A Prognosis System for Vehicle Brake-pads

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An in-vehicle brake-pad prognosis system is described that provides an indication to the driver of the time-to-inspect the brake pads. The system can also provide the percentage remaining material and the remaining drivable miles on that material. The system uses measurements of the wheel speeds and the brake pressure to estimate the energy dissipated by the brakes by each braking event and the corresponding effect on brake rotor temperature. The system was installed on a development vehicle and test results on a test track and using a vehicle dynamometer showed good correlation with measured values.

I. INTRODUCTION

SEVERAL vehicle components, such as the battery, the tires, the engine oil and the brake-pads, typically need to be replaced throughout the life of a vehicle. The useful life of each of these components varies considerably and is dependent amongst other things on vehicle usage, environmental operating conditions and vehicle design. The large variations in these factors can make it difficult for most drivers to assess when replacement is required. This can lead, in the case of engine oil to a conservative estimate of replacing the oil every 3000 miles, which can add unnecessary cost. Prognostic systems are being developed to monitor the state-of-health and state-of-life of these components. For instance, General Motors has had an engine oil life prognosis system in its vehicles for a number of years that provides an indication to the driver of when the oil needs changing. This is now provided to customers monthly through OnStar vehicle diagnostics email. The email also contains state-of-health information for various systems as well as tire pressure information. This paper describes the development of a brake-pad wear prognosis system that can provide a similar indication to the customer on the condition of the brake-pads.

The wear rate of the brake-pad material is dependent on the brake temperature, the hotter the brake-pads the more wear results. The brakes temperature is a result of the energy that is dissipated by the brakes when stopping. The wear rate is a function of driving style, traffic and usage conditions, road grade and ambient temperature, as well as the vehicle mass, brake design and material properties. These factors result in the life of a brake-pad typically being between 20,000 and 80,000 miles. An in-vehicle prognosis system is described that monitors available vehicle variables to account for the majority of observed variations. Experimental results on a development vehicle demonstrate the systems effectiveness.

Many different approaches were considered when initially examining the problem of estimating the brake-pad wear. One considered was the need to estimate the energy dissipated by the brake-pads. The approach adopted obviates the need to estimate down to this detail. Test data obtained using the actual vehicle brake caliper designs is used. This provides brake-pad wear versus rotor temperature for a fixed amount of brake energy. The test details are provided in the next section.

A CAE system that can estimate lining life [3] was used to determine the relative influence of various factors in the wear of a brake-pad, see Fig 1.

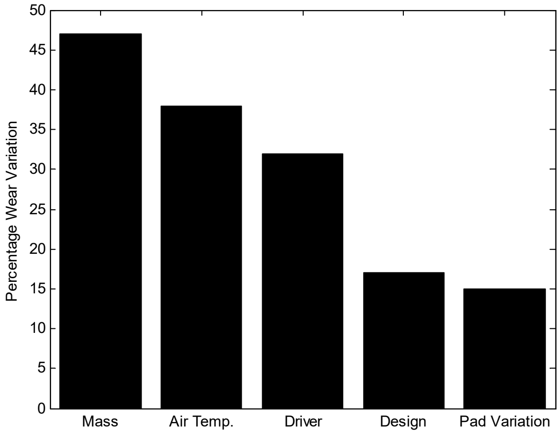

Fig. 1. Contributors to Brake-pad wear

The factors considered are vehicle mass, outside ambient air temperature, driving style, vehicle design and pad to pad variations. As expected the major influence on the brake-pad wear is the vehicle mass. The range was obtained by using the CAE system to estimate the lining life for a sedan vehicle that was fully laden compared to an empty one. Another major influence was the air temperature which affects the brake cooling. The driver's style can also have a high impact on wear. For example, aggressive driving, braking late and consequently harder heats up the brakes more than normal and results in a higher degree of wear. The vehicles brake and rotor design affects the air flow and the cooling of the brake pads.

The other major influencing factor is location. Driving in urban LA stop and go traffic is much more detrimental to the life of brake linings than highway or rural driving. While this is not a parameter we can control it is one that the model of brake-pad wear needs to comprehend.

The paper is organized as follows. An overview of the

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system model is given in the next section. Section III then describes the brake-pad material testing that provides a consistent wear versus temperature data. The brake rotor temperature thermal model is described in Section IV. The instrumentation of the development vehicle is shown in section V and the model validation results are then presented in section VI.

