

A Study of Mass Drivers in the Brake System

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ABSTRACT

It is obvious at this point even to the most casual observer of the automotive industry that efforts to reduce mass throughout the vehicle are at a fervor. The industry is facing its most significant increase in fuel economy standards in its history, and light-weighting the vehicle is a major enabler. Despite the performance and quality of the brake system being intensely related to its mass, it too has not been spared scrutiny. However, like many modern automotive subsystems, it is very complex and mass reduction opportunities that do not sacrifice performance or quality are not always obvious. There are some interesting and sometimes even profound relationships between mass and other vehicle attributes built into brake system design, and making these more visible can enable a better balancing of brake system with the rest of the vehicle design objectives. Examples include - what is the cost, in terms of brake system mass, of added engine power? Of tire and wheel size? What is the mass cost of brake pad volume and service life? Can the mass compounding between the vehicle and brake system put forth in earlier works be confirmed with a detailed model? To explore these, and other questions, an integrated brake system performance and mass prediction model was constructed. This model (with mass prediction based on benchmarking and regression) was used to explore, in a general sense, some of the interesting mass versus performance relationships in the vehicle, as well as show through system-level optimization how mass can be saved while retaining performance and quality.

CITATION: Antanaitis, D., "A Study of Mass Drivers in the Brake System," *SAE Int. J. Passeng. Cars - Mech. Syst.* 7(4):2014, doi:10.4271/2014-01-2506.

INTRODUCTION

The modern automotive braking system is relatively complex, featuring many interacting subsystems, and designed to meet many (often conflicting) performance objectives and government regulations. There are many facets of integration with the rest of the vehicle to take care of in the design as well - the proper design of the brake system must consider (to cite a partial list) engine power, tire/wheel size, tire traction, vehicle mass and mass distribution, and available cooling (usually in competition with other systems requiring airflow, such as powertrain and HVAC).

Computer models, generally with parametric representation of the brake system components, have been used to perform brake system sizing and component selection calculations for many years [1]. However, ramifications of the design such as the mass of the brake system generally results from painstaking tallying component by component. Similarly, Computer Aided Design (CAD) software has been suitable to generate mass predictions of components for many years, but are not easily integrated into a full brake system model for performance and thermal calculations, nor can the designs be easily changed.

This study was based on the premise that there is value in quantifying - even coarsely so - the relationships between vehicle and brake system attributes and design constraints on brake system mass. Making these relationships visible, such as with a simple mathematical relationship, makes it easier to optimize mass at a system level. To this end, the present study attempted to find a "middle ground". A brake system model with simple parametric representations of the components was combined with regression models for the mass of the components, with the regression parameters driven off of the brake system model component parameters. This model allowed for brake system mass to be calculated in real time as the brake system model inputs were changed.

The presentation of this study follows the cadence below:

1. Description of the Brake System and the Mass Regression Models.
2. Brake System Mass versus Vehicle Mass
3. Effect of Tire and Wheel Size
4. Effect of Engine Peak Power
5. Effect of Modern Brake System Design - NVH
6. Cold Start Engine Vacuum and Mass
7. Vehicle Mass Distribution and Brake System Mass

8. Mass vs. Apparent Friction
9. Effect of Brake Rotor Cooling (Mass and Fuel Economy)
10. Full Brake System Optimization
11. Summary/Conclusions

1. BRAKE SYSTEM AND MASS REGRESSION MODELS

In order to allow for simultaneous optimization of mass and brake system performance, detailed brake system performance, thermal, and mass regression models were programmed using a ubiquitous spreadsheet-based platform. Brake system performance and thermal modeling has been covered extensively before, and will not be belabored here. A summary of the key model features, followed by a more detailed description of the mass regression models is offered in this section.

Brake System Models

Fluid Consumption and Pedal Travel

The fluid consumption of the brake corners was modeled using a linear-exponential regression model fit to discrete measured data points. The model is described in [4]. Sources of pedal travel include brake corner fluid consumption (includes caliper and hoses), lost travel in the apply system, and apply system travel efficiency losses (as measured on an apply system performance bench).

Pedal Force and Deceleration

Brake corner output was modeled as a user selectable linear brake factor (relating brake hydraulic pressure to brake torque), or an exponential relationship between brake torque and braking pressure. For simplicity, the analyses in this paper used a linear relationship between torque and pressure. Braking torque is converted to tractive force, added to user-specified coastdown deceleration force (simulating engine braking and road load drag), and deceleration is computed from the effect of this force acting on the vehicle mass.

