

# Brake System Performance at Higher Mileage

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## ABSTRACT

The purchase of a new automobile is unquestionably a significant investment for most customers, and with this recognition, comes a correspondingly significant expectation for quality and reliability. Amongst automotive systems -when it comes to considerations of reliability - the brakes (perhaps along with the tires) occupy a rarified position of being located in a harsh environment, subjected to continuous wear throughout their use, and are critical to the safe performance of the vehicle. Maintenance of the brake system is therefore a fact of life for most drivers - something that almost everyone must do, yet given the potentially considerable expense, it is something that of great benefit to minimize. Additionally, the performance of the brake system (like the tires) can change over the useful life of the components, realized in the form of changing friction levels, fluid consumption, and drag at a brake corner level, and realized to the driver in the form of changing pedal effort, travel, response time, and fuel economy.

Most studies of brake system performance, and most regulatory requirements that affect the design of the brake system, focus on the "near-new" condition. This is not accidental, the simple fact is that it is extremely difficult, expensive, and time consuming to realistically accelerate wear of brake components so that performance can be assessed in a worn condition. On a well-designed brake system, components in the hands of an average customer can last 5-10 years before wear out occurs, meaning that any practical study of wear effects must be greatly accelerated to occur within a typical vehicle development timeline. Environmental exposure involves many complex and time-dependent chemical reactions, which puts an upper limit on how much simulated field exposure can be accelerated.

The present study is based primarily on evaluation of brake corner performance after vehicle-level durability test exposure. Brake corners from a diverse selection of vehicles (including two hybrid vehicle examples) were retrieved from end-of test vehicles that had received the structural equivalent of 160,000 km of test exposure, along with 10 years of simulated corrosion exposure, and then subjected to performance and residual drag tests. To supplement the findings, lab-based studies of brake hardware with simulated 50% worn use and corrosion exposure are also referenced. Brake corner performance including apparent friction level, fluid consumption, drag, torque variation, and torque hysteresis were studied and related to observations of the physical condition of the parts. The effect of the measured brake corner level performance was then accounted for at a vehicle level in the form of pedal feel, fuel economy, and lining life for representative case studies.

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## INTRODUCTION

Simulating the effects of corrosion exposure, debris exposure, and brake component wear simultaneously throughout an entire brake corner lifecycle is a difficult task, and one often left to vehicle level durability type evaluations. As a result, detailed bench level measurements of key performance characteristics with all three of these inputs are frequently unavailable. In order to bridge this gap, brake corner hardware from an array of different vehicle types were collected following a 10 year accelerated corrosion exposure durability test, and subjected to a number of bench level brake corner dynamometer performance evaluations to capture caliper fluid consumption, residual brake drag, apparent friction, and brake torque variation. By first comparing this measured data to the population averages from new condition product validation data sets, an assessment of performance degradation can be made. Following this,

predictive simulation tools can be used to assess the impacts to customer facing attributes - namely pedal feel and fuel economy. Additionally, subjective evaluations of cosmetic corrosion and service considerations are made.

The authors will note that the study represented in this paper results from review of internal test reports published over a span of about 4 years. Vehicles were included in this internal benchmarking activity somewhat opportunistically. The present study attempts to tie together and draw comparisons between results from what had been a series of self-contained measurement programs.

A cursory internet search on corrosion related brake complaints yields a number of examples of recent model vehicles generating significant customer dissatisfaction - one does not have to look hard to identify exasperated vehicle owners with corrosion related brake complaints.

As such, an investigation into various design strategies' efficacy in preventing corrosion related brake failure modes is of crucial importance.

For the benefit of the reader, an index of topics covered and their organization within this paper is noted below:

1. Description of Samples and Test Exposure
2. Summary of Findings and Discussion
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  - b. Analysis of Pad to Caliper Bracket Corrosion Binding Effects in Sliding Calipers
  - c. Comparison of Brake Caliper Corrosion Binding With and Without Regenerative Braking
  - d. Effect of FNC rotors on corrosion of braking and mounting surfaces
  - e. Effect of Regenerative Braking on Rotor Surface Corrosion Cleaning (Vehicle G to I)
  - f. Effect of Usage on Brake Hose Expansion
  - g. Different Effects of Corrosion Binding on Front and Rear Axle Hardware
  - h. Different Effects of Corrosion Binding on Aluminum vs. Cast Iron Calipers
  - i. Comparison of carbon ceramic to traditional cast iron rotors in a high performance system
  - j. Assessment of Cosmetic Corrosion Performance (zinc vs. zinc-nickel vs. paint)
  - k. Effect of Long Term Usage on Rotor Lateral Runout (LRO) and Disc Thickness Variation (DTV)
1. 5 year vs. 10 year corrosion exposure
3. Test Case: Corrosion Induced Fuel Economy Degradation through Vehicle Life
4. Test Case: Corrosion Induced Pedal Feel Degradation through Vehicle Life
5. Summary/Conclusions

