

Methodology for Sizing and Validating Life of Brake Pads Analytically

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ABSTRACT

An area of brake system design that has remained continually resistant to objective, computer model based predictive design and has instead continued to rely on empirical methods and prior history, is that of sizing the brake pads to insure satisfactory service life of the friction material. Despite advances in CAE tools and methods, the ever-intensifying pressures of shortened vehicle development cycles, and the loss of prototype vehicle properties, there is still considerable effort devoted to vehicle-level testing on public roads using "customer-based" driving cycles to validate brake pad service life. Furthermore, there does not appear to be a firm, objective means of designing the required pad volume into the calipers early on - there is still much reliance on prior experience. This paper builds upon previous work by GM [1], where short duration, objective vehicle and dyno tests were combined with a computer model to allow for accurate pad service life prediction without vehicle tests, and expands it into a methodology combining CAE (CFD), computer modeling, objective friction material characterization data, to enable confident sizing of the brake pads very early in the vehicle development process. In the present work, this method is extended to global vehicles, considering a European-market vehicle (low-metallic lining materials). A case study vehicle will be used to illustrate how these tools and methods can be used to design the initial pad volume, develop the brake system to avoid lining life issues, and then validate the brake pad service life for global vehicles, without using expensive, time consuming, and often inaccurate public road testing.

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INTRODUCTION

General Motors had moved to an analytical and short duration brake dynamometer and flat track (on road) method of validating brake lining life several years before the work covered in this paper. In fact, customer-usage simulation tests, including public roads and proving grounds-based, have not been a part of the standard testing protocol for close to a decade. Ironically, as dependence on customer-usage simulation tests waned, customer satisfaction in the field actually increased. Figure 1 shows a typical recent result for the occurrence rate of brake pad replacement, from a yearly large-scale customer survey of areas requiring service in the vehicle over a three year period of time:

Results similar to the above have been noted over a period of several years (along with a great deal of more proprietary data), which tends to validate the strategy of moving public road and long duration customer usage testing to analysis and highly focused dynamometer and flat track tests.

The same tools that enable validation of brake pad life in service, also provide a method for objective sizing calculations for the brake pad. This allows the area and volume of the brake pad to be determined very early in the development of the vehicle program. Initial sizing calculations can be done well in

advance of physical hardware, and these data may even be used to influence vehicle design factors that control the operating environment of the brake (with factors affecting brake cooling being a significant portion of these).

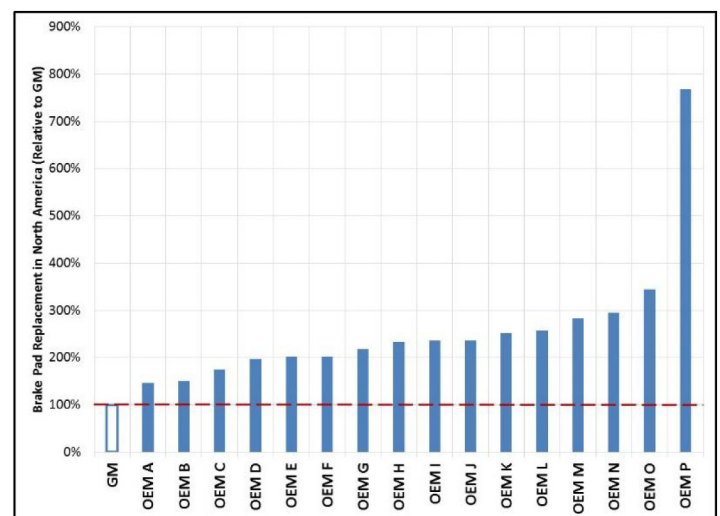


Figure 1. GM and Industry Pad Replacement Rate at 3 Years in Service (Major North American Customer Survey)

The present work ultimately describes a process, spanning from the earliest design state of the vehicle to the final preproduction validation, for sizing the brake pads, developing the brake system to meet customer expectations for service life of the pads, and for validating the final design for service life.

