizing the gas flow resistance and confine it to specified range depending on the engine model to achieve maximum efficiency.
- Suppressing the exhaust noise to meet the automobile regulations and requirements.
- Providing sufficient clearance between exhaust system components and engine components so as to minimize the impact of high exhaust temperature.
- Ensuring that the system does not overstress engine components with excess weight as overstressing can shorten the component life.
- Ensuring that the exhaust components are able to reject heat energy as intended.

VI. RESULTS AND DISCUSSION

The TPT report provides a summary of all tests carried out. It also shows which test cases fail. The signal viewer allows to view each signal as it is displayed in the figures below. Figure 5 shows a graph of an engine in operation. Figure 6 displays a graph of time as a function of engine speed. Figure 7 depicts a graph of time versus catalyst brick temperatures. Figure 8 depicts a graph of time versus the catalyst's maximum temperature. Figure 9 shows a graph in which time is plotted against the catalyst's maximum temperature. Figure 10 displays a graph of the time v/s signal for catalyst heating brought on by a cold start. A graph displaying the catalyst heating's time v/s signal Figure 11 depicts the graph of catalyst warming, Figure 12 depicts the graph of time versus heating mode, Figure 13 depicts the graph of controller output for air charge control actors, Figure 14 depicts the graph of controller output for idle speed, and Figure 15 depicts the graph of controller output for lambda coordination. Figure 16 displays the output graph for the controller used to set the maximum torque during idle speed.