## 1. DESCRIPTION OF SAMPLES AND TEST EXPOSURE

Brake corner hardware from a variety of vehicle types were evaluated, including cars and trucks, hybrid and traditional powertrains, and different corrosion protection design strategies. A high level summary of the vehicles from which hardware was retrieved is shown in [Appendix A](#) at the end of this paper.

Each set of brake corner hardware was subjected to vehicle level general durability testing including accelerated corrosion exposure. The test cycle simulates the effect of 10 years of use and corrosion exposure in a 95th percentile severity corrosion environment. Vehicle E is an exception, in that only 5 years of equivalent corrosion exposure was simulated. Following durability testing, the brake

calipers, pads, and rotors were retrieved from the vehicle for component testing. Where possible, rotor LRO and DTV measurements were recorded prior to component removal, and other relevant disassembly information was noted.

Vehicle A front calipers have an anodized and painted aluminum body, and use brake pads with phosphate treatment (NAO only) and a powder paint. One test began with low met brake pads, and completed the entire schedule using the original pads. The second test began with low met brake pads, but required a pad replacement mid test, at which point NAO pads were used. The front and rear rotors are cast iron and treated with ferritic nitrocarborization (FNC). Rear corner hardware from this vehicle was not available for analysis.

Vehicle B front calipers have an anodized and painted aluminum body, and use brake pads with powder paint only. Rear calipers have an anodized and painted aluminum body, and use brake pads with powder paint only. The front and rear rotors are standard cast iron.

Vehicle C front calipers have an anodized and painted aluminum body, and use brake pads with powder paint only. The front rotors are standard cast iron. Rear corner hardware from this vehicle was not available for analysis.

Vehicle D opposed piston front calipers have an anodized and painted aluminum body, and use brake pads with powder paint only. Rear opposed piston calipers have an anodized and painted aluminum body, and use brake pads with powder paint only. The front and rear rotors are standard cast iron, with cross-drilling.

Vehicle E front and rear calipers are identical to vehicle D, though they are paired to a carbon ceramic front rotors, and use pads with carbon ceramic compatible friction material. Brake pads are protected with powder paint only.

Vehicle F twin piston sliding front calipers have a Zinc plated cast iron body and bracket with clear coat sealer, and use brake pads with phosphate treatment and a powder paint. The front rotors are cast iron and treated with ferritic nitrocarborization. Rear corner hardware from this vehicle was not available for analysis.

Vehicle G single piston sliding front calipers have a Zinc plated cast iron body and bracket with clear coat sealer, and use brake pads with phosphate treatment and a powder paint. Single piston sliding rear calipers have a Zinc plated cast iron body and bracket with clear coat sealer, and use brake pads with phosphate treatment and a powder paint. Rear calipers have a mechanical integral park brake feature. The front and rear rotors are treated with ferritic nitrocarborization.

Vehicle H single piston sliding front calipers have a Zinc-Nickel plated cast iron body and bracket with clear coat sealer, and use brake pads with powder paint only. Single piston sliding rear calipers have an anodized aluminum body and Zinc-Nickel plated cast iron bracket with clear coat sealer. Rear calipers have a motor on caliper electric

parking brake feature. Brake pads with Zinc-Nickel plating and a powder paint are used in the rear. The front and rear rotors are treated with ferritic nitrocarborization.

Vehicle I single piston sliding front calipers have a Zinc-Nickel plated cast iron body and bracket with clear coat sealer. Front pads are protected with powder paint only. Single piston sliding rear calipers have a Zinc-Nickel plated cast iron body and bracket with clear coat sealer. Rear calipers have a motor on caliper electric parking brake feature. Brake pads with Zinc-Nickel plating and a powder paint are used in the rear. The front and rear rotors are treated with ferritic nitrocarborization.