The paper is organized into the following sections, starting with a description of the model and methodology, and illustrating the process steps by following a case study vehicle:

1. Review of Lining Life Model
2. Description of Process
3. Description of Case Study Vehicle
4. Early CAE work - determining brake operating/cooling environment
5. Early Program Design - Initial Sizing Calculations
6. First Hardware - refining the models
7. Final Validation
8. Summary/Conclusions

1. REVIEW OF LINING LIFE MODEL

The analytical tool used for assessing brake lining life was covered previously by Riefe et al [1] and Johnson et al [2], so this section will afford only a brief review. The basic principle of the model is to compute brake pad wear during a customer usage schedule by computing the energy absorbed into the friction brakes during braking events, the temperature of the brake rotors during braking, and the incremental wear volume for each braking event. The latter is computed using a volumetric wear per unit energy versus temperature relationship measured on an inertia dynamometer. More descriptively:

- A simple 2-d vehicle dynamics model based on vehicle mass, mass distribution, center of gravity height, and deceleration, combined with a temperature-sensitive calculation of brake force distribution, allows the distribution of braking energy into front vs. rear brake corners to be determined.
- An aerodynamic drag model and constant-deceleration powertrain drag term allows energy absorbed to decelerate the vehicle to be portioned into friction brakes vs. aero/powertrain losses.
- A lumped-capacitance brake thermal model uses brake rotor material and pad material properties, measured or CAE-predicted brake rotor cooling data, and the calculated braking energy input to the individual friction brakes to determine the bulk temperature of each brake rotor. Energy input includes energy from residual brake drag.
- Inertia dynamometer data (similar to SAE J2707 [3]) is used to characterize the linear wear rate versus temperature over the course of 1000 brake applies, in a temperature range of 100 °C to 400 °C. From the inertia and rolling radius settings of the dynamometer test, and the area of the brake pad tested, the volumetric wear rate per unit energy input versus temperature relationship is

computed and provided as an input to the wear model.

- The data from the thermal model and the braking energy to the friction brakes calculation are combined with the converted inertia dynamometer wear rate data. This relationship is used to compute the incremental wear rate during each time step of the simulation.

The model has been validated with both Non-Asbestos Organic (NAO) and Low-Metallic (Low-met) brake pad materials, comparing model predictions with public road, customer usage schedule results [1].

The underlying principle of this model facilitates a property that is critical to the proposed methodology - that the volumetric wear rate per unit energy absorbed versus temperature is a fundamental property of the lining material, and is therefore scalable to different pad areas and caliper configurations. This property allows for wear testing to be conducted on "surrogate" brake corners, or to even be given as a target value (volumetric wear per unit energy input at temperature), and then scaled to a range of possible sizes for a new application. As will be described in [section 2](#), generating wear data on the application specific design is built into the process. This refinement is considered necessary, because although the above described principle is substantially true, there are many factors specific to a brake corner design that can influence the lining wear rate. This includes pressure and heat flux distribution, the overall mechanical load (which at a tribological level can influence the normal fatigue and fracture damage to structural components of the lining material and the rotor surface), differences in surface finish, and differences in friction material processing, to name a few.

2. DESCRIPTION OF PROCESS

The sizing process occurs in three distinct stages, intended to align with a typical vehicle development process. Each stage is described below:

Phase 1. Initial Design

The first stage of sizing the brake pads is target (specification)-driven. The best available knowledge about the vehicle parameters is combined with wear and friction target values to create an initial, coarse pad wear model. If a friction material selection is made up front, then surrogate wear and friction data may be used instead of target values. In this stage, a map of predicted lining life versus pad area and thickness is generated for the front and rear brakes, and this is compared to a "feasible domain" for caliper design. There are strong trade-offs that accompany adding pad volume, in the form of component mass, cost, fluid consumption, difficulty in controlling pressure distribution (and resultant taper and cupping wear), and residual drag - and there is therefore a "sweet spot" for pad volume that preserves sufficient pad life for customer satisfaction and low cost of ownership, while performing well to the competing objectives. In a friction

material is planned for re-use for which wear data exists already, then modeling at this stage can progress directly to using friction-material specific surrogate wear data.

