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Automotive Emissions Control

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Abstract— **Local and global environmental concerns regarding automotive emissions motivate legislative action by governments throughout the world. Aggressive regulation of both tailpipe and evaporative emissions of passenger vehicles is the norm in most developed countries. These governmental regulations produce significant challenges and opportunities for control, particularly when combined with other system objectives such as fuel economy and performance. This tutorial presents an overview of the challenges related to emission control in the design and development of powertrain systems for modern passenger vehicles.**

I. INTRODUCTION

AUTOMOTIVE emissions have been regulated for more than four decades. Tailpipe and evaporative emissions standards are legislated to some degree in most automotive markets. The most stringent standards are applied in the high volume markets of the United States, the countries forming the Europe Union and Japan.

Current tailpipe regulations for gasoline engines focus on carbon monoxide (CO), the oxides of nitrogen (collectively called NOx) and hydrocarbons (HC). These standards have become increasingly stringent since their introduction in the 1960's [1]. This is demonstrated in Figure 1, which shows the change in HC emissions from gasoline powered vehicles in the United States since 1966.

Tailpipe emissions of diesel engines are also regulated, with a focus on particulate and NOx emissions. Historically, diesel engines have had more relaxed emission standards. California, however, is applying the more severe gasoline standards to diesel vehicles [3], with other regulatory bodies following suit in the next few years [4-6].

Evaporative emissions standards consider the emission of fuel vapor from the vehicle during operation and while parked [7]. The zero emissions vehicle (ZEV) standards recently introduced in California [3] are so severe that evaporative emissions from the fuel system must approach zero grams [8].

Each of these regulations provides a control challenge on its own, but when combined with other regulations and system objectives, such as fuel economy and performance, the challenges become significant.

This tutorial summarizes some of these challenges, as well as state of the art solutions. Control of tailpipe emissions for gasoline and diesel powered vehicles is discussed in Section II. Evaporative emissions control is presented in Section III.

II. TAILPIPE EMISSIONS

The composition of the exhaust gases varies significantly for gasoline and diesel engines; and differences in operating conditions affect the performance of potential aftertreatment devices. As such, control of emissions from these two types of automotive engines is handled in very different ways and therefore, these applications will be discussed separately.

A. *Gasoline Engines*

In conventional port fuel injection (PFI), gasoline engines, fuel is injected into the intake port of each cylinder, where it combines with air. The air fuel mixture is inducted into the cylinder and ignited. Spark ignited (SI) engines typically operate with air to fuel ratio (A/F) ranging from 12:1 to 18:1. Engine out emissions vary over this A/F range, with HC and CO highest at rich conditions and NOx emissions peaking near an A/F of 16:1 [9].

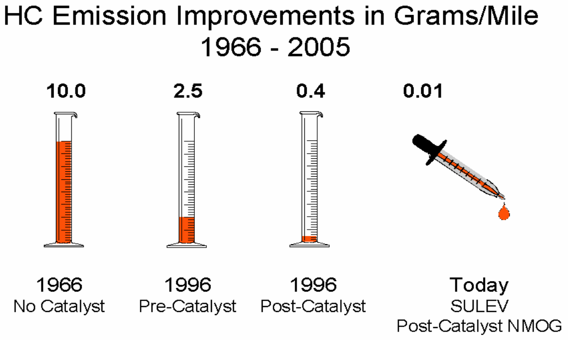

Fig. 1. HC emission standards have changed dramatically since their inception. This figure [2] illustrates the reduction in HC emissions in the United States since 1966.

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A three-way catalyst (TWC) is widely used to simultaneously convert emissions of CO, HC and NOx from an SI engine. Conversion occurs via catalysis over a precious metal, typically Pt and/or Pd, and is highly dependent on the A/F of the exhaust gas. As demonstrated in Figure 2, useful conversion efficiency for all three species occurs only in a narrow band about stoichiometric A/F [1, 9], which is near 14.6:1 for typical formulations of gasoline. This narrow band can be widened slightly via A/F modulation [10], but A/F control remains critical to effective emissions control with a TWC.

1) A/F Control

A/F is typically controlled with fuel via implementation of feed forward (open loop) control, in addition to feedback utilizing an exhaust gas oxygen sensor (EGO) located upstream of the TWC [11]. The feed forward control is critical in this approach since the feedback signal is delayed by several engine cycles due to gas transport and sensor dynamics, and the EGO sensor is unreliable when cold [11].