Thermal Model

Front and rear brake cooling was modeled as a lumped-capacitance convective heat exchange, with the user specifying rotor thermal mass, and cooling coefficients. The cooling coefficient vs. vehicle speed relationship was modeled as linear. The model allowed the use of a vehicle-dependent "cooling velocity ratio" that scaled the brake rotor cooling coefficient relative to its geometry and thermal mass. The state equations were solved numerically in small time steps for three standard evaluation schedules: (1) a low speed, repeated snub thermal equilibrium test used for brake sizing, (2) Auto-Motor Und Sport magazine's standard fade test "AMS-2", and (3) Auto-Motor Und Sport magazine's high performance fade test, "AMS-3". Fade schedule cycle times are user selectable, or can be computed via a simple powertrain and aero drag model.

Mass Regression Models

Brake Calipers

A database of front and rear brake calipers was analyzed to compute suitable linear regression models for fitting the data. The database had calipers for subcompact vehicles up through full size trucks. Many possible predictive factors and model combinations were tested, and the best performing model was selected. Strong correlation was found between caliper material, wheel envelope size, piston total area, pad volume, caliper type (fixed or sliding), and parking brake type (integrated parking brake or none).

The model performance for brake caliper mass regression was an R-squared of 87%. All factors tested as significant with at least 95% confidence, save for the parking brake presence, which tested as significant with only 86% confidence.

Brake Rotors

A database of "modern" (NVH-tuned) brake rotor designs was analyzed and regression models to predict the total mass of the brake rotors were fitted. All brake rotors were full-cast, cast iron construction (no two piece or co-cast designs were included). Strong correlation was found between brake rotor mass, the square of the outer diameter, and brake rotor thickness (not surprisingly). The rotor "working mass" (portion of the rotor participating most strongly in the braking heat exchange process) was computed via a second regression model, with separate models used for front versus rear brake rotors. The working masses of rotors in the database were computed for regression model fitting using the assumption that the working mass included the brake plates (machined areas) and the cooling vanes (if applicable). The working mass excluded the brake rotor hat sections and brake plate to hat connection. The regression model performance for brake rotors was an R-squared of 98%, with all factors in the model testing as significant with >98% confidence.

Apply System

A regression model to predict the mass of the brake apply system was created by fitting models to a database of brake power booster and master cylinder combined masses. The database was comprised of single and tandem vacuum-based power boosters, and predominantly aluminum master cylinders. Strong correlation was found between vehicle lightly loaded mass, and brake power booster peak output (which of course is in turn related to total diaphragm area).

Model performance was approximately 65% R-squared, with both vehicle mass and apply system output testing as significant with >99% confidence. An effort was made to improve the model by including whether the power booster was single or tandem; however, adding this factor did not improve the model performance (likely the effect was already included in the peak output factor). A review of the database entries indicated that there was a lot of variation in mounting design

and brackets, which did not necessarily relate to fundamental brake system design - therefore, the model was accepted as is with no further efforts to improve it. It is also possible that there was some influence by the growing trend of using chassis-controls based features such as boost assistance to enable different apply system sizing.

THE COST OF VEHICLE ATTRIBUTES IN TERMS OF BRAKE SYSTEM MASS

2. Relationship between Vehicle Mass and Brake System Mass

It is intuitive to most that there is a strong correlation between vehicle mass and brake system mass. Reducing vehicle mass enables reduced brake system mass. Various efforts have been made to describe the relationship between vehicle and automotive subsystem mass (including brakes), often expressing the results in the form of a mass de-compounding coefficient (mathematically the ratio of subsystem mass savings opportunity to vehicle mass saving). Research by Caterina Bjelkengren [2] using regression models determined a coefficient of 0.032 for brakes and steering (every 100 kg of vehicle mass corresponds to 3.2 kg of brake system and steering system mass). Adjusting this for a typical ratio of steering to brake system mass results in a coefficient of approximately 0.024 for the brake system only. Work by Malen [3] suggested a coefficient of 0.24 for brakes. Research by GM (not published externally) ranges from 0.038 in an older study, to 0.01 in a more recent study. Differences from study to study were likely due to differences in statistical methods, and differences in the input data sets.

This "top down" regression model can be checked against the "ground up" or component-based regression model employed in the present study. As vehicle mass increases, the thermal capacity and cooling capacity of the brake system must increase to match - this is done to keep the brake system components in a workable temperature range. A common brake thermal sizing criterion is to maintain an equilibrium temperature during a repetitive braking test below a specification limit. In this study, a repetitive braking cycle of 64 to 24 kph snubs, with a 20 second cycle time in between, was run until an equilibrium temperature is reached. The specification this temperature is proprietary and is therefore not cited explicitly. Suffice it to say that it is set at a limit that promotes everyday operating temperatures low enough to preserve brake quality by protecting features such as noise insulator adhesive, rotor transfer film, and pad material integrity.

