

Proof-of-Principle Investigation into the Use of Custom Rapid Aging Procedures to Evaluate and Demonstrate Catalyst Durability

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ABSTRACT

The application of accelerated catalyst aging procedures on an engine dynamometer test bed for the purpose of demonstrating catalyst durability is examined. A proof-of-principle approach is followed using catalysts from vehicles certified to U.S. Tier 2 Bin 4 and California SULEV 2 levels. Accelerated durability demonstration methods based upon conventional fuel cut cycles were employed to age catalysts to levels predicted by quantification of thermal catalyst bed severity on the Standard Road Cycle (SRC) relative to the fuel cut aging cycle using the Bench Aging Time (BAT) equation. Emissions deterioration on the accelerated aging cycle is compared to the automobile manufacturers' certification values and to whole vehicle emissions performance results from several different in-use vehicle fleets. The influence of technology on whole vehicle emissions levels and deterioration characteristics is also evaluated. Statistical analysis and modeling results support the conclusion that both catalyst and vehicle technologies play significant roles in achieving improved emission performance.

INTRODUCTION

TECHNICAL BACKGROUND

Recent advances in computer engine management have enabled vehicle emission levels to be controlled at very low levels. In order to meet the durability requirements for Tier 2 emissions standards, emission and engine control systems must work together and maintain a high level of performance for an extended duration, up to 150,000 miles in some certification options. Over the past three decades, this objective has been achieved in part through advances in automotive catalyst technology, including improvements in

catalyst stability to minimize deterioration, the sources and impacts of which have been studied extensively. [1, 2, 3, 4] The loss of conversion efficiency performance associated with different modes of catalyst deterioration, including thermal exposure, chemical poisoning, physical/mechanical shock and other stressors that occur during mileage accumulation, can be characterized differently in terms of underlying causative mechanisms, such as sintering of precious metals, loss of oxygen storage capacity, reduction of catalytic surface area, increased diffusion resistance within the washcoat and loss of active catalytic sites. [5]

Performance loss resulting from thermal exposure is widely accepted as being the most significant mode of catalyst deterioration experienced in modern (Tier 2, Euro V) vehicles across the full spectrum of real-world conditions. Thermal degradation reduces catalyst efficiency by both sintering of precious metals and by reduction in catalyst surface area. The exponential nature of thermal mechanisms means that the level of deterioration resulting from a single, short duration, high temperature event may be equivalent to many miles of normal in-use operation. Modern catalyst technologies exhibit excellent tolerance to high temperature exposure, even at temperatures exceeding those encountered during the most severe real-world driving. [6] Controlling cold start vehicle emissions was a primary driver over the last three decades to improve catalyst thermal durability. As catalyst thermal durability improved, automakers had the option of reducing cold-start emissions by moving catalysts closer to the exhaust manifold ("close-coupled") and achieving light-off more quickly, especially in combination with advanced control strategies like secondary air injection and/or retarded spark timing.

Poisoning by engine-oil derived phosphorous compounds is recognized as the other dominant mode of catalyst

deterioration that occurs in real world vehicle use. [7] While thermal exposure may play the larger role in determining overall in-use catalyst deterioration across different vehicle fleets as a whole, phosphorous poisoning is still the subject of considerable investigation in recent technical literature, which suggests that its impact in real-world vehicle operation is not insignificant. [8-9] Efforts to reduce catalyst poisoning attributable to engine oil phosphorous has been affected primarily by the use of tighter engine designs that lessen engine oil consumption and reductions in phosphorous content allowable under engine oil specifications.

Other catalyst deterioration modes, especially mechanical failure modes like catalyst cracking, washcoat flaking, substrate erosion, and intumescent mat degradation, which may be influenced by operating temperatures, are relatively common and occur with varying frequency across different manufacturers, vehicle models and emission system designs. [10]. Operational problems with the engine control system, often requiring reprogramming and malfunction or deterioration of other engine systems are found to be the typical core of the mechanical failures modes and thermal deterioration observed on in-use vehicles. [11]

ACCELERATED CATALYST AGING

The true measure of catalyst durability is found in real world experience. Vehicle regulations require that emission systems are capable of meeting emission specification throughout their lifetime with lifetimes approaching 150,000 miles. A method of accelerating the catalyst aging process to demonstrate the catalyst durability to meet lifetime performance requirements is obviously desirable. Such a procedure enables demonstration of catalyst durability to meet performance and life time requirements in a relatively short period of time. A critical aspect of any accelerated aging process is that it must reflect the realities observed under real world conditions and not introduce artifacts arising from the process itself.