## 2. SUMMARY OF FINDINGS AND DISCUSSION

### 2a. Comparison of NAO and Low Met Friction Behavior Following Corrosion Exposure

In an attempt to contrast friction behavior differences in NAO and Low Met formulations following 10 year equivalent accelerated corrosion, data from vehicle A front corners is analyzed. Vehicle A offers both NAO and Low Met friction variants, with otherwise the exact same opposed piston aluminum front caliper design. The rotors paired with both friction sets are also identical, and FNC treated.

As can be seen in Figure 1, the general tendency for both friction material types is to experience a nominal drop in apparent friction with corrosion accumulation, which varies depending on the type of stop conditions in question (pressure ramp and FMVSS135 style stop conditions are evaluated). A combination of taper wear and corrosion binding of the pads within the caliper assembly work to reduce the overall efficiency of the caliper as a clamping device, reducing the net apparent friction of the brake corner. Additionally, accumulated corrosion on the braking surfaces reduces pad to rotor surface contact, and the ability of the friction material to form and maintain a stable tribofilm, reducing the friction output of the brake pads. The result is a net decrease in apparent friction which will be evident in vehicle level pedal feel, though in this example, little difference between the NAO and low met friction is evident.

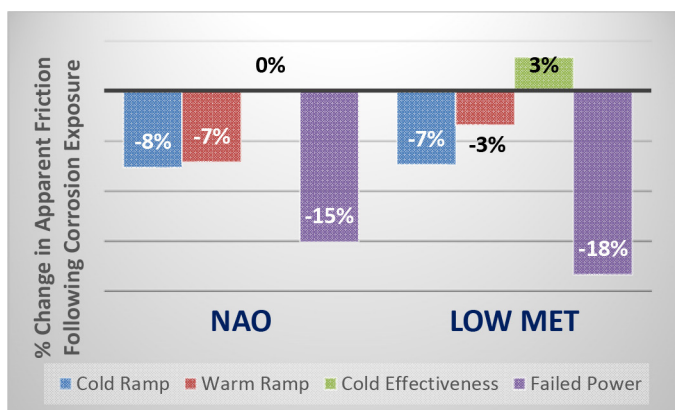


Figure 1. Apparent Friction of NAO and Low Met Linings on Vehicle A following corrosion exposure.

### 2b. Analysis of Pad to Caliper Bracket Corrosion Binding Effects in Sliding Calipers

In order to quantify the effects of different brake pad and caliper bracket corrosion protection strategies, we can compare fluid consumption and brake drag results from vehicle G and vehicle H rear hardware. These particular corners offer a unique look at corrosion effects, as vehicles G and H have similar strong hybrid powertrains, leading to greatly reduced foundation brake duty cycle throughout the durability test. It is clear in visual analysis of the hardware that corrosion growth in the brake pad to caliper bracket contact area is present, and may lead to increased slide forces. In the new condition, drag torque values between vehicle G and H calipers are quite similar. In Figure set 2, we show post 10 year equivalent corrosion vehicle G front and rear corner drag results as a percentage of drag exhibited by the respective vehicle H corners. It should be noted that in all cases, the data set is an average of both LH and RH samples, excepting vehicle G rear hardware, as one corner was fully seized, and exhibited drag torque exceeding the maximum torque capabilities of the test machine (20 Nm).