The most common approach to feed forward control is a calculation of fuel from desired A/F and an estimate of cylinder air charge. On-line implementation of an air charge model is typically based on either measurement of air flow rate or intake manifold pressure. A block diagram of a typical air flow meter based approach [11] is given in Figure 3. Compensation for nonlinearities and sensor dynamics, such as air charge maldistribution [11] and air flow meter dynamics [12], is included in many applications.

Feedback control of fuel is typically implemented with a switching EGO sensor (sometimes referred to as a HEGO, if heated). This sensor simply reports whether the exhaust gas is lean or rich; the magnitude of the deviation from stoichiometry is unknown. In most cases, the feedback control is a conventional proportional plus integral (PI) algorithm [13]. This approach has been very successful for the last two decades. Decreasing emission standards, however, continue to push sensor and control technology.

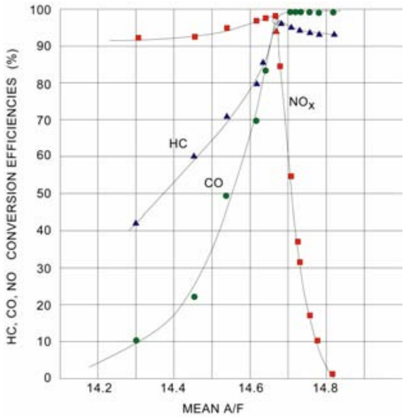

Fig. 2. TWC conversion efficiency varies with A/F. Efficient simultaneous conversion of CO, HC and NOx occurs only near stoichiometry [1].

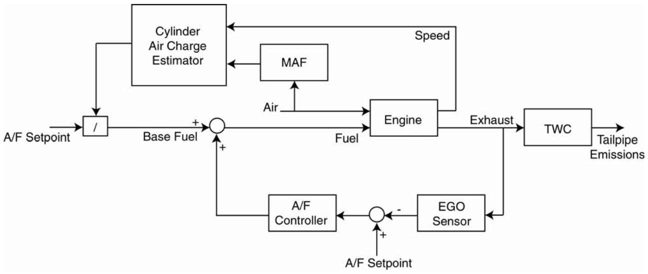

Fig. 3. This schematic represents a typical A/F control algorithm. In this case, feed forward control is based on an air flow meter measurement and feedback is implemented with a HEGO sensor.

Some implementations now utilize a universal EGO (UEGO), which is a linear exhaust oxygen sensor providing an output proportional to A/F over a wide range [14]. More advanced control methods and architectures have been explored, with some considering use of multiple HEGO and/or UEGO sensors for A/F control [15].

Nonlinear fuel dynamics add significant uncertainty to the A/F control problem. Some of the fuel injected in the port impacts the wall, forming a puddle and affecting the amount of fuel entering the cylinder. To complicate matters, the dynamics vary with fuel properties, aging and other factors. As such, adaptive, transient compensation of this effect is important to effective A/F control over the life of the vehicle. One approach to this difficult problem using a switching EGO sensor is described in [16] and [17].

Considerable effort is made to minimize engine out emissions to reduce the amount of costly precious metal required in the TWC. A common method for NOx reduction is recirculation of exhaust gases (EGR), which lowers combustion temperatures to conditions where less NOx is produced. EGR can be introduced externally to the engine, via a valve that connects the intake and exhaust manifolds, or directly via control of intake and/or exhaust valve timing. EGR displaces fresh air in the cylinder at a given operating condition and must be accounted for in the estimation of air charge. Estimation of EGR is difficult, however, due to the unsteady flow conditions in the exhaust and durability of sensors in the harsh exhaust environment. This adds to the uncertainty associated with air charge estimation and A/F control, in general.

Uncertainty prevents precise control of A/F, leading to departures from stoichiometry. Steady state variation is managed with feedback control. Brief transient deviations are enabled by the oxygen storage behavior of the TWC. Ceria is added to the TWC to provide the capability to store a limited amount of oxygen for release when needed to complete oxidation reactions. The dynamics introduced by this behavior complicate control and TWC models including oxygen storage dynamics [18] are critical to effective control development.

2) Cold Start

Another challenging aspect of the TWC is its sensitivity to temperature. In fact, the TWC is considered ineffective at low temperatures, as it does not efficiently convert CO, NOx or HC. Cold start emissions of HC and CO account for more than 80% of the total HC and CO emissions over common test cycles [19]. Conversion efficiencies increase with temperature and the condition commonly referred to as "light off" occurs when HC conversion efficiency reaches 50%.