II. SYSTEM MODEL

An overview of the system model is shown in Fig. 2. The figure shows the various different parts of the onboard dynamic brake-pad wear estimation system. The system model iteratively estimates the rotor temperature and determines the wear during a braking event. The system does not provide resolution down to each individual brake-pad but only to a per axle level. This is because it is generally recommended the entire front or rear sets of brake-pads should be replaced together.

The main elements of the system are a brake energy model, a brake rotor thermal model and an energy-to-wear estimate. An optional indicator sensor can also be included which can be used to remove accumulated errors in the system wear estimate.

The braking energy and power dissipated by the brakes is estimated from the brake torque and angular wheel speed. This is input, together with the outside air temperature, into a first-order dynamic model of the brake rotor temperature. The brake rotor thermal model is described in section IV.

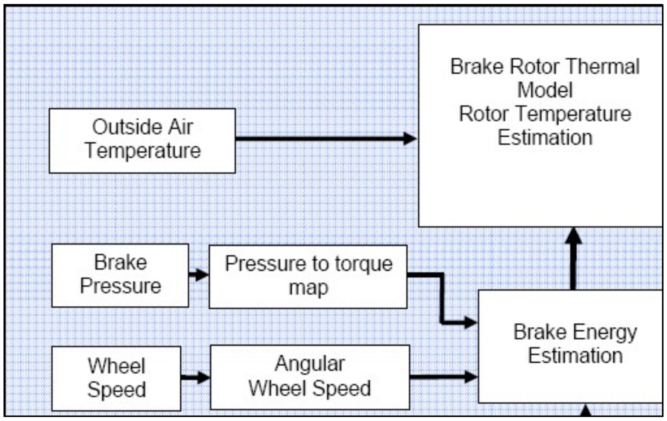

Fig. 2. Brake-pad prognosis system model

The rotor temperature estimate and energy dissipated by the brakes are input into an energy-to-wear estimation block. The energy-to-wear block has various buckets into which is added the calculated braking energy dependent on the rotor temperature. The calculated braking energy is put into the bucket corresponding to the closest rotor temperature at that iteration. The equivalent wear is then determined by relating the energy dissipated at each temperature to that from corresponding experimental wear versus temperature test data. The wear estimate is the sent to a brake-pad status block that updates an estimate of the percentage brake-pad wear loss so far. The remaining drivable miles can be estimated in a number of ways, the simplest being to linearly extrapolate from the number of miles driven given the current wear estimate to that corresponding to a completely worn pad.

The brake-pad indicator sensor module can be used to improve the estimate. The indicator sensor has a wire imbedded in plastic. The plastic wears through as the pad wears and at the set thickness the wire breaks. This is detected onboard. This type of sensor has been used in the past to give a direct indication to the driver that the brake-pad needs replacing. The sensor wire is set to a depth where the difference between the estimated wear and the true value can be by ramping out over a next few thousand miles. The brake-pad thickness when it is replaced will then be close to that estimated by the system.

III. BRAKE WEAR VERSUS TEMPERATURE

This section describes a brake–pad wear versus rotor temperature test. The test is used to evaluate new lining materials to determine if the wear characteristics as a function of temperature meet a vehicles brake system design requirements. Conducting these tests multiple times on new lining materials provides an indication to the robustness of the manufacturing process.

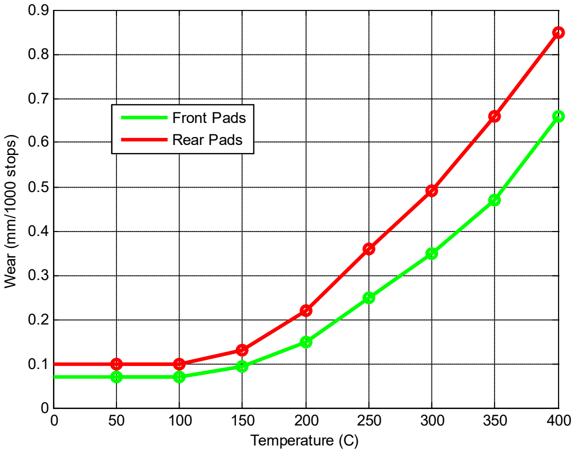

Fig. 3. Brake-pad prognosis system model

A standard test procedure has been developed to assess a brake-pad materials wear versus temperature characteristics. 1000 brakes stops are performed for predetermined initial brake bulk rotor temperatures. This is repeated in 50°C intervals to obtain a graph similar to that shown in Fig. 3. The test is conducted on the actual brake corner hardware with the rotor spun up to 50kph each time.