The ideal accelerated catalyst procedure would exactly replicate normal real-world operating conditions from both performance and mechanistic perspectives. However, in order to fulfill the demonstration requirements within a shortened period of time, an accelerated aging process subjects the catalyst to severe operating conditions that emphasize deterioration mechanisms associated with a limited number of expected real-world failure modes, namely thermal aging. [12, 13, 14] The accelerated aging process can take the form of vehicle operation on a road, track, or chassis dynamometer. It may also be a process that relies on using an engine, burner or oven to thermally stress the catalyst. These thermally based accelerated aging processes need to be correlated with real world performance to ensure that they provide a meaningful demonstration of catalyst durability to meet performance requirements. This correlation to real

world performance is critical as accelerated catalyst aging procedures have been shown to introduce artifacts that do not correlate with normal real-world use, such as abnormal deposition of engine-oil derived ash deposits or the relationship between oxygen storage and catalyst conversion. [15-16].

GLOBAL VEHICLE CERTIFICATION AND TYPE APPROVAL PROCESSES

Background

Vehicle manufacturers must obtain advanced, pre-production approval from regulatory authorities prior to introducing a vehicle for sale for use with a specified fuel type (e.g., gasoline, diesel, ethanol, natural gas). In effect, as part of this pre-production approval process, vehicle manufacturers must demonstrate in advance that the vehicles they produce are capable of meeting applicable emission standards over the useful life of the vehicle using whatever commercially available fuels are available within the respective markets in which their vehicles will operate. This determination is based in part upon a prediction of emissions levels and emissions system deterioration developed during the durability demonstration process, including emissions test data and other information submitted to the certifying party by the manufacturer with the application.

Global vehicle emissions certification processes provide mechanisms to facilitate the use of accelerated aging cycles to rapidly demonstrate that the vehicle emission systems are capable of meeting the required standards. The United States, the European Union and China explicitly describe accelerated aging process for demonstrating catalyst performance capabilities. In North America, the regulatory program that specifies appropriate emission durability demonstration procedures for the vehicle certification process is known as "CAP 2000," which was issued by the U.S. Environmental Protection Agency ("EPA") in 1999. [17] The types of durability demonstration procedures allowed under CAP 2000 fall into two basic categories: whole vehicle aging and bench aging. Whole vehicle aging involves a vehicle accumulating mileage on a track or a dynamometer using an aggressive driving cycle, which, along with periodic emissions testing, facilitates estimation of emissions deterioration that a substantial majority of vehicles are expected to experience in real-world use as a function of mileage. Bench aging entails aging critical emission-related components, namely catalysts and oxygen sensors, on an engine dynamometer bench under accelerated conditions designed to yield emission deterioration equivalent to that expected to occur in-use during the useful life of the vehicle. During most bench aging tests, catalyst deterioration results primarily from thermal exposure, and, in fact, CAP 2000 allows for non-thermal catalyst deterioration that is expected to occur in real-world use to be represented by an additional

amount of thermal deterioration during the bench aging process.

EPA has specified accelerated whole vehicle and bench aging procedures called the Standard Road Cycle (SRC) and the Standard Bench Cycle (SBC), respectively. The SRC is a whole vehicle cycle that can be run on a track or on a mileage accumulation dynamometer and serves as a reference for the thermal severity experienced by the catalyst in a given vehicle/engine design, in addition to being a valid option for the durability demonstration process. The SBC is an engine bench aging cycle that was established as an official standard procedure for the durability demonstration process and is conceptually similar to the General Motors Rapid Aging Test (RAT) procedures. [17]

In order to confirm that vehicles are meeting emissions standards in real-world use, manufacturers are required to procure and test in-use vehicles for the In-Use Verification Program (IUVP). [18] IUVP data are also used to measure the validity of the procedures employed to predict vehicle emissions performance and deterioration during durability demonstration for certification. The comparison between IUVP data and durability demonstration predictions in North America serve as a feedback mechanism to guide refinement of durability demonstration procedures by manufacturers that improve correlation with real-world vehicle experience.