To perform this study, gross (laden) vehicle mass for a typical front wheel drive configuration was varied from 1500 kg up to 2500 kg, while holding factors such as brake force distribution constant. Two cases were analyzed, one with brake cooling inputs typical for a steel wheel, and the other with brake cooling inputs typical for an aluminum wheel. The thermal mass of the front rotor was solved for to keep the brake

equilibrium temperature at the specification limit, and the geometry of the rear rotor was scaled to maintain brake balance. The size of the apply system was scaled according to vehicle mass as well. The results are plotted in [figure 1](#) below:

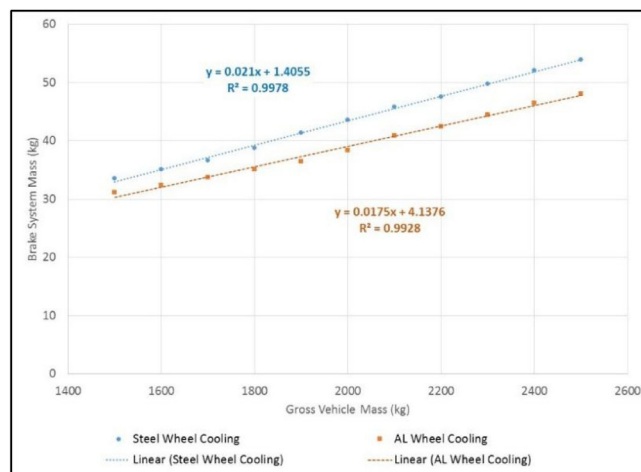


Figure 1. Summary of Brake System Mass versus Vehicle Gross Laden Mass for Steel and Aluminum Wheel Cooling

There are some interesting features in this plot - firstly, the coefficient relating brake system mass to vehicle mass is 0.021 kg brake system mass per kg of vehicle mass. This shows that a ground-up model driving sizing by a single thermal sizing criterion alone results in a mass compounding coefficient well within the ranges cited by previous work. Secondly, if brake operating temperatures are kept similar, the selection of steel versus aluminum wheels has a 2.4 kg to almost 6 kg impact on brake system mass. In this manner, the mass savings of an AL wheel set is intensified through brake system mass savings. (The author acknowledges that in many instances the brake system mass is not actually added - instead the operating temperatures are allowed to increase, of course still within a safe operating range, but to the detriment of factors such as brake lining life and NVH performance).

3. Effect of Tire and Wheel Size in Brake System Mass

It is intuitive that as the tire and wheel of a vehicle get larger - or more specifically, the "static loaded radius" of the tire/wheel assembly that defines the moment arm for brake torque - the brake must produce more torque to achieve the same tractive force at the tire contact patch. A common brake system sizing metric that applies in this situation is a hydraulic pressure limit. There are three major motivations for limited brake working pressure. Firstly, to limit apply system size, secondly, to maintain comfortable chassis controls operation (antilock brakes, traction control, and electronic stability control), and finally, to keep the working pressure in a well understood range for component durability. A common design criteria in the industry is to achieve 1.0g of deceleration with a maximum of 100 bar hydraulic pressure.

Applying this pressure limit with a typical friction assumption (0.32 coefficient) in a compact sedan with a fixed wheel size creates a situation where the caliper piston size must be scaled to keep pressure under control. As the caliper piston size increases, the master cylinder size must increase proportionally to keep pedal travel and master cylinder stroke under control. This in turn drives increases in apply system output to keep apply system runout at an acceptably high level. For the purposes of this analysis, rear caliper piston area was increased proportionally to the front to keep the brake balance constant, master cylinder size was increased to keep pedal travel constant, and apply system output was increased to keep runout at the same (deceleration) level as the baseline.