The dissipated energy for each braking event is determined from the inertial loading and speed information. Since we are braking to zero speed, the energy E is calculated by

$$E = \frac{1}{2} I \varpi^2$$

where I is the test inertia and ϖ is the initial angular wheel speed.

The test data for the brake-pad material specified for the vehicle is entered into the software as calibrations. For each of the buckets the ratio of the estimated energy in the bucket is divided by the energy and multiplied by the wear. The values are summed from each bucket to provide an indication of the total wear. This can then be converted to a percentage of the total brake lining wear so far.

IV. BRAKE ROTOR TEMPERATURE

The brake rotor thermal model is a first-order dynamic model with calibrateable parameters that are dependent on the rotor material and brake cooling properties. The brake-pad wear monitoring and prognosis system requires only a brake rotor thermal model and not a brake-pad thermal model, since this is the temperature recorded in the wear versus temperature test. The input wheel speed is converted from km/h to m/s through a gain block with a value of (1/3.6). It is subsequently converted to radians per second (rads/s) by dividing by the effective rolling radius.

TABLE I
UNITS FOR THERMAL MODEL

Symbol	Quantity	Units
T	Rotor Temperature	
M	Rotor Working Mass	
τ_f, τ_r	Front & Rear brake Torque	
m	Wheel Speed	
M	Angular Wheel Speed	
$4\pi M$	Cooling Coefficient	
σ	specific heat capacity of rotor	
j	Rotor Cooling Coefficient	

The transfer function between the input braking power P, and the rotor temperature T, is a first-order dynamic equation given in Laplace form as:

$$\frac{T}{P} = \frac{1/(C_p M)}{(s+\mu)}$$

where M is the effective rotor mass and C_p is the specific heat capacity of the rotor material

$$C_p = K_1 + T \cdot K_2$$

The Cooling Coefficient μ is a function of speed

$$\mu_{Rotor} = K_{\mu 1} + K_{\mu 2} V$$

and V is the wheel speed in m/s.

The input power is $P = \tau \cdot \varpi$, where $V = \varpi \cdot r$, with r is the (effective) wheel radius and τ is the braking torque.

The model is implemented in discrete-time form. At iteration n,

$$T(n+1) = T(n) + \Delta t\left(\frac{\tau \cdot \varpi}{C_p \cdot M} - \mu_{Rotor}\left(T(n) - T_{ambient}\right)\right)$$

V. DEVELOPMENT VEHICLE SETUP

Fig. 5 shows the development vehicle, a mid-size passenger sedan car, which was instrumented with some brake-pad wear sensors, brake pressure sensors, wheel torque and thermocouples on the brake rotors. The additional instrumentation was converted from analogue signals to CAN (Controller Area Network) format. Several signals from the vehicle CAN bus were also recorded these were the wheel speeds, outside air temperature, brake apply and odometer. A duel channel CAN data logger recorded all these signals to flash memory cards.

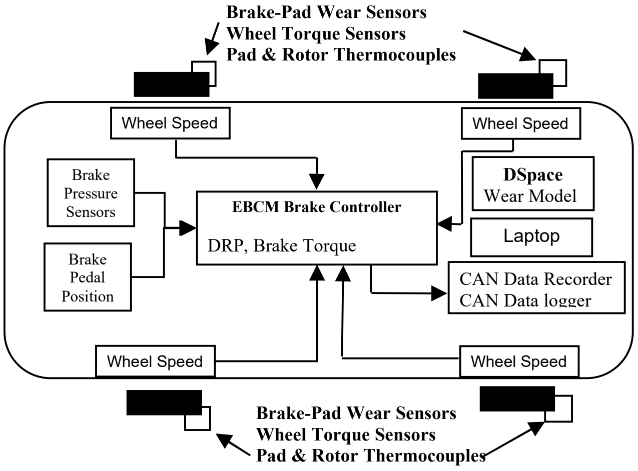

Fig. 5. Test Vehicle Setup

A DSpace rapid prototyping system was also used to implement the system in an on-line real-time Simulink model.

Fig. 4 shows the results of the thermal rotor model described in section IV. The results are compared to measured rotor temperatures obtained during vehicles tests.