The pre-production approval process for motor vehicles in Europe is similar to, but not identical to, the North American CAP 2000 program. As in North America, modern vehicle “type approval” in Europe relies upon the SRC and SBC. Similar to the North American IUVP program, vehicles must meet specified “in service conformity” standards after operating on commercially available fuels in use. [19] However, Europe, unlike North America, requires use of the SRC and SBC as the basis for vehicle type approval whenever vehicle manufacturers opt to conduct vehicle testing. (Europe also has an assigned deterioration factor option for a segment of the vehicle fleet.) In the North American CAP 2000 program, by contrast, vehicle manufacturers can develop and use “proprietary” bench aging and whole vehicle driving cycles so long as they provide an “equivalency factor” to EPA with their certification applications that relates the proprietary cycles to the SRC and SBC defined in the applicable regulations. For those vehicle manufacturers that use proprietary cycles, EPA publishes the requisite equivalency factors so that the public can relate the thermal severity of proprietary cycles to the SRC and SBC. [20]

Catalyst durability demonstration

The calculation approach employed with the Bench Aging Time (BAT) equation is based on the Arrhenius equation which relates chemical reaction rates as a function of

temperature and provides the relationship between aging time and thermal exposure condition. [11, 17] The effective reference temperature (T_r) of the SBC (or alternative approved OEM cycle) is defined as the characteristic single temperature representing the entire temperature-history experienced during the SBC on the catalyst aging bench. The calculated T_r value is inserted into the BAT equation along with SRC catalyst temperature histogram data to calculate the total bench aging time equivalent to 120,000 miles (or other durability objective) of aging on the road as the vehicle is driven on SRC cycle. The BAT equation aging time is typically multiplied by a factor of 1.1, which accounts for all other sources of non-thermal aging, to determine the adjusted total bench aging time,

Deterioration factors (DFs) are calculated from periodic emission data collected during the durability demonstration process. The calculation of the DF must be based on the linear regression or another regression model approved in advance by EPA. Two types of DFs can be reported, which are a multiplicative DF and an additive DF. The multiplicative DF (MDF) is the ratio of the full or intermediate useful life mileage level to the stabilized mileage (e.g. 4000-mile) level from the regression results. The additive DF (ADF) is the difference between the full or intermediate useful life mileage levels to the stabilized mileage (e.g. 4000-mile) level from the regression results. All the regressed emission levels as well as the additive DFs need to be rounded to the same precision. Published DF values can provide a useful reference for EPA and other parties to compare certification predictions of vehicle emissions performance versus actual in-use emission performance, in order to improve the real-world predictability of durability demonstration methods.

The objective of this work is to implement, on a proof-of-principle basis, the correlation between accelerated aging procedures for a given vehicle and real world performance. A key issue that is investigated is the approach outlined by EPA that facilitates the use the accelerated catalyst aging testing procedures by third parties to demonstrate catalyst durability and to predict in-use vehicle emissions performance in a manner analogous to that employed by automakers for certification purposes. Emissions performance durability on a customized accelerated aging cycle is examined in the context of certification emissions data as well as in-use vehicle performance data. The impact of catalyst technology and vehicle technology on vehicle emissions and durability performance are also examined.

EXPERIMENTAL

Two different compact passenger cars equipped with four-cylinder gasoline engines of approximately 2 liters displacement were used for this test program. The first slave vehicle was from the 2005 model year and was certified to

the Tier 2 Bin 4 (“T2B4”) standard. The second slave vehicle was from the 2004 model year and was certified to the California SULEV 2 (“SULEV”) standard. The two slave vehicles were of the same model nameplate, but from different model years and certified to different emissions standards. Results from duplicate FTP emissions tests conducted with both vehicles in as-received condition met applicable standards, and on this basis were judged to be operating properly, as designed and produced by the manufacturer.

The general layouts and designs of the three-way catalyst (TWC) catalyst systems on both vehicles were similar and, most importantly, interchangeable. Both vehicles were equipped with a manifold-mounted close-coupled (CC) converter and an under-floor (UF) converter. The converter in each location comprised two catalyst bricks; however, the second brick on the under-floor converter of the T2B4 vehicle was not washcoated. The close-coupled catalysts on the T2B4 vehicle were 400 cells per square inch (cps) while the close-coupled catalysts on the SULEV vehicle were 900 cps. All UF catalysts bricks were 400 cps. These details are summarized in [Table 1](#). Equivalency factors for OEM procedures defined in CAP 2000 were not published for 2004 and 2005 model year vehicles. Based upon 2008 model year equivalency factors published by the manufacturer of the vehicles used in this study, which ranged over a fairly tight span from about 0.8 to about 1.2, with an average of approximately 1.0 for the 2008 model year, the equivalency factors for the OEM procedures used to certify the vehicle models used in this study were estimated to be 1.0. [\[20\]](#)