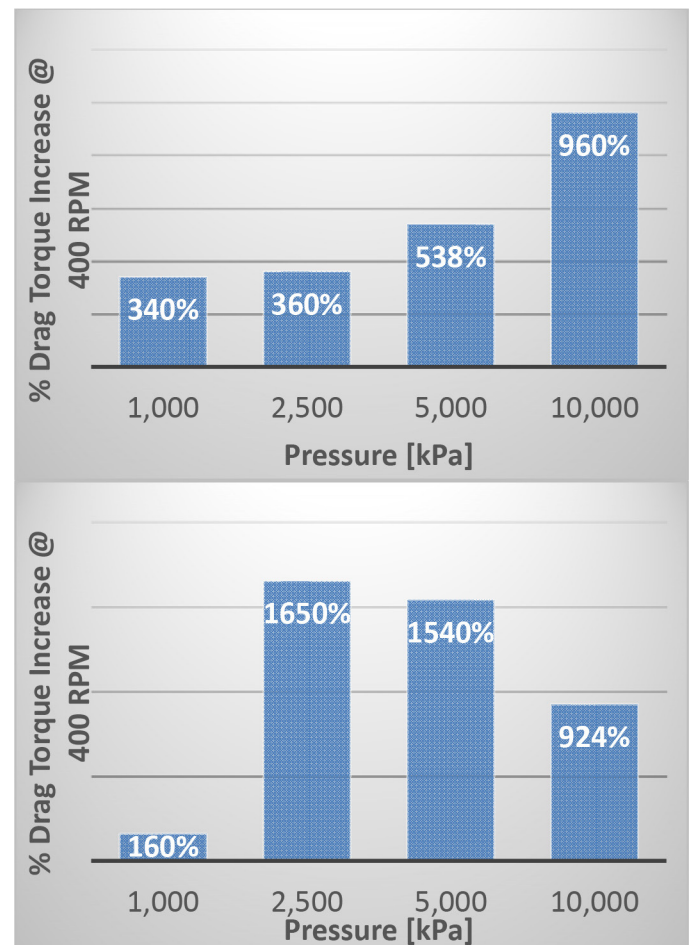


Figure Set 2. Post Corrosion Brake Drag Torque Presented as a Percentage of Vehicle G over Vehicle H (front corner on top, rear corner bottom)

As one may expect, the increased corrosion protection performance of the Zinc-Nickel caliper bracket plating over the Zinc only configuration leads to a considerable improvement in drag torque

performance after 10 years equivalent corrosion exposure.

Additionally, the addition of Zinc-Nickel plating on the vehicle H rear pads demonstrates considerably more contrast with the rear hardware from vehicle G. It should be noted that the front brake pads and rotors in vehicle H were replaced at 80% of completion of the durability test (thus the tested hardware had 20% corrosion durability exposure on the pads and rotor, and 100% exposure on the caliper).

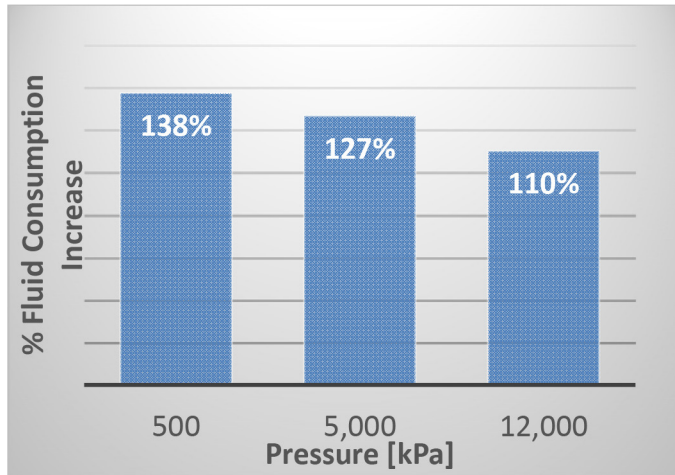


Figure 3. Post Corrosion Brake Fluid Consumption Presented as a Percentage of Vehicle G over Vehicle H Front Corners

