

Effect of Regenerative Braking on Foundation Brake Performance

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ABSTRACT

Regenerative braking is one of the key enablers of improved energy efficiency and extension of driving range in parallel and series hybrid, and electric-only vehicles. It is still used in conjunction with friction brakes, due to the enormous amount of energy dissipated in maximum effort stops (and the lack of a competitive alternate technology to accommodate this power level), and to provide braking when on-board energy storage/dissipation devices cannot store enough energy to support braking. Although vehicles equipped with regenerative braking are becoming more and more commonly available, there is little published research on what the dramatic reduction in friction brake usage means to the function of the friction brakes themselves. This paper discusses -with supporting data from analysis and physical tests - some of the considerations for friction brakes related to usage on vehicles with regenerative braking, including corrosion, off-brake wear, and friction levels. It also proposes how a brake system configuration for a regenerative braking-equipped vehicle may be balanced differently than a system for a vehicle with conventional braking.

INTRODUCTION

A quick perusal of online forums for enthusiasts of some popular regenerative braking system-equipped vehicles confirm that there are indeed some notable interactions between foundation brake and regenerative brake system (including the electro-hydraulic system) that affect customer satisfaction. Complaints of 'grabby' brakes have been attributed to corrosion issues in the foundation brakes, and come complete with customer-generated procedures for 'cleaning' them with use (usually involving braking while in neutral). Changes in pedal feel near the end of a stop (during regen blending) also show up as customer complaints. Available data from the field show that brake-related

performance complaints range from on par with, to significantly higher (double or more) than non-hybrid counterparts.

Regenerative braking refers to any of a number of systems used for adding a braking force to the vehicle to assist in deceleration, while re-directing the kinetic energy of the vehicle into an on-board storage device and allowing the energy to be recovered later to propel the vehicle. The most common regenerative braking system in use in passenger cars today uses an electric motor, capable of providing both propulsion and braking forces, and an electric battery storage system. Braking force from the electric motor is added, and in most cases, actively 'blended' with friction brake force to generate enough braking torque to fulfill the deceleration request indicated by the driver pressing on the brake pedal. Energy recovery and storage systems in common use today are unable to absorb the tremendous amount of peak power that modern friction brakes can absorb, and most act only on one axle set of wheels, which maintains the need for friction brakes to be able to use all available traction and enable higher deceleration capability.

Regardless of how regenerative braking is mechanized, it can cause significant reduction in total energy directed into the friction brakes over time. This, in turn, can have a significant effect on the friction couple transfer film and surface characteristics. In terms of performance of concern to the owner of a vehicle, the differences in braking energy and friction surface characteristics can have some significant effects, both positive and negative, on brake system performance. On the positive side, the reduction in friction brake usage can substantially decrease operating temperatures and increase the life of the friction materials. On the negative side, the reduction in friction brake usage can increase the risk of damage due to poor cleaning of corrosion of the friction surface. Friction behavior is also of increased

concern, due to the dependence of algorithms responsible for combining friction and regenerative braking force via regulating hydraulic pressure (clamp load in an electric caliper) on knowing the pressure (clamp load) to friction braking torque relationship. Finally, the decrease in friction brake usage with regenerative brake system-equipped vehicles (henceforth referred to, for brevity, as 'regen-equipped') can increase the risk of uneven off-brake rotor wear due to a reduction in protective transfer film generation.

The present work attempts to illustrate some of the effects of regenerative braking on friction brake performance, by covering them in the following sections:

1. Operating Temperatures and Lining Life
2. Corrosion Issues
3. Apparent Friction Behavior and Regen-Blending
4. Off-Brake Rotor Wear

All of the above studies that involved physical testing were completed with brake corner configurations using Non Asbestos Organic (NAO) lining materials, designed to be 'rotor friendly' (low rotor wear), which appears, from benchmarking, to be the industry standard friction material choice for regenerative brake-equipped vehicles at the time of this publication. Each section will use analyses and/or physical test data to illustrate how regen brake systems can affect foundation brake performance (and how brake system performance is affected by the foundation brakes).