Figure 2 below shows the relationship between brake system mass and tire static loaded radius. Front caliper piston size is also plotted for reference:

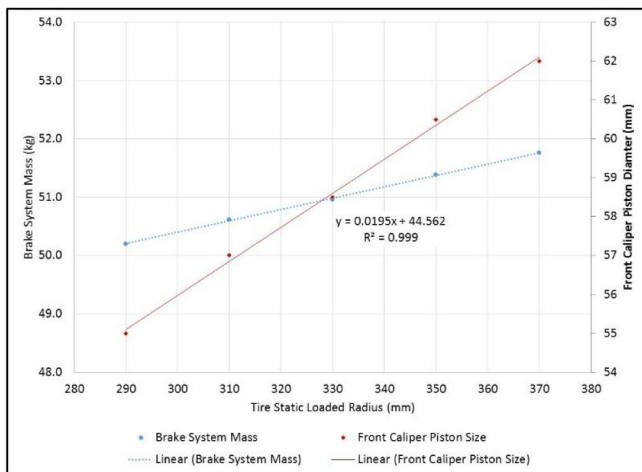


Figure 2. Summary of Brake System Mass versus Tire Static Loaded Radius (mass is driven by hydraulic pressure limits)

The data in figure 2 shows a relationship of approximately 195 grams of brake system mass per 10mm of tire static loaded radius. The front caliper piston size progressed from about 57mm at a tire static loaded radius of 290mm up to about 62mm (or a 2x44mm equivalent twin piston caliper area) at a tire static load radius of 370mm. Of potential greater significance than the mass penalty is the effect on the size and packaging of the brake components - for example, constraints on packaging a larger piston size and achieving proper fitment to the brake pad may actually drive a larger wheel envelope size brake rotor, with a significantly higher mass penalty.

4. Relationship between Brake System Mass and Engine Peak Power

It is intuitive to many that as engine power increases, the brake system must also increase in capability to match; indeed, this argument has been made for over eighty years of brake system design [5]. Brake sizing and cooling requirements are generally related to engine power objectively through well defined fade tests that match acceleration capability against braking capability.

The German publication Auto Motor Und Sport, runs brake fade tests that are acknowledged in the industry to the point of being ubiquitous. The most common test (run on most vehicles reviewed by the magazine - see [9] for more information), consists of a cold stopping distance test from 100 kph. This is followed by 10 back to back cycles of full throttle acceleration to a speed of 100 kph, followed by maximum effort braking. Successful performance in this test (referred to henceforth as "AMS2") is reflected in minimal degradation of deceleration capability (stopping distance) over the course of the test. A second, more stringent test, "AMS3", consists of a series of 9 back to back cycles of wide open throttle acceleration from 70 kph to 80% of the vehicle's maximum speed, followed by moderate deceleration back down to 70 kph. A tenth, maximum effort stop (after accelerating back to 80% of maximum speed) is performed immediately following the heating snubs. The simplest possible method to design brake systems to perform well in these tests is to keep the peak brake rotor temperature below a certain threshold (although brake fade performance will often depend on much more than this).

A compact sport sedan was the basis for this study. Engine power was varied from 150 hp to 500 hp for AMS2, and 200 to 550 hp for AMS3. Brake rotors were sized to meet both the equilibrium temperature-based specification cited in the previous section (XXXX) and a defined AMS temperature limit.

Figure 3 below shows the results for the AMS2 simulation. Two vehicle masses were analyzed (a baseline, design intent mass, and a case of 200 kg heavier).

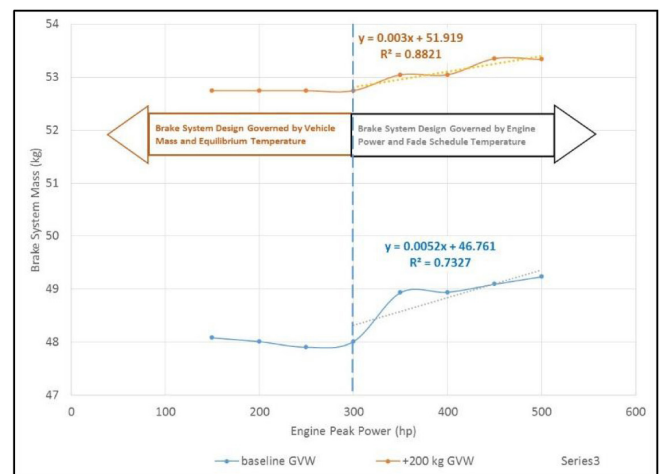


Figure 3. Summary of Brake System Mass vs. Peak Engine Power for Compact RWD Sedan Meeting "AMS2" Temperature Limits

The plot shows that the standard equilibrium-temperature based requirement drives the brake system design up until approximately 300 hp. After this, the brake system mass becomes sensitive to engine power as the AMS2 temperature limit becomes the deciding factor. As engine power increases, the brief cooling interval afforded the brakes during the acceleration run becomes shorter and shorter, which drives brake rotor size up to maintain a temperature limit. However, the short duration of the cooling cycles makes thermal storage