Warming the TWC more rapidly is one approach to improvement. A common control methodology for catalyst heating is aggressive spark retard, which increases the specific heat flow to the exhaust. This moves ignition from the optimal torque condition, increasing fuel usage and can increase engine out HC emissions. These competing objectives lead to a tradeoff requiring optimization for full benefit [19]. In advanced technology engines, where fuel is injected directly into the cylinder, at least one additional injection can be made prior to ignition to enable more aggressive spark retard for improved heating.

Another approach to reducing cold start emissions is reduction of engine out emissions while cold. For example, variable valve timing can be used to improve HC emissions at low temperature. Optimum intake valve timing can reduce wall wetting and improve mixture preparation [20, 21], while control of exhaust valve timing can improve secondary burning of HC and heat flow to the exhaust [21].

3) PZEV

California has legislated particularly aggressive emission regulations with the partially zero emissions vehicle (PZEV) standards. Achievement of these very low emissions is a formidable challenge, particularly when combined with fuel economy, vehicle performance and cost constraints.

As discussed earlier, the majority of tailpipe emissions occur during cold-start. As such, PZEV efforts are highly focused in this area. In some applications, the engine is operated rich with aggressive spark retard, producing significant CO and HC. Secondary air is injected into the exhaust path, providing the oxygen necessary for oxidation of these species. The large exotherm created by these reactions significantly improves the catalyst light off time.

In addition to several engine hardware and catalyst actions, such as introduction of charge motion control devices and increased TWC cell density, sensor modifications are also considered. For example, a fast light off HEGO, which reaches operating temperature very quickly, or a UEGO may replace the conventional HEGO sensor. Additional HEGO or UEGO sensors may also be added at other locations in the exhaust path to improve performance of sophisticated A/F control algorithms, for example fore-aft oxygen storage control [22].

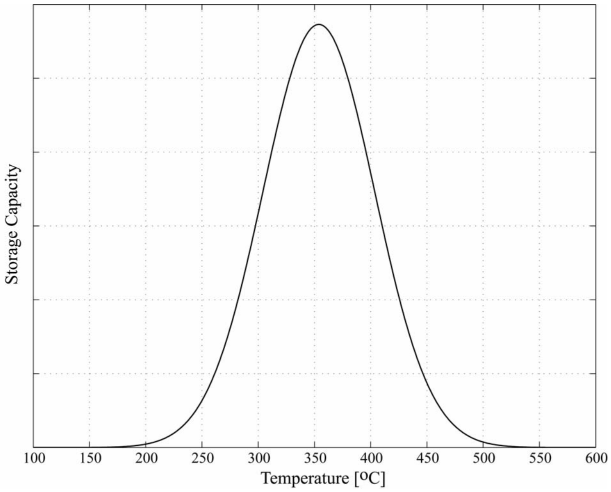

Fig. 4. LNT storage capacity is highly dependent upon temperature.

4) Lean Burning Gasoline Engines

Some advanced technology engines operate lean of stoichiometry to take advantage of improved fuel economy via reduction in pumping loss and enhanced thermal efficiency. PFI engines can be designed to operate with their homogeneous mixture at A/F near 20:1. Direct injection spark ignition (DISI) engines can operate at very lean conditions, potentially 60:1 or higher depending on the combustion system design. This very lean operation occurs during stratified combustion, when fuel is injected late in the compression stroke to form a small region of near stoichiometric mixture near the spark plug. The remainder of the cylinder is filled primarily with fresh air, forming an overall mixture that is very lean.

As seen in Figure 2, conversion of NOx by the conventional TWC is not efficient at lean conditions. Therefore, another catalyst specifically aimed at NOx conversion at lean conditions is added. A Lean NOx Trap (LNT) is currently the preferred approach.

Storage capacity of a typical LNT, shown in Figure 4, is high only in a relatively narrow temperature window [23]. The size and location of the temperature window varies with catalyst formulation, but an efficient operating temperature is generally in the neighborhood of 300-350^{o}C. Passive control of exhaust gas temperature limits the operating conditions at which the engine can operate lean. Active control with an exhaust gas heat exchanger and/or flow diversion device adds complexity, but can potentially lower overall system cost if the quantity of precious metal in the catalyst can be reduced.

As the name suggests, the LNT stores NOx; and it must be periodically regenerated by exposure to rich conditions. These frequent transitions from lean to rich operation must not be perceptible by the driver, making torque management a critical control feature. This control problem is especially challenging in DISI engines, where this transition entails switching to and from stratified operating conditions [24].