The engine bench used for catalyst aging consisted of a Ford 4.6-liter V8 coupled to a General Electric direct current dynamometer Model 42G407BT. A MoTec engine management system was used to control engine operating conditions, specifically to achieve desired volumetric space velocities, air fuel ratios and catalyst inlet temperatures. The Ford 4.6-liter engine was used solely as an exhaust generator in this study and was chosen for this purpose based upon extensive experience with this engine in Afton laboratories. Only exhaust from the left bank of the Ford V8 was used for catalyst aging. A custom adapter plate was fabricated to mate the (non-Ford) catalyst systems to the Ford's engine block with minimal additional distance between the close-coupled catalyst front face and the exhaust valves. Exhaust inlet temperatures were measured at the center of the exhaust stream approximately 2.5 cm upstream of the front face of the close-coupled catalyst. Exhaust backpressure (differential pressure across the close-coupled catalyst) was monitored, but not controlled during aging. For catalyst aging experiments, new catalysts were purchased from a local dealer based upon the VIN numbers of the emissions test vehicles. New catalysts were de-greened for four hours under stoichiometric air-fuel ratio (AFR) at 600°C inlet temperature

to stabilize performance and reduce variability for “zero” hour emissions performance measurements.

The performance of aged catalysts was evaluated at Roush Laboratories in Livonia, MI, using duplicate emissions tests on the Federal Test Procedure (FTP) with one or both emissions test vehicles at prescribed intervals of aging (either 50 hours or 100 hours). Modal and second-by-second emissions were measured at the engine-out, mid-catalyst (between the close-coupled and under-floor catalysts) and post-catalyst locations, in addition to tailpipe FTP bag emissions. Criteria developed during the Air Quality Improvement Research Program (“AQIRP”) were used to ensure repeatable emissions results. Specifically, a triplicate FTP emissions test was conducted whenever the ratio of weighted bag emissions between the first two tests was greater than 1.33 for HC, greater than 1.70 for CO or greater than 1.29 for NOx. [\[21\]](#) All emission data presented were average values of either duplicate (or triplicate, if necessary) based on this criterion. MDFs were calculated based on the linear regression of emission data collected at the assigned aging intervals.

Note that only the impact of catalyst aging was evaluated in this study. Initial tests conducted with match sets of aged catalysts and oxygen sensors resulted in a substantial amount of variability during vehicle emission testing. On that basis, the decision was made to focus solely on the impact of catalyst aging and a single set of vehicle oxygen sensors were used for all emissions tests resulted reported in this paper.

All catalyst aging experiments reported in this paper were conducted using a simple fuel cut cycle. Each repeating element of the cycle consisted of sixty seconds of stoichiometric operation followed by five seconds of fuel cut operation. With this aging cycle, catalysts were exposed primarily to high temperatures at stoichiometric operating conditions with a lesser amount of exposure to high temperature lean operating conditions. The same general criteria were applied to the development of engine operating parameters for the aging cycle for both catalyst system designs, specifically: (1) close-coupled catalyst inlet exhaust temperature adjusted to $840 \pm 10^\circ\text{C}$ for the stoichiometric portion of the cycle and (2) space velocity of $75,000 \text{ hr}^{-1}$ based upon volume of the close-coupled catalyst only. Characteristic catalyst inlet and bed temperature profiles for T2B4 and SULEV catalyst systems during the fuel cut accelerated aging cycle are shown in [Figure 1](#). Using these control parameters, the lower cell density T2B4 catalyst design displayed slightly higher operating temperatures during the stoichiometric portion of the engine aging cycle compared to the SULEV design. The SULEV catalyst exhibited slightly elevated peak temperatures and a sharper transient during the actual fuel cut segment, but this does not result in overall greater thermal exposure over duration of the

aging program. [22] This observation is confirmed further in the discussion of the BAT equation calculations below.

Haltermann EEE fuel was used for all catalyst aging experiments. Certification grade Tier 2 unleaded gasoline was used for vehicle emissions testing.

Nine additional vehicles of the same make and model as the slave vehicles were procured from two different areas of the U.S. to facilitate comparisons between certification data and emissions results generated with engine-aged catalysts from this program. All nine vehicles were certified to the same engine family as the T2B4 slave vehicle. Three of these vehicles were from an area of the U.S. where conventional gasoline is used (the T2B4 slave vehicle was also acquired from this area) and six vehicles were purchased from an area of the U.S. where reformulated gasoline (RFG) is required. Once received at the emissions test lab, normal maintenance procedures were performed to ensure all vehicles were in proper mechanical condition for testing.