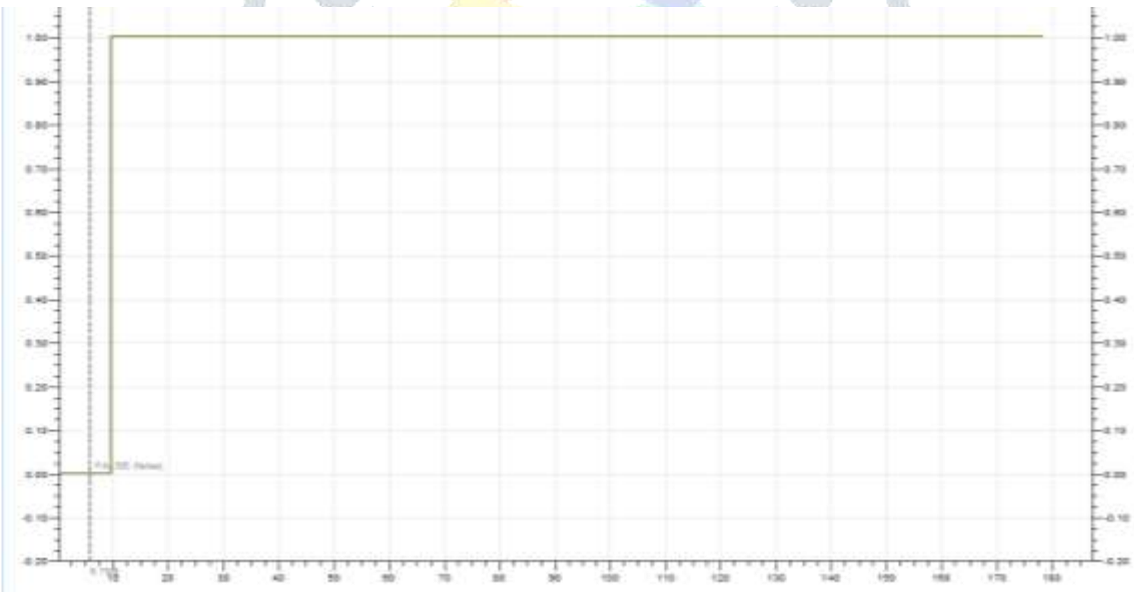

Fig.5 Graph showing engine in running mode

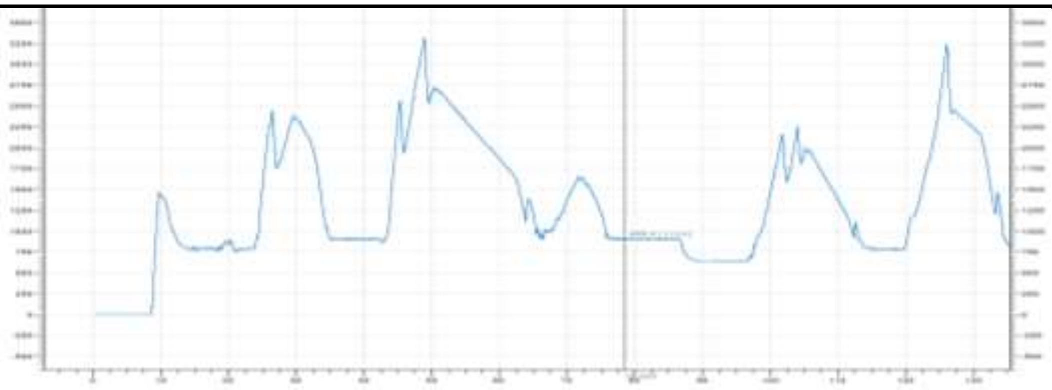

Fig.6 Graph showing time v/s engine speed

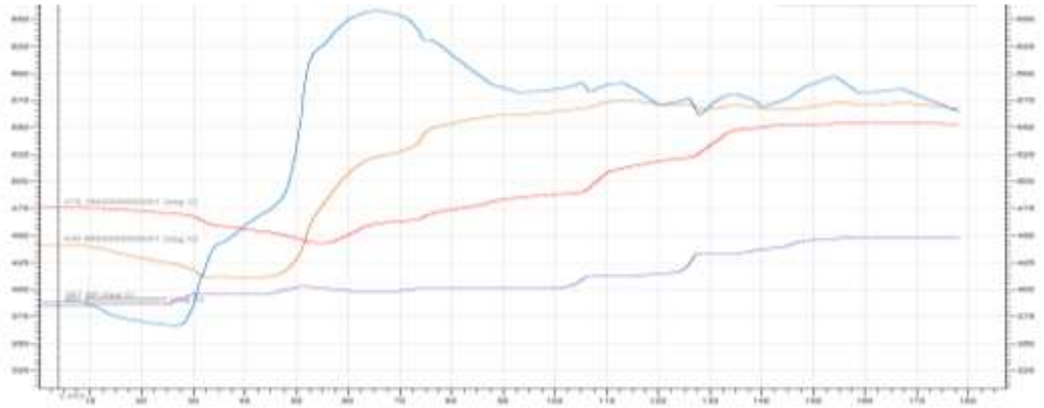

Fig.7 Graph showing time v/s catalyst brick temperatures

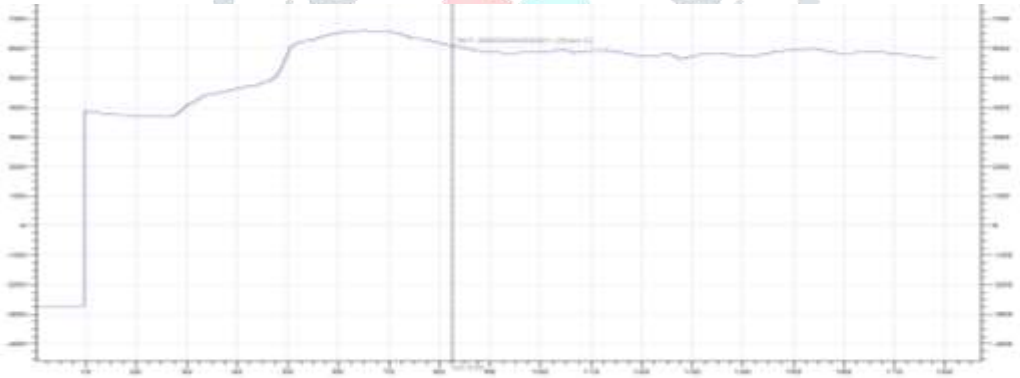

Fig.8 Graph showing time v/s maximum temperature of catalyst