1. OPERATING TEMPERATURES AND LINING LIFE

In most operating conditions, regenerative braking will reduce friction brake operating temperatures. There are some system configurations and operating conditions (such as mountain descent with the energy storage system near capacity with no additional powertrain braking) that can actually result in higher temperatures with a regenerative braking-equipped vehicle, however, over the life of the friction materials, the energy absorption by the friction brake system is substantially reduced. Modeling by Gao, Chen, and Ehsani [1] indicated that the fraction of total traction energy consumed by regenerative braking ranged from 28% to 89%; this represents work that can be off-loaded from the friction brakes to the energy storage system in a regenerative brake system equipped vehicle. Calculations by Walker, Lamperth, and Wilkins [2] for a hypothetical heavy truck indicated that under their proposed control strategy, 89% of total braking energy would be absorbed by the regenerative braking system. Both sources lead to a reasonable expectation of a significant reduction in friction brake operating temperatures.

In order to illustrate the effect of regenerative braking on two parameters of keen interest to the foundation brake engineer -

brake operating temperatures and brake lining life - modeling was performed on an example compact-size regen equipped vehicle using a General Motors analysis tool [3]. Los-Angeles City Traffic (LACT), a customer usage schedule that is popular in the friction brake industry for measuring brake lining life, provided the basis for predicting severe use, but realistic operating temperatures and lining life. The example vehicle has a 1726 kg test weight, and a 16" wheel envelope brake system. Regenerative brake systems ranging from 8 kW to 50 kW maximum brake power absorption were modeled. Ambient temperature was 15 deg C.

Two very simple regenerative brake control strategies were modeled to show the effects of each on operating temperatures and lining life (the details of control strategies is beyond the scope of this paper; the intent here is to show the effect in very broad terms). The first ("Control A"), which could in practice be implemented on vehicles with front-axle regenerative braking, applied the maximum available regenerative brake torque first to the front wheels, and then applied front and rear brakes with equal pressure for any driver brake torque requests above and beyond what could be supplied by regenerative braking. This control strategy allows regen to have the maximum possible impact on friction brake usage. It is more likely in a front axle regen vehicle due to the need to maintain vehicle stability on a low-coefficient surface. The second control strategy ("Control B"), which is likely in a rear-axle regen system, applies front friction brakes and rear axle regen braking to maintain a fixed brake force distribution, adding in additional rear friction brake torque as needed when the maximum available regen torque is used to fulfill the driver's braking request. This control strategy requires independent front and rear axle brake hydraulic pressure control, and reduces the risk of vehicle stability issues on low-coefficient surfaces. A maximum regen torque level corresponding to 0.20g of deceleration in the example vehicle was used for all modeling (different regen power levels controlled how close to this peak regen braking could come, or how long this peak could be maintained in-stop). This is consistent with typical electric motor modeling, where a torque peak controls motor input/output at lower speeds, and the motor becomes power limited (constant power but variable torque) at higher speeds [4].

The analysis tool employed generates front and rear rotor temperature vs. time data, but for ease of reporting, only the schedule average and peak values are shown. [Figures 1](#) and [2](#) below shows the effect of the range of regen power and the two control strategies on peak and average rotor temperatures during LACT. A conventional vehicle case (no regen) is also shown for comparison:

The brake system was sized such that peak and average rotor temperatures during LACT were approximately 330 deg C peak front / 335 deg C peak rear, and 197 deg C average front / 195 deg C average rear. Even a relatively small amount