RESULTS AND DISCUSSION

CYCLE DEVELOPMENT AND ANALYSIS

Each catalyst system design was run on the vehicle corresponding to its certification over the SRC and catalyst bed temperatures were recorded to enable thermal severity calculations and analysis via the BAT equation. Catalyst bed temperature histogram data and BAT equation calculations at the second and the third rows in [Table 2](#) show the reference temperatures for the SRC with the T2B4 catalyst system and the SULEV catalyst system were 735°C and 740°C, respectively.

BAT Equation calculations using catalyst bed temperature histogram data measured for the fuel cut aging cycle, seen in [Table 2](#), showed that the effective reference temperatures for the fuel cut aging cycle were 932°C for T2B4 catalyst and 923°C for SULEV catalyst, respectively. As mentioned previously, the effective reference temperature calculated using the BAT equation allows the thermal severity of a bench or road cycle to be compared to that of other cycles, with a higher T_r indicating more severe aging in terms of the thermal aging mechanism. Therefore, the T_r for the SRC cycle was roughly 200°C lower with both catalyst designs than the corresponding T_r values during the engine bench aging cycle, demonstrating the disparity in thermal severity between whole vehicle mileage accumulation, even on an aggressive cycle like the SRC, compared to a typical engine bench aging cycle. Catalyst bed temperature histogram data on the SRC, and the calculated T_r values, showed that the SULEV catalyst system experienced slightly higher temperatures than the T2B4 system. This observation revealed that the 900 cpsi close-coupled catalyst on the

SULEV platform was not exposed to a noticeably more severe thermal environment than the 400 cpsi T2B4 close-coupled catalyst over the same bench or road aging cycle, similar to observations made previously by another researcher. [23]

Following the procedures for BAT equation calculation, the total adjusted bench aging time equivalent to full useful life for the T2B4 catalysts were calculated to be 165 hours for 120,000 miles of vehicle operation on the SRC. The total adjusted bench aging time for the longer 150,000 mile SULEV durability requirement was significantly higher at 255 hours.

VEHICLE EMISSIONS TESTING

Weighted bag FTP emissions results as a function of aging time are shown in [Figures 2](#), [Figure 3](#), [Figure 4](#). Vehicle emissions testing with the the T2B4 catalyst system was conducted only on the T2B4 vehicle. Vehicle emissions testing with the 900 cpsi SULEV catalyst system was conducted on both the SULEV-certified vehicle as well as on the T2B4 certified vehicle. For all testing purposes, including aging and emissions testing, a single close-coupled catalyst and a single under-floor catalyst were considered as a matched set and not interchanged with individual catalysts from other sets. Hence there are three groups of data for vehicle emissions testing: (1) T2B4 catalysts on the T2B4 slave vehicle, (2) SULEV catalysts on the T2B4 slave vehicle and (3) SULEV catalysts on the SULEV slave vehicle. Comparison between the first and the second datasets facilitated determination of differences in performance attributable to the catalyst technology, while differences between the second and the third data groups were assigned to differences in engine technology and/or calibration approach.

Overall emissions testing results generally exhibited the expected trend of increasing emissions with increasing bench aging time on the fuel cut cycle. However, catalyst performance and deterioration were more complex than a simple linear function of aging time. For NMOG emissions, much greater deterioration was observed for T2B4 aged catalysts tested on T2B4 vehicle than for SULEV catalysts on either slave vehicle. Advanced catalyst technology incorporated into the SULEV catalyst design, like higher cell density, provided a significant improvement in the hydrocarbon emissions reduction, although vehicle technology appeared to convey some additional benefit as well. Most of the benefit observed for HC emissions reduction with vehicle technology was apparent in the cold start emissions. Analysis of engine-out air-fuel ratio (AFR) during the first twenty to thirty seconds showed that the SULEV vehicle employed a lean cold-start strategy which reduces engine out HC emissions as well as hastening catalyst light-off. The net result can be seen in [Figure 5](#).

which shows a substantial decrease in bag 1 HC emissions for a SULEV catalyst on the T2B4 slave vehicle compared to those for the same SULEV catalyst on the SULEV vehicle.

