

Thermal Mapping of an Automotive Rear Drive Axle

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ABSTRACT

In recent years, there has been a sustained effort by the automotive OEMs and suppliers to improve the vehicle driveline efficiency. This has been in response to customer demands for greater vehicle fuel economy and increasingly stringent government regulations. The automotive rear axle is one of the major sources of power loss in the driveline, and hence represents an area where power loss improvements can have a significant impact on overall vehicle fuel economy. Both the friction induced mechanical losses and the spin losses vary significantly with the operating temperature of the lubricant. Also, the preloads in the bearings can vary due to temperature fluctuations. The temperatures of the lubricant, the gear tooth contacting surfaces, and the bearing contact surfaces are critical to the overall axle performance in terms of power losses, fatigue life, and wear. It is therefore important to understand the temperature variations in an automotive rear axle as a function of operating loads and speeds. However, quantitative understanding of the axle thermal behavior is limited and published information is sparse. This study attempts to bridge this gap.

In this paper, an automotive rear drive axle is used to investigate the thermal behavior and power losses under a range of speed and load conditions developed from a typical EPA fuel economy driving cycle. The test axle is instrumented with thermocouples at various critical locations on the rotating and stationary components. A wireless telemetry system was used to extract the temperature readings of those rotating thermocouples. The axle tests were run on a dynamometer with simulated wind cooling and the tests were

run till the lubricant reached steady state conditions. Findings from these tests will be discussed in this paper.

INTRODUCTION

It has been well established that the automotive rear axle is one of the major sources of power loss in the driveline [1]. It therefore represents an area where potential power loss reductions can have a significant impact on overall vehicle fuel economy. Power losses from a rear axle mainly come from 1) friction induced mechanical losses at loaded hypoid gear mesh, bearings and seals; and 2) spin losses associated with lubricant pumping and churning and bearing pre-load. The power loss under operating conditions and the temperature reached under those operating conditions are interdependent. Both the mechanical losses (also known as load dependent losses) and the spin losses (also known as load independent losses) vary significantly with the operating temperature of the lubricant. Also, the axle and lubricant temperature rise itself is a function of the heat generated due to axle power losses. Temperature variations also have an effect on bearing preloads which in turn influence the power loss at the bearings. The operating temperature of the lubricant and temperature rise at the gear mesh and bearing locations also have an influence on common gear and bearing failure modes such as scuffing, scoring and wear. Therefore, axle thermal behavior is critical from both an efficiency and a durability standpoint.

Conducting an accurate measurement of axle power loss is challenging since small differences in power must be determined precisely. Only a limited number of studies have been reported since 1970s, mostly through SAE publications, on the measurement of axle efficiency or power loss [2, 3, 4,