Regeneration, frequently referred to as purge, must be carefully controlled to avoid emissions breakthrough. Purge frequency and duration, as well as the A/F profile during purge are key control variables [25].

Knowledge of the storage state of the LNT is critical to effective control, particularly for decisions regarding purge initiation. Since the storage state cannot be directly measured, models are key components of an LNT control strategy. Some control schemes rely on models of incoming and breakthrough NOx to determine the state of the LNT [25]. Others utilize a NOx sensor downstream of the LNT to measure NOx breakthrough for initiation of purge. These methods also require estimation of incoming NOx to ascertain the state of the LNT.

End of purge is typically detected with an EGO sensor, either HEGO or UEGO. The oxygen sensor senses reductant breakthrough with a rich reading, indicating that conversion is nearly complete. Reductant breakthrough contributes to CO and HC emissions. Therefore models are often utilized in control in an effort to end purge before breakthrough occurs.

Optimization of purge frequency and duration requires sophisticated techniques due to the LNT storage element. Linear programming methods commonly used for optimization of engine operating conditions are not applicable. The dynamic programming approach presented in [26] is an excellent solution provided in a framework accessible to development engineers.

Another factor that must be considered in LNT control is the effect of sulfur. Sulfur is found in most fuels and sulfur oxides (SOx) are a component of combustion gases. The presence of SOx at the LNT results in formation of high temperature stable sulfates [27], which deplete NOx storage capacity. Regeneration, referred to as deSOx, requires exposure to high temperatures. Spark retard and/or lean rich cycling are common methods to increase exhaust gas temperatures to the levels required for deSOx. Initiation of deSOx is dependent upon knowledge of the state of the LNT, with modeling again playing a key role in the control strategy.

Thermal durability of the LNT is another challenge [27]. LNT storage capacity reduces with time and the effects of thermal aging are not recoverable. Therefore, adaptation is important to effective NOx control over the lifetime of the vehicle [2, 25].

B. *Diesel Engines*

A diesel engine operates with compression ignition of fuel injected directly into the cylinder. Time of fuel injection controls initiation of spontaneous combustion that occurs as the diesel fuel mixes with the high-temperature, high-pressure air in the cylinder. Diesel engines typically operate unthrottled at very lean A/F, providing significant improvements in pumping loss and efficiency, as compared to conventional SI engines [9]. These and other factors lead to improved fuel economy. This, combined with tax incentives and advances in driveability, contributes to the dramatic rise in popularity of diesel vehicles in recent years in many locations around the world. Diesel systems, however, face arduous challenges in emissions control as emission standards become more stringent.

Tailpipe emission concerns for diesel engines focus on gaseous emissions of HC and NOx (CO production is very small due to lean operation) and particulate matter (PM) emissions. PM consists primarily of soot on which other compounds are absorbed and results mostly from incomplete combustion [9].

1) *Particulate Emission Control*

Particulate emissions are currently controlled by diesel particulate filters (DPF). These devices effectively store PM by filtering it from the exhaust gas, but must be regenerated periodically by exposure to high temperature or by catalytic means.

Since diesel combustion temperatures are relatively low, heating the exhaust gas to a temperature where soot will burn typically requires an additional device. Electric heaters or fuel burners are an option but are costly and problematic [28]. An alternative is a diesel oxidation catalyst (DOC), which can be placed upstream of the DPF to heat the exhaust gas via exotherm from chemical reactions [29]. Reductant, for example fuel, is injected upstream of the DOC into the lean combustion gases, leading to the desired exothermic oxidation within the DOC. At least one temperature measurement in the exhaust path is typically available for DPF monitoring; however aggressive feedback control is difficult due to the slow temperature dynamics caused by thermal inertia. As such, temperature control relies heavily on open loop methods.

Regeneration is typically initiated based on the time since the last regeneration or measured pressure difference across the DPF, which is an indicator of loading level. The duration of the regeneration period can be fixed a priory, although more sophisticated approaches that account for changing DPF conditions due to aging and other factors can also be considered.

As the DPF ages, non-volatile PM accumulate, resulting in loss of storage capacity [29] and more frequent regeneration. This accumulation also leads to an increase in engine back pressure, which affects performance and fuel consumption. The change in back pressure over time may possibly be inferred from the measurement of the pressure difference across the DPF, making it a promising candidate for use in regeneration control schemes.