Very little if any deterioration in CO emissions performance was observed for T2B4 catalysts tested on the T2B4 vehicle, even after 300 hours of aging. When the SULEV catalyst was tested on the T2B4 vehicle, a slight amount of deterioration was present after the first 50-hour period and may be related to catalyst stabilization. However, SULEV catalyst CO emission levels were mostly flat from 50 hours of aging through 250 hours of aging, similar to the trend of T2B4 catalysts. However, results were quite different for SULEV catalysts tested on the SULEV slave vehicle, which showed a consistent linear deterioration as a function of aging time, although overall CO emissions were lower than for the SULEV catalyst on the SULEV slave vehicle compared to the T2B4 slave vehicle. The lack of CO deterioration with either catalyst type on the T2B4 vehicle is suspected to be linked with the fact that this vehicle has a manual transmission. T2B4 vehicle operation was characterized by fuel cuts of greater frequency and longer duration during deceleration events in the FTP cycle compared to the SULEV vehicle, which was equipped with an automatic transmission. Presumably the more noticeable fuel cut strategy on the manual transmission vehicle results in the compensation/maintenance of an oxygen-rich catalyst surface during deceleration and subsequent idling. This excessive oxygen subsequently provides additional oxygen to react with the higher levels of CO typically associated with acceleration events that follow decel and idle events. This benefit becomes more significant as the catalyst has been exposed to a certain degree of aging, when some initial oxygen storage capacity has been lost and less oxygen is available for CO conversion.

Both T2B4 and SULEV catalysts displayed consistent, relatively linear deterioration in NO_x emissions with increasing bench aging time, with T2B4 catalysts showing faster deterioration. Advanced SULEV vehicle control technology yielded additional noticeable improvement towards lowering NO_x emissions.

As described in the CAP 2000 final rule, MDFs can be calculated through regression of periodic emission data. Linear regression was used to calculate multiplicative DFs for T2B4 catalysts on the T2B4 slave vehicle. As mentioned earlier, the BAT equation predicted 165 hours of accelerated aging using the fuel cut cycle would be equivalent to the deterioration of 120K miles on-road usage for the T2B4 vehicles. [Figure 6](#) presents interpolated MDFs for T2B4 catalysts aged for 165 hours and published 120K mileage certification data. The NMOG DF from 165 hours of fuel cut aging is in good agreement to 120K certification data. As discussed previously, aged catalysts showed very little CO deterioration and therefore CO DFs at 165 hours were much lower than the certification CO DF, probably as a result of the

emissions slave test vehicle having a manual transmission. The NO_x DF after 165 hours of aging was somewhat higher than the certification data.

STATISTICAL ANALYSIS OF FTP TAILPIPE EMISSION

The impact of factors including aging time, catalyst technology and vehicle technology on catalyst performance was analyzed through statistical modeling. All factors as well as interactions involved in the model are listed in [Table 3](#). For each factor or interaction in the model, a p-value was calculated using the linear regression model that indicates the possibility of accepting the hypothesis that there is no significant difference in the average emissions between the factor levels. All statistical analysis was made at the 95% confidence level. Thus, a p-value less than 0.05 indicates a statistically significant (non-zero) difference in the average emissions for that factor. Regression analysis results and p-values are summarized in [Table 4](#).

Results showed that the zero-hour emission levels (i.e., intercept in [Table 4](#)) were statistically significant and played an important role in determining emission levels. These differences arose not only from catalyst and vehicle technologies, but also from variability among individual catalysts of the same design during the production process. Catalyst performance deteriorated with increased aging time for NMOG and NO_x emissions, but aging time was not a significant factor for CO emissions. The potential technical reason for this result has already been described. Advanced catalyst technology makes a significant contribution for emission improvement for all three exhaust streams. Higher cell density substrates reduce catalyst light-off times. Advanced washcoat technology can also lead to advantages for vehicle emissions. The interaction between catalyst technology and aging time is more significant for CO and NO_x, while the contribution from technology regarding HC conversion is less impacted by aging time. Sophisticated vehicle technologies (such as more precise AFR control) can also be beneficial to improve catalyst performance and decrease emission levels, especially for NMOG and CO in this work.

CATALYST EFFICIENCY AND AGING

[Figures 7, 8, 9](#) show close-coupled catalyst conversion efficiency (CCCE) as a function of aging time, and [Figures 10, 11, 12](#) show conversion efficiency of the total catalyst system (TTCE), which includes combined performance of close-coupled and under-floor catalysts, as a function of time. These figures indicate that catalyst performance deteriorated with increased aging time, but the degree of the deterioration varied with exhaust species and catalyst location (i.e. close-coupled or under-floor).