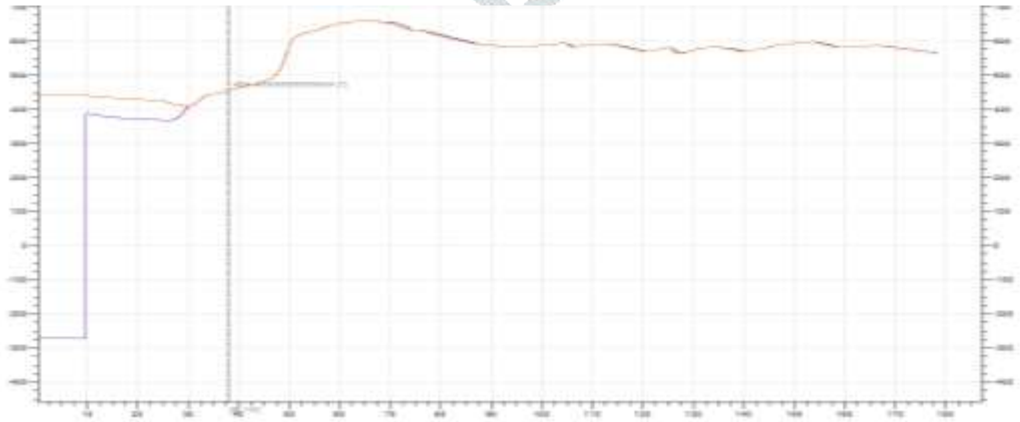

Fig.9 Graph showing time v/s selection of maximum temperature of catalyst

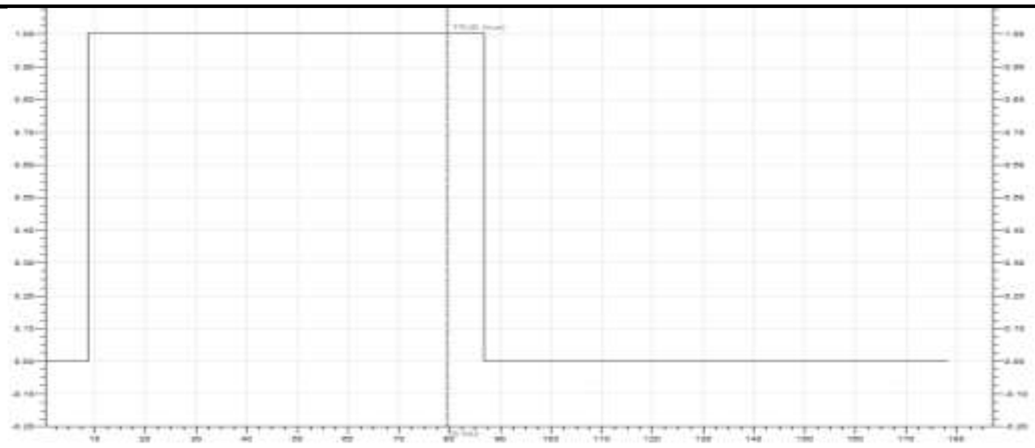

Fig.10 Graph showing time v/s signal for catalyst heating due to cold start

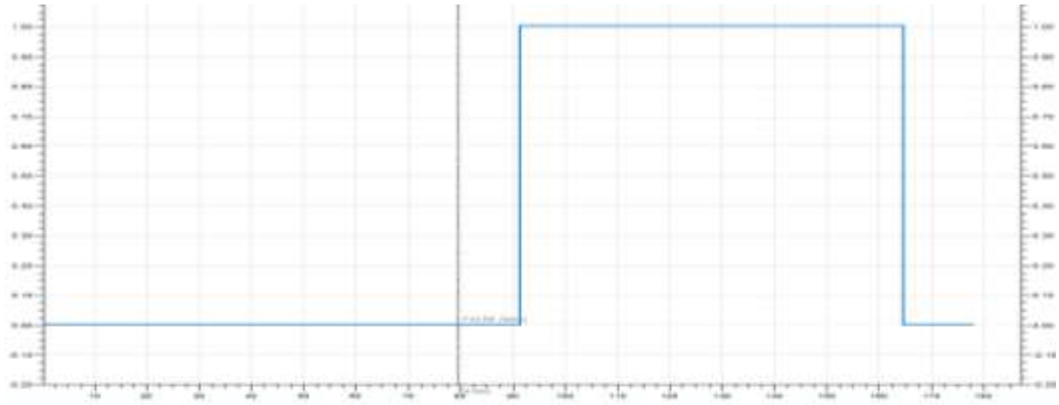

Fig.11 Graph showing time v/s signal for catalyst heating due to catalyst warming