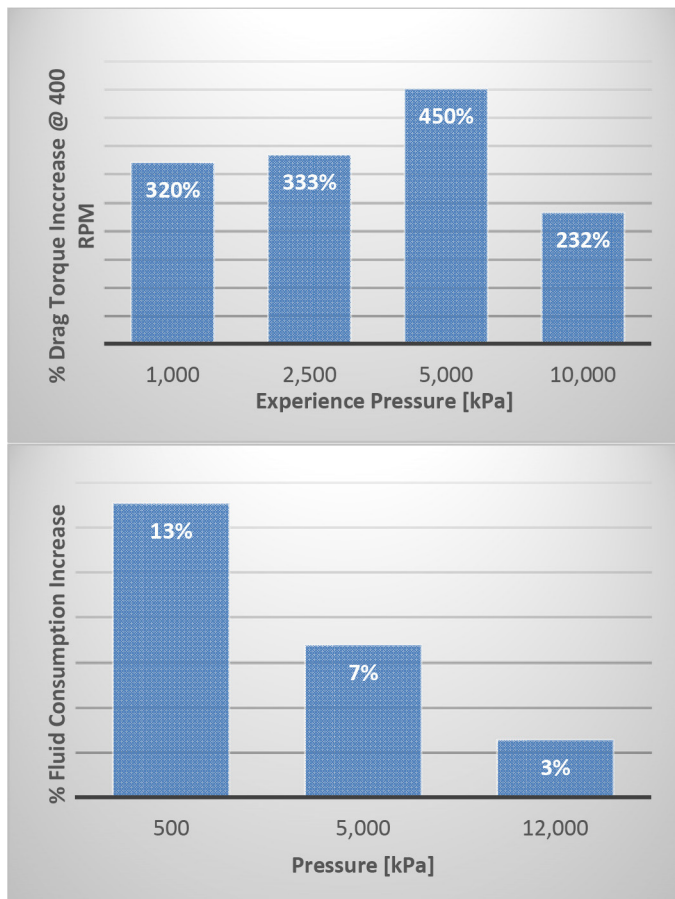


Figure Set 4. Vehicle F Front Corner Drag Torque and Fluid Consumption Increase following Accelerated Corrosion

Next, we will analyze fluid consumption in a similar manner. Only the front corner was included in this analysis, as the rear data are skewed by having one caliper completely seized (and thus nonfunctional for testing), and presenting only the functional caliper for comparison would present misleading conclusions.

Additionally, we can evaluate vehicle F to assess performance degradation following corrosion exposure. This vehicle's brake corner loading, as a heavy truck, is considerably higher than vehicles G and H which were previously compared. Note vehicle F was tested only to 5 years equivalent exposure. As no other corners presented an interesting comparison within the same vehicle segment, Figure set 4 displays the average degradation in drag and fluid consumption for these front brake corners from this design's new state. Again we see calipers with zinc only plating and brake pads with no additional corrosion protection beyond phosphate treatment and paint resulting in significant binding, and degraded performance as a result. This observation is key, as drag torque degradation is present and severe after only 5 years of corrosion exposure - well within the typical life of a single set of brake pads for many vehicles in the field.

## 2c. Comparison of Brake Caliper Corrosion Binding Corrosion with and without Regenerative Braking

We can next analyze vehicle H (strong hybrid) and vehicle I (traditional ICE) data to compare the effects of reduced friction braking duty cycle on corrosion binding effects. As can be seen in appendix A, these two vehicle applications have very similar brake corner content, so the addition of regenerative braking capability on vehicle H over vehicle I poses an interesting comparison.

In figure 5 fluid consumption post corrosion is shown as a percentage increase from each analyzed corner's new condition performance. We find that the increase in fluid consumption trends on the front and rear axles of these vehicles are mixed. Vehicle H front hardware exhibits a nominal decrease in fluid consumption after 10 years equivalent corrosion exposure, primarily at low pressures, whereas the vehicle I hardware exhibits a nominal increase. The resulting data provides no clear indication that the reduced duty cycle has negatively impacted the fluid consumption behavior due to corrosion. In reality, the fluid consumption changes over time are due to the competing effects of reduced lining thickness due to wear, piston seal relaxation over time, taper wear and pad shape abnormalities, and corrosion binding - thus the competing factors lead to mixed results in this comparison. More significant differences may have been apparent had the data been available to make this comparison on hardware with less robust corrosion protection available, such as vehicle G. Additionally, the pad and rotor replacement at 80% of vehicle H corrosion durability testing further complicates the data analysis.

The opposite trend is shown on the rear hardware fluid consumption data, where vehicle I exhibits more than 50% increase in fluid consumption throughout the entire pressure curve, where vehicle I hardware exhibits a nominal decrease, primarily at low pressures. Considering that rear brake duty cycle is notably lighter than fronts in standard passenger vehicles, combined with the additional weight

debris flow that will be discussed later in this paper, we see evidence of more pronounced rear caliper fluid consumption degradation in the regenerative braking vehicle analyzed due to corrosion binding.

Drag data from these two vehicles, shown in [figure 6](#) again as a percentage increase from each analyzed corner's new condition performance, shows other differences. The front hardware from vehicle H shows a drag increase at low experience pressure, with higher experience pressures reversing the trend. Vehicle I front hardware shows a nominal increase in drag, becoming more pronounced as experience pressure increases. Similar to the fluid consumption data, it would seem that corrosion binding did not occur any more significantly on the regenerative braking vehicle H compared to vehicle I, rather the opposite may be true based on the measured drag torque. Again, this may not have been true in a comparison of vehicles with less robust corrosion protection.