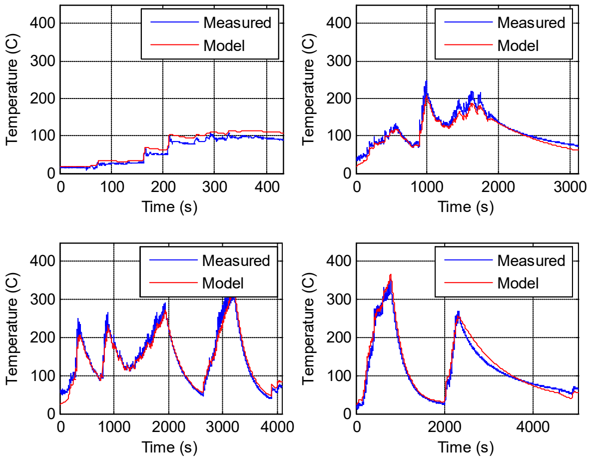

Fig. 4. Thermal Model Validation

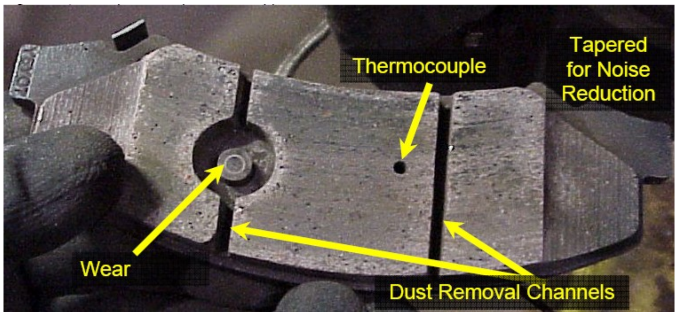

Fig. 6. Brake-pad prognosis system model

VI. MODEL VALIDATION

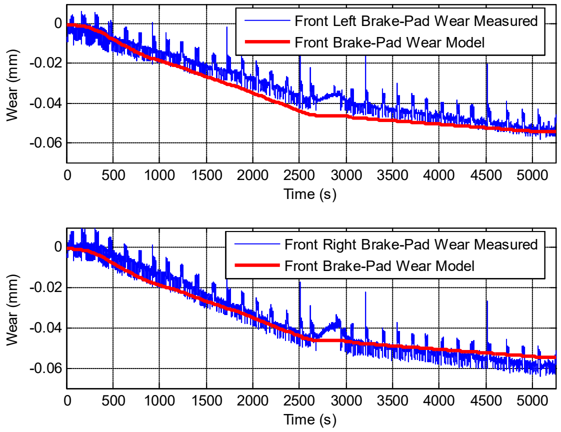

Fig. 7. Brake-pad wear results

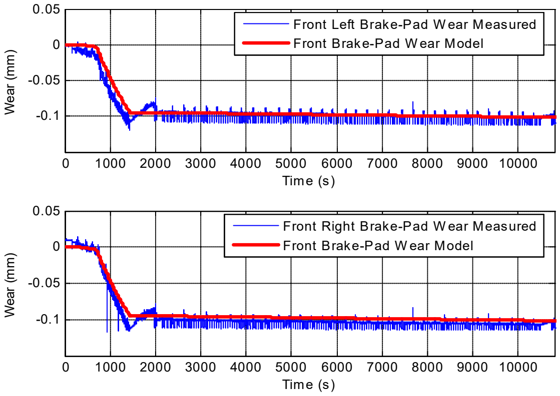

Fig. 8. Brake-pad Wear

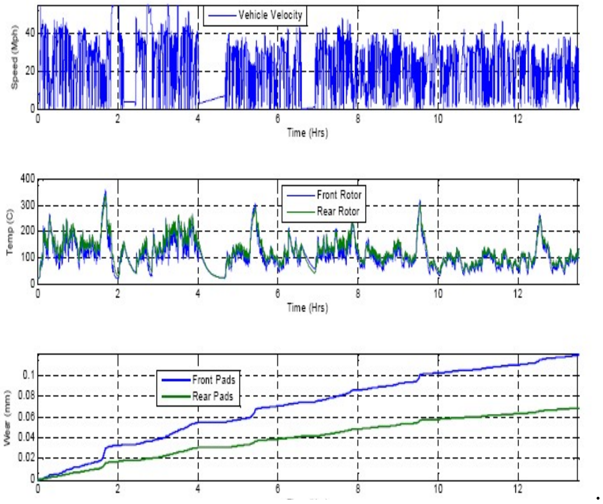

Fig. 9. Simulated City Driving Results

VII. CONCLUSION

The development of a brake-pad wear prognosis system has been described. The system has shown to provide good results on a development vehicle with a known brake-pad material. The system will be limited to specified brake-pads materials because the aftermarket products available show considerable variations in wear versus temperature tests.

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