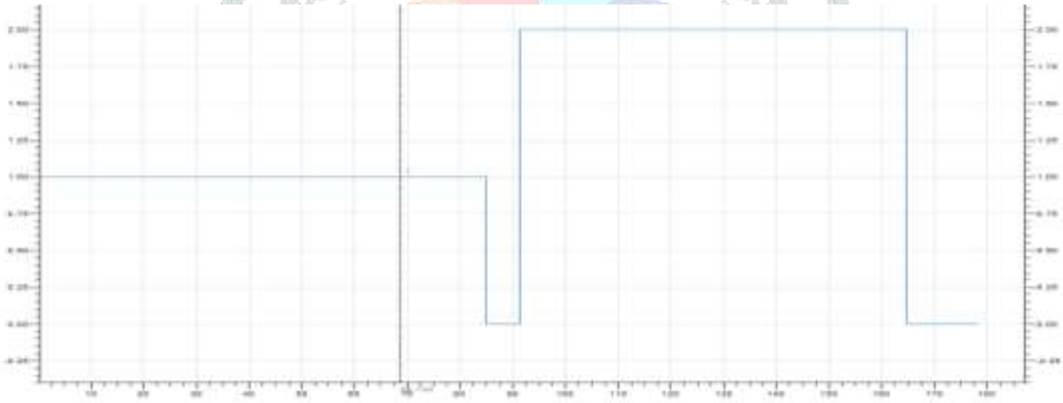

Fig.12 Graph showing time v/s heating mode

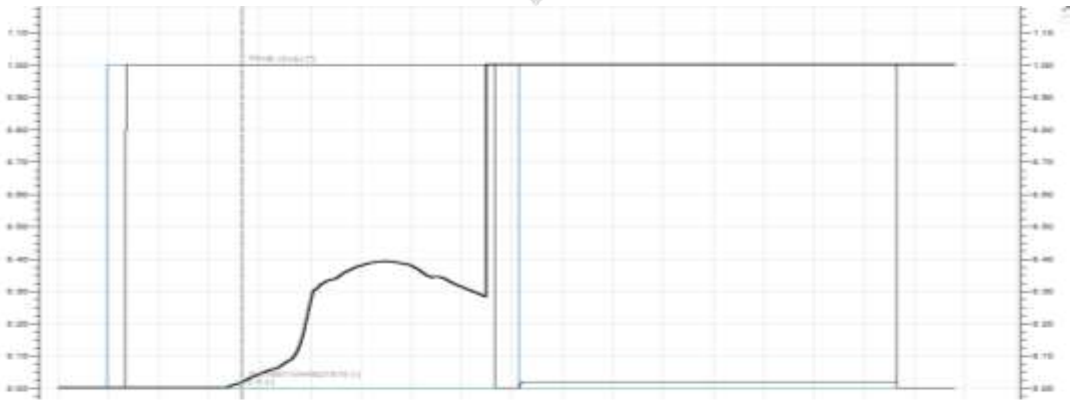

Fig.13 Graph output for controller for air charge control actors

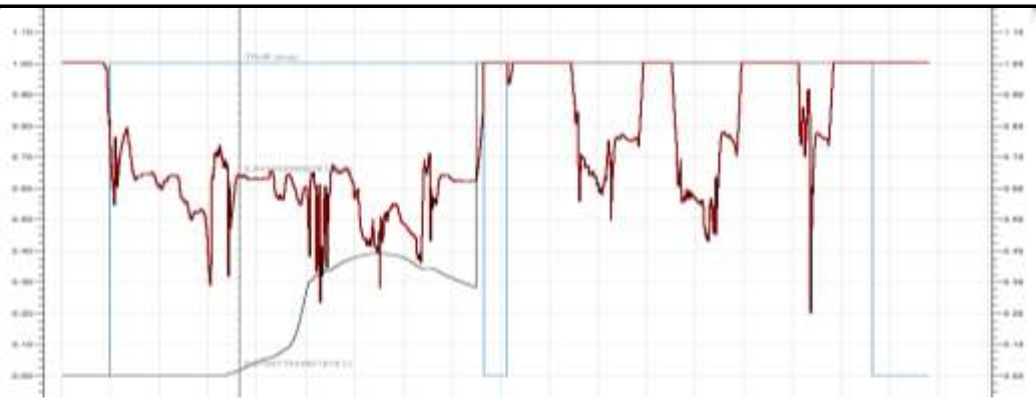

Fig.14 Graph output for controller for idle speed

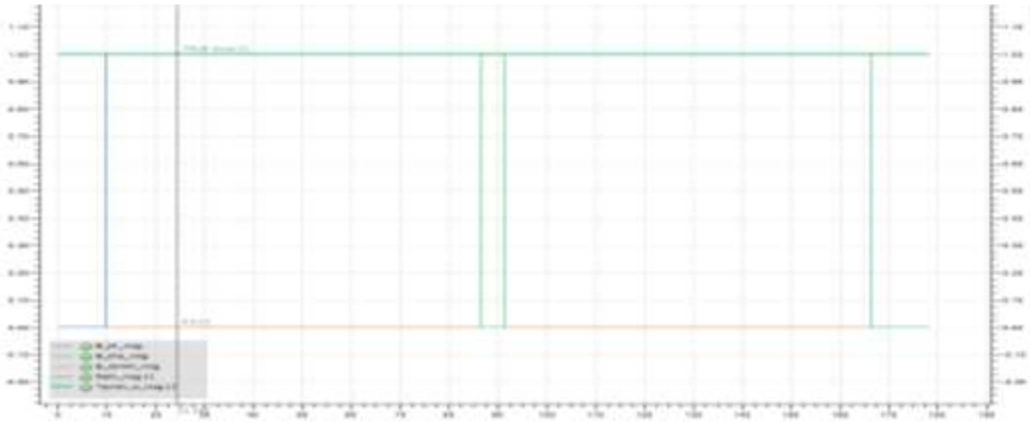

Fig.15 Graph output for controller for lambda coordination

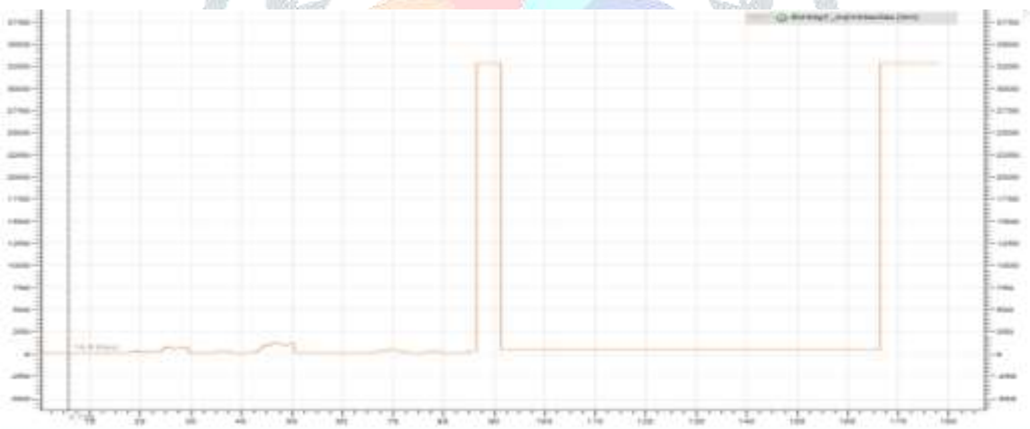

Fig.16 Graph output for controller for setting maximum torque during idle speed

VII. CONCLUSION

Automobile emissions are linked to environmental and health risks, prompting the establishment of severe emission regulating regulations. Over the last decade, our country has taken a variety of steps to reduce emissions from our automobile fleet. For engines functioning normally, significant reductions in exhaust emissions have already been realized. However, such emissions are still considerable during cold start and warm up due to important engine-out emissions and poor catalyst efficiency due to low cylinder and exhaust temperatures.

Exhaust gas temperature is a characteristic that has proven crucial in determining engine performance. This study examined thermal management strategies for quick catalyst light-off in order to reduce cold stat and warm up emissions, as well as component protection approaches for automotive emission reduction. Thermal management, in contrast to earlier techniques, resolves the trade-off between energy consumption and pollution reduction by preheating the catalytic converter.