2) *NOx Emission Control*

NOx emission control currently focuses on engine out emissions. EGR is used, just as in the gasoline application, to reduce combustion temperature, and therefore NOx formation. Since the exhaust gas is very lean and contains a significant amount of oxygen in addition to burned gas, relatively large EGR rates are utilized to achieve NOx reduction in diesel engines.

As NOx emission regulations become more stringent for diesel vehicles, a catalyst may be required for NOx control. The characteristics of combustion are such that visible smoke and increased PM are generated when the engine is operated at A/F less than approximately 20:1. This is considerably leaner than stoichiometry making the TWC inefficient for NOx reduction. As an alternative, an LNT like that used in lean burn gasoline applications can be considered for diesel engine NOx control. This application is particularly challenging due to the low temperatures of diesel combustion [30] and availability of reductant for LNT purge.

LNT temperature can be controlled for both purge and deSOx with engine-based methods or by external methods, such as flow control devices in the exhaust and/or a DOC placed upstream of the LNT. Each approach presents its own control challenges. Engine-based control has limited authority given competing objectives of fuel economy, performance and engine out emissions. Exhaust flow control devices involve additional hardware, including control valves, which increase cost, complexity and durability issues. A DOC works well in a lean environment but duration of rich conditions must be fairly short to avoid loss of authority.

Providing reductant to the LNT for regeneration via rich operation of a diesel engine, although feasible, is difficult [28]. Combustion is inefficient at rich conditions and significantly larger amounts of PM are produced. This leads to more frequent regeneration of the DPF and potential durability issues due to deposits. Another potential approach, injection of fuel into the exhaust, is also challenging due to difficulty in achieving proper atomization of the fuel to prevent reductant breakthrough.

A fully robust solution to the challenge of NOx emissions control utilizing an LNT requires further development. Research in this area is intense as automakers strive to meet the strict diesel emissions standards of the future.

A potential alternative to the LNT is selective catalyst reduction (SCR) technology. In current production systems, Urea is injected upstream of a selective reduction catalyst [31]. Urea decomposes to ammonia, which serves as the reductant in the conversion of NOx. Accurate control of Urea injection is critical for conversion efficiency and to avoid breakthrough of ammonia, which can lead to a foul odor at the tailpipe. The complex behavior of the SCR catalyst [32], as well as the transient nature of automotive applications, complicates the control problem. Observer based feedforward control, along with feedback from a NOx sensor is a potential solution [33]. Compensation for NOx sensor sensitivity to ammonia, however, must be considered for effective feedback control.

NOx conversion with SCR technology is efficient, but implementation requires a reductant distribution and storage system, as well a change in societal infrastructure to support refilling. These issues are expected to limit application in the United States.

III. EVAPORATIVE EMISSIONS

Evaporative emissions regulations apply to emission of hydrocarbon from locations other than the tailpipe, when the vehicle is operating or parked. Three categories of evaporative emissions are typically considered: running loss, hot-soak and diurnal breathing loss (DBL) emissions [7].

Running losses include any vapor that escapes through seals, valves, etc. in the fuel system. Another consideration while running is crankcase emissions, which contain small particles of oil [34]. These emissions have been regulated since the early 1960's [3] and are typically controlled with a positive crankcase ventilation (PCV) system. This is passive system that diverts the ventilation gases to the intake manifold for combustion.

Hot soak is the period just after a hot engine is shut down. Hot soak emission sources are similar to running loss sources, but also include any fuel vapor remaining in the engine after combustion has stopped.

DBL emissions occur while the vehicle is parked [7]. The most prominent source of DBL emissions is the fuel system. A canister system is typically used to control emission of fuel vapors that develop in the fuel tank, generally as a result of temperature changes or during refueling [35]. These vapors are stored in the canister and later burned as part of a normal combustion event. The hydrocarbons in the canister are purged into the intake manifold for induction into the cylinder. A/F control during canister purge is challenging due to uncertainty in the quantity of vapor released.

DBL in the system can break through in several locations [8]. These include the air intake, the canister, the fuel tank and any piping or connection in the system that contain gaseous hydrocarbon. A proposed passive solution for the air intake system is a hydrocarbon filter located with the air filter [8]. Improved canister systems [35] and fuel systems [7] are also considered for improved DBL emission control.

IV. CONCLUSIONS

Control has played a critical role in the dramatic reduction in tailpipe and evaporative emissions of automobiles over the last four decades. Customer demands and rising environmental concerns will continue to motivate introduction of advanced technologies, leading to new and exciting challenges for research in this area for years to come.

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