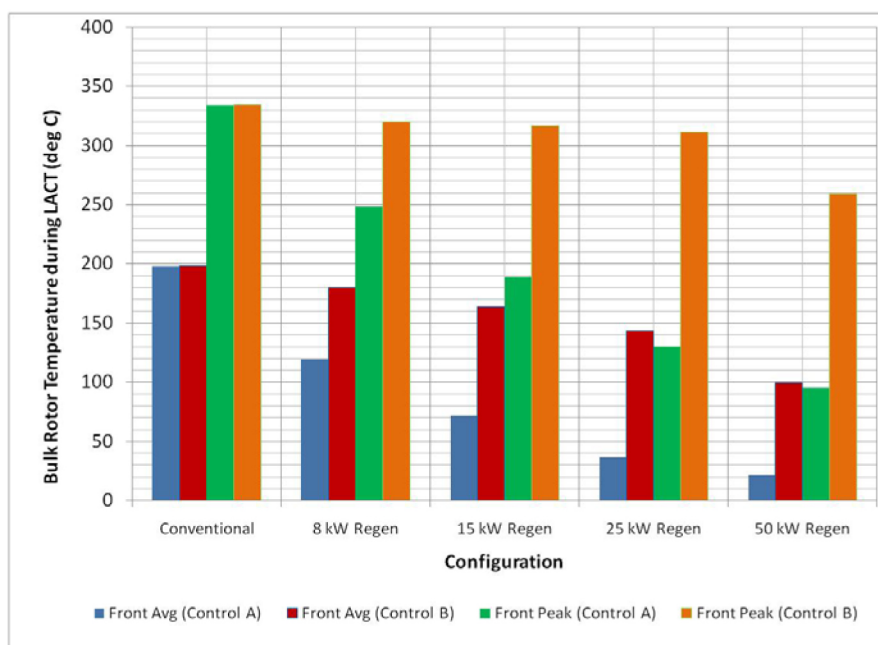


Figure 1. Modeled Front Rotor Temperatures during LACT Testing vs. Max Regen Power and Control Type

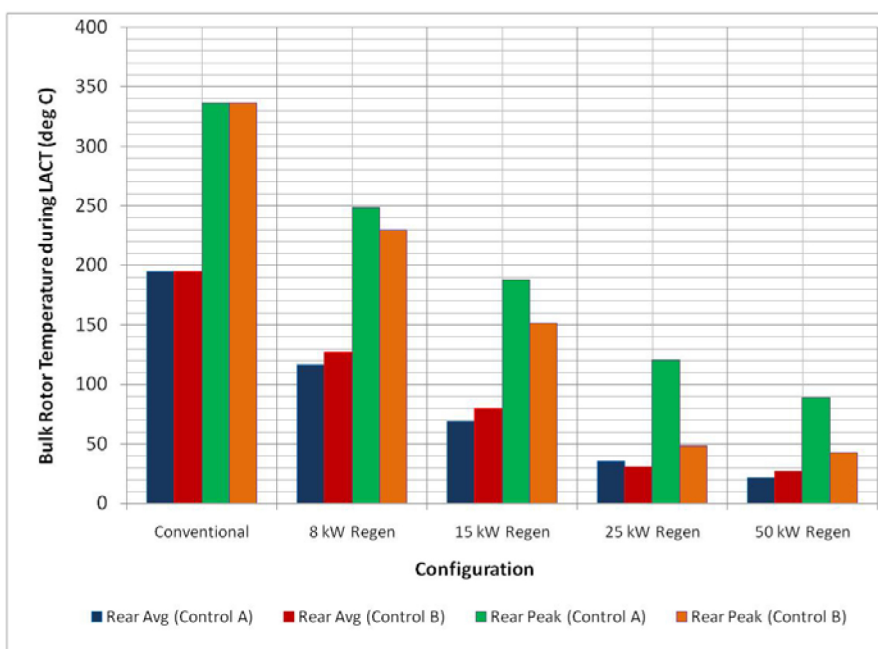


Figure 2. Modeled Rear Rotor Temperatures during LACT Testing vs. Max Regen Power and Control Type

of regen with control strategy A (8 kW, typically available in integrated alternator/starter systems) reduced average temperatures to 120 deg C front, and the maximum regen analyzed -50 kW - reduced front average temperatures down to barely above ambient (23 deg C). As would be expected with control strategy B - in which regen replaces the rear friction brakes but not the front - front brake operating temperatures were much less sensitive to regen power limit

than with control strategy A. The temperature statistics shown in [figures 1](#) and [2](#) indicate that typical customer use brake applies - even during a relatively severe schedule such as LACT - are in a range that can be significantly covered by regenerative braking, allowing foundation brake operating temperatures to be significantly reduced.

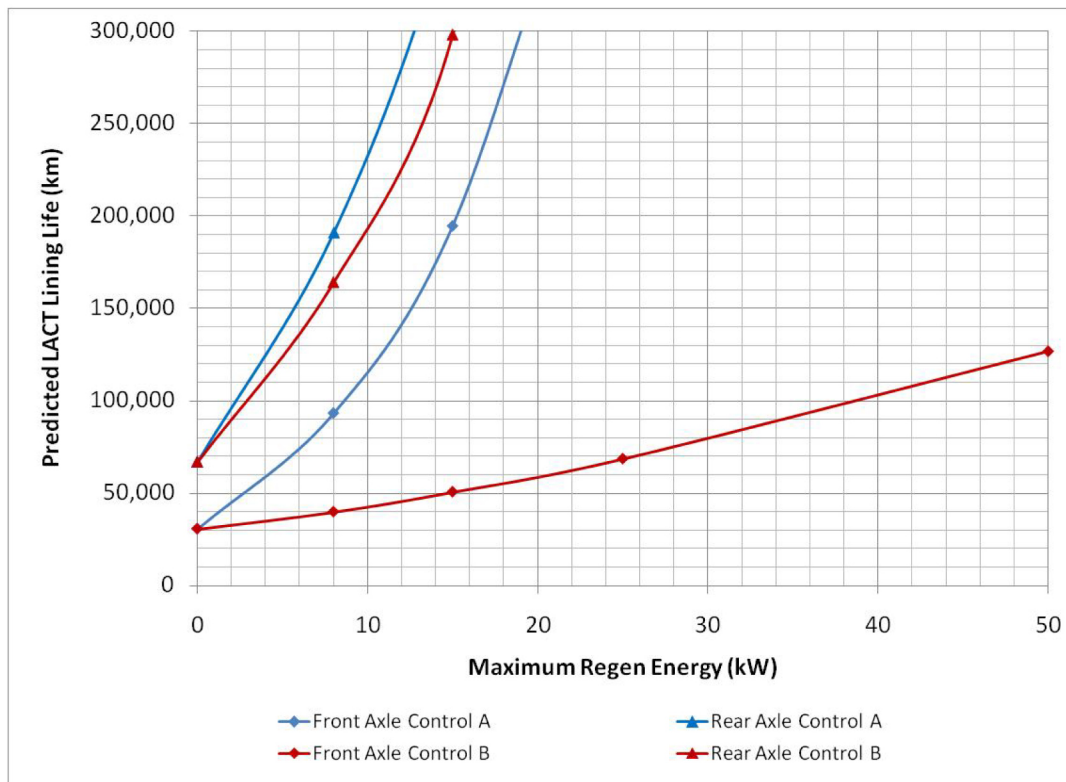


Figure 3. Modeled Front and Rear Lining Life during LACT vs. Max Regen Power and Control Type

The next figure shows predicted brake lining life for the same schedule (LACT), using a typical NAO lining with typical lining volume for a compact car. Results are truncated at 300,000 km (a typical ‘life of vehicle’ design target):

The data in this figure show that for the example vehicle analyzed, around 20 kW of regen power is sufficient to reduce front and rear brake lining wear to a ‘life of vehicle’ level with control strategy ‘A’. In many vehicle usage conditions, other friction material life limitations may claim the brake linings or rotors well before normal wear-out, including corrosion and debris damage. Issues related to corrosion and debris damage that result in brake drag may result in drag becoming a significant lining wear driver. This leads to a somewhat philosophical question for the brake engineer to ponder - the anti-corrosion treatments applied to components such as brake lining pressure plates and noise shims have been historically engineered with the expectation that the brake lining is a consumable item, lasting perhaps 2-4 years. As the wear life of the consumable items such as brake pads is increased by regen systems, improved anti-corrosion coatings and/or more corrosion-resistant materials may be needed to prevent both cosmetic and functional corrosion issues. If corrosion performance needs exceed available technology, then additional service procedures (such as cleaning of pad abutment areas) during brake service inspections may need to be added.

Trends in sizing foundation brake systems (including brake rotors) have been towards providing a safety margin for conditions such as mountain descent, and focusing more on reducing brake operating temperatures during typical customer usage and during performance-oriented driving conditions. This trend has been driven by the need to minimize warranty and customer complaints related to brake operating temperatures, and can be a more stringent condition to design to than mountain descent. With more powerful regen brake systems, it is clear from [figures 1](#) and [2](#) that typical customer usage conditions will not drive temperatures that define brake sizing; therefore, it becomes possible to focus on other more extreme usage conditions to make sizing decisions (such as mountain descent). In some implementations of regen-capable powertrains, mountain descent may actually be more severe than with a conventional brake system and powertrain due to a reduction in available powertrain braking when regen is not available.

To illustrate the effect of a range of regen braking operating conditions on mountain descent, a 1-D thermal model (with conductive and convective heat transfer models) was used to model brake rotor temperatures during a simulated mountain descent condition for two brake sizes (15" wheel envelope and 16" wheel envelope). The tool used for modeling rotor temperatures is the same tool used for lining life calculations [3]. Brake fluid temperatures were also modeled using a very simple 1-D thermal model that balanced conduction of rotor

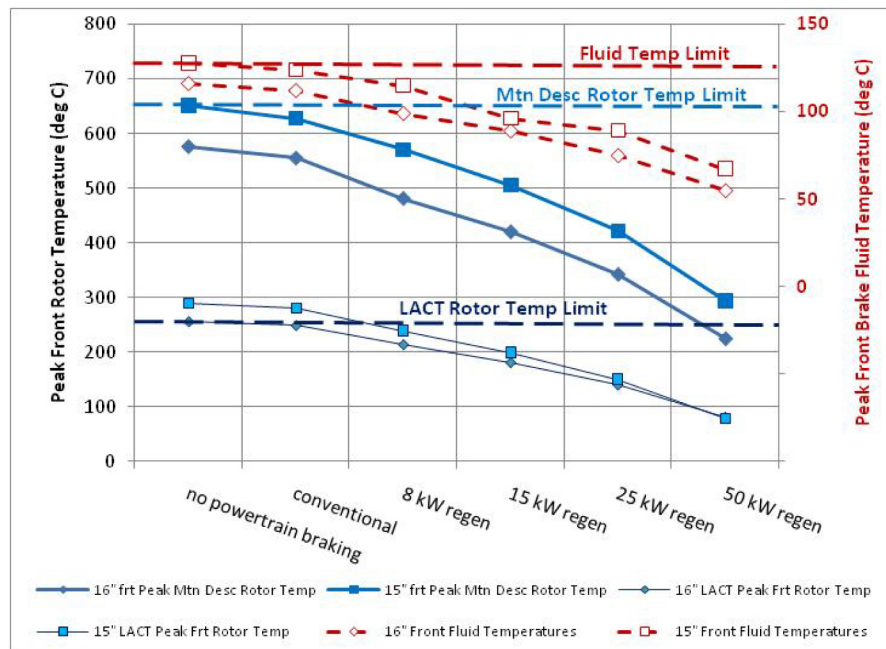


Figure 4. Case Study Summary - Brake Temperatures vs. Regen Capacity

heat through the pad/piston with convection through the housing. The model was tuned to match vehicle performance and then used provide a crude calculation of fluid temperatures subject to rotor temperature profile changes (this model is not accurate enough for sizing calculations, but is used here for illustrative purposes). Rotor temperatures during a simulated LACT test were calculated as well. By comparing these temperatures with design limits, it is possible to see how brake sizing could be affected by regen. Three potential design limits were considered in this study - brake fluid temperatures during a long mountain descent, rotor temperatures during the same mountain descent, and rotor temperatures during customer usage (LACT). For sake of example, some logically defensible temperature limits to be used for design were selected. For brake fluid temperature during mountain descent, 120 deg C was selected (based on the minimum observed fluid boiling point for light duty service vehicles measured in the study by Hunter et al [5]). For rotor temperatures during mountain descent, 650 deg C was selected based on benchmarking observations for the mountain descent condition of interest. For LACT peak temperatures, a limit of 250 degrees C was selected to avoid the temperature range of significant thermal decomposition of the lining (as would be shown in a typical TGA plot) - temperatures above this level increase risk for transfer film and rotor damage leading to judder, and for degradation of noise performance due to changes in the lining friction properties and due to damage to the noise insulator. [Figure 4](#) below summarizes the resultant set of peak temperatures with the design limits for comparison:

Review of the data in [figure 4](#) supports some discussion points:

- Sizing the system to meet all temperature limits with a conventional powertrain (with some engine braking required) the 16" system. Sizing was driven by the LACT temperature limit, which was met by a small margin by the 16" system.
- Regen at or above 8 kW capacity brought the LACT temperatures below the design limit, essentially removing it from consideration as a design temperature limit. Since the customer usage temperature limits are well within safe operating temperature limits for most modern automotive brake friction materials, it is not necessary to consider the effect of a fully charged battery or failed regen on this temperature metric for brake sizing.
- For the most severe possible mountain descent - that of having no powertrain braking and no regen (as could happen with regen inoperative due to a failure mode or to a fully charged battery in a hypothetical battery electric or series hybrid), the 16" brake system could meet the rotor and fluid temperature limits. The 15" system could as well, but was right at the limit (and in an actual sizing exercise would require significantly more accurate modeling that what was employed for this illustrative case study to determine if it would be an appropriate selection).
- For a regen-capable vehicle that can provide powertrain braking, the 15" brake system can meet the rotor and fluid temperature limits with failed regen.

As the performance of energy storage/management systems and therefore regenerative braking systems in the field, subject to customer usage, becomes better understood, brake sizing calculations can be based on more and more detailed models of regenerative braking behavior and vehicle operating conditions. This in turn will allow more optimized brake sizing, saving appreciable mass.

2. CORROSION ISSUES

For many reasons including favorable heat capacity, wear behavior, conductivity, cost, machinability, and NVH behavior, cast iron is by far the most commonly used material for brake rotors. Unfortunately, for regenerative brake equipped vehicles, the issue of dealing with cast iron corrosion becomes even more difficult than it already is with conventional braking systems. Brake systems with cast iron discs rely on some level of abrasive wear or corrosion product on the surface of the disc through use. Regular usage of the friction brakes also helps to ‘correct’ issues with the transfer film on the rotor surface by re-distributing it (building up lower areas and wearing down higher areas). As noted by Osterle et al [6], Iron oxide is an important constituent of friction brake transfer films. The high amount of debris flow through the friction interface during use after major corrosion events, or the frequent but lighter debris flow during use after mild corrosion events such as parking overnight, provide the ‘building material’ for a heavy and dynamic transfer film on the rotor and pad surfaces. Because the transfer films are quite dynamic, adjusting in thickness and chemical makeup continuously to local operating conditions, heavier films by their nature have greater risk of developing issues such as thickness variation (post-corrosion transfer film related DTV has been noted by Cho et al [7]).