Electronic engine control is important in emission control. The minimal emissions achieved by current engines would not be achievable without electronic control. The purpose of an engine management system in terms of emissions is to supply the needed quantity of air, fuel, and EGR at the required temperature and pressure in the required time. This control is carried out throughout the engine's lifespan, correcting for wear and degradation.

A thorough examination of the different functional components of the exhaust temperature management package was conducted, and a few functional components were adjusted to fulfil the emission limits specified by the client. The fuel and fuel system, the engine and its combustion system, sensors, and the design and position of the catalyst and filter all work together with the electronic control system to reduce emissions to the greatest extent possible. Developing an optimal system will therefore improve engine exhaust emissions for better adaptability to various exhaust laws, encouraging improved environmental circumstances and health advantages.

Until recently, a carbon-neutral combustion engine was the stuff of science fiction. The principle is found in synthetic fuels, often known as carbon-neutral fuels, whose manufacturing process collects CO2. As a result, greenhouse gases become a raw material from which gasoline, diesel, and other fuels are produced and replacement natural gas may be produced using sustainable energy sources. Synthetic fuels will make gasoline and diesel vehicles carbon-neutral, and therefore a substantial contribution to preventing global warming. This might soon become a reality around the year 2025.

VIII. ACKNOWLEDGMENT

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