Phase 2. 1st Hardware Test and Model Refinement

The next major stage occurs when design-specific subsystem data become available. At this stage, physical test based model inputs based on the design intent brake corner, including wear versus temperature, caliper drag, and potentially friction versus temperature, become available. Early flat-track vehicle level tests may also be available, such as brake rotor cooling coefficients and aerodynamic drag. This phase of lining life evaluation may be done several times, as the brake system and surrounding environment design are often evolving continuously throughout the development phase of the vehicle. Lining life modeling may be used to help make decisions about certain design changes, such as the allowable pad chamfer volume to address squeal noise, judder, or taper wear issues, or to support the need for added brake cooling features.

Phase 3. Final Validation

The final stage of the process occurs when the brake system design and the design of the interfacing subsystems has stabilized. In this stage, the brake lining life model is updated meticulously with dynamometer (wear, drag, and output) and vehicle flat-track (cooling) data on the production intent designs and vehicle configuration. The final "test vehicle" mass and mass distributions are used, and ideally the brake corner dynamometer test data will be from production-tooled parts.

3. DESCRIPTION OF CASE STUDY VEHICLE

As noted in the introduction, the process that will be detailed in the upcoming sections is very well established for GM in the US market, allowing for regular public-road and even proving ground-based customer usage road tests to be completely eliminated from the development and validation process. The selection of a European-market oriented vehicle was with the express intent of demonstrating how the process works equally well for different customer usage schedules and friction material types.

The case study vehicle was a variant of a mid-sized passenger car global vehicle architecture. It was developed for the European market, with low-metallic (Low-met) pad material on the front axle and a European-market oriented higher friction Non Asbestos Organic (NAO) pad material on the rear axle. It was primarily front wheel drive (with all-wheel drive available) with 4-wheel disc brakes and single piston, sliding calipers front and rear. Engine power ranges from approximately 180 hp to over 330 hp. Manual and automatic transmissions were available.

A completely unsurprising figure to those familiar with working with global architectures is the sheer complexity of vehicle configurations - in considering only the number of

configurations that can affect brake performance, there can be several hundred to several thousand. It is neither practical nor necessary to analyze every individual configuration, and the methodology for developing brake system sizing and component selection for such a complex set of vehicle configurations is a topic worthy of its own literature. For purposes of staying focused on the present topic, the authors request the reader to accept that a method was applied that resulted in equipping each of the vehicle variants with a suitable brake system design, specified in terms of basic brake rotor sizing, hydraulic piston sizing, and actuation sizing. For each brake system, the parameters important to brake performance (such as mass, mass distribution, tire/wheel sizing, etc) were reduced into a single "test vehicle" configuration. This "test vehicle" configuration was intended to be representative of the "worst case" buildable vehicle configuration. This "test vehicle" configuration concept was used throughout the process, including (in this case study), the build of physical vehicles for testing.

It should be noted that the test vehicle configuration also includes the "worst case" buildable powertrain configuration for brake performance - which for brake lining life, is the manual transmission combined with the assumption of zero engine braking.

In the interest of full disclosure, the case study vehicle used to illustrate the proposed methodology did not follow it during its original development. It was selected due to availability of a complete set of subsystem and vehicle level data, as well as having actual public road test data to show the correlation between the model and physical test.

4. EARLY CAE WORK - DETERMINING BRAKE OPERATING/COOLING ENVIRONMENT

Inputs to the lining life prediction tool are various vehicle parameters, brake cooling performance, and customer schedule files. Various vehicle parameters and customer schedules were examined in other sections. Brake cooling performance at the early stage of program can be estimated in one of ways described below:

- Refer to brake cooling information readily available from previous programs.
- Use an empirical equation that relates cross cooling flow velocity and brake cooling coefficient to estimate brake cooling coefficient.
- Use a full vehicle CFD model to calculate brake cooling coefficient.

How to estimate brake cooling coefficient from cross cooling flow velocity was explained by many literatures [4, 5, 6, 7, 8]. Below briefly summarizes how it works (please note that additional notation appears in the Definitions and Materials section at the end of the paper).