To simulate the effects of regen on brake performance after corrosion events, a laboratory and inertia-dynamometer based test procedure was used. The subject brake corner was a 16" wheel envelope, NAO lining variant used on a mid-sized vehicle (about 2400 kg Gross Vehicle Weight). The details of the procedure are considered proprietary, but a high level description is below:

- 1). burnish
- 2). corrosion exposure (circumferentially non-uniform corrosion created with tape on rotor surface)
- 3). re-burnish
- 4). corrosion exposure (uniform exposure around friction surfaces)
- 5). shortened re-burnish
- 6). repeat 4 and 5 three times for a total of 5 complete corrosion and re-burnish cycles

Three samples each were tested with full inertia (no regen) and with reduced inertia, simulating regen (stops were to a

target deceleration, which allowed the brake dynamometer to reduce hydraulic pressure but maintain overall stop duration in the simulated regen configurations, much like an actual regen-equipped vehicle would do). The three samples representing simulated regen were tested first at 2/3 of the conventional vehicle inertia (for the first two corrosion - burnish cycles) and then at 1/3 of the conventional vehicle inertia (for the remaining corrosion - burnish cycles). Results are summarized in [figures 5](#) (apparent friction behavior) and [6](#) (in-stop maximum brake torque variation) for the 1st post corrosion burnish, and in [figures 7](#) (apparent friction) and [8](#) (Brake Torque Variation) for the subsequent corrosion and re-burnish cycles. Photos of the rotor friction surfaces for a representative sample from each group appear in [figures 7](#) and [8](#):

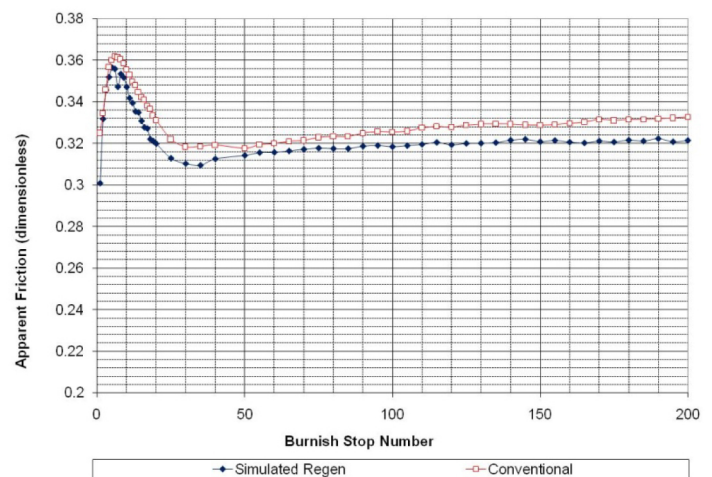


Figure 5. Comparison of Post-Corrosion Apparent Friction Behavior with and without Simulated Regen Braking - 3 sample average (first post-corrosion burnish)

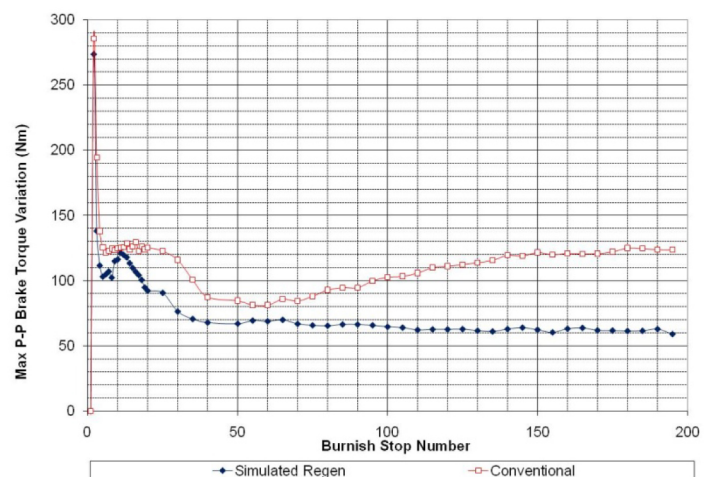


Figure 6. Comparison of Post-Corrosion Brake Torque Variation Behavior with and without Simulated Regen Braking - 3 sample average (first post-corrosion burnish)