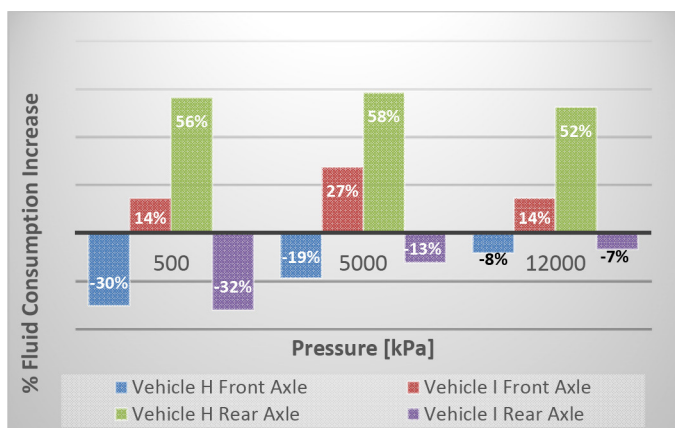


Figure 5. Fluid consumption increase from new condition to post corrosion durability - vehicle H and vehicle I

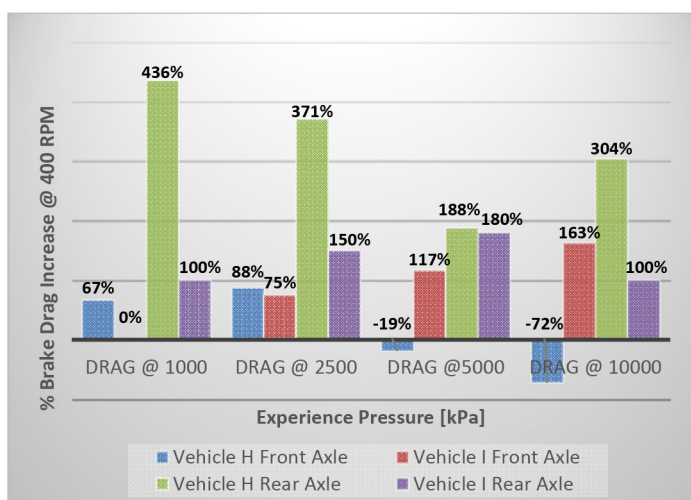


Figure 6. Drag Torque increase from new condition to post corrosion durability - vehicle H and vehicle I

The rear brake corner drag data shows the clearest evidence of reduced friction braking usage resulting in measureable consequences. Vehicle H rear hardware exhibits a drag increase between 188% and 436% of the new vehicle condition, whereas vehicle I ranges from 100% to 180%. This demonstrates the potential for rear brakes on regenerative braking vehicles to be subject to considerably more drag torque increase over time than non-regenerative braking vehicles, even with more robust corrosion protection strategies in place. It should be noted that drag data are not available on these exact brake corners in the new condition, however it is a fair assumption that new condition drag is comparable to the established averages from production validation.

## 2d. Effect of FNC Rotors on Corrosion of Braking and Mounting Surfaces

Often servicing brake rotors becomes difficult due to the corrosion growth that occurs between the rotor and hub mounting surfaces after prolonged exposure in a corrosive environment. The use of FNC treatment on the rotors provides a clear difference in this corrosion potential, as is evidenced by the comparison of vehicle B and vehicle D front rotors in [figure set 7](#). While objective forces for removing the rotors was not directly measured, it can be observed in the post test photographs that the FNC rotors used on vehicle B exhibit considerably less corrosion growth in this interface following a 10 year accelerated exposure compared to the standard cast iron rotors used on vehicle D. This difference is observed despite the fact that both rotors used the same zinc rich protective top coating in this area. It can be expected that the removal forces of the FNC rotor will be considerably lower following prolonged exposure.

Additionally, differences can be clearly observed in the braking surfaces in these two rotors. Vehicle B FNC rotors exhibit small, localized spotting of red rust around the braking surface. The localized nature of rust formation indicates that the corrosion penetration into the rotor is limited. Comparatively, the vehicle D non-FNC rotors exhibits significant red rust formation and smearing, with additional pockets of uncleaned rust forming in the countersunk cross-drilled holes in the brake plate. Additionally, vehicle D brake plate surfaces have several pad "shadows" evident of prior corrosion adhesion of the pads to the rotor. The benefits of FNC treatment evident here on rotor brake plate surfaces relative to corrosion growth and pad to rotor corrosion adhesion are similar to other published investigations on these topics documented to date, and will not be explored in depth in this paper. The interested reader may find further information in the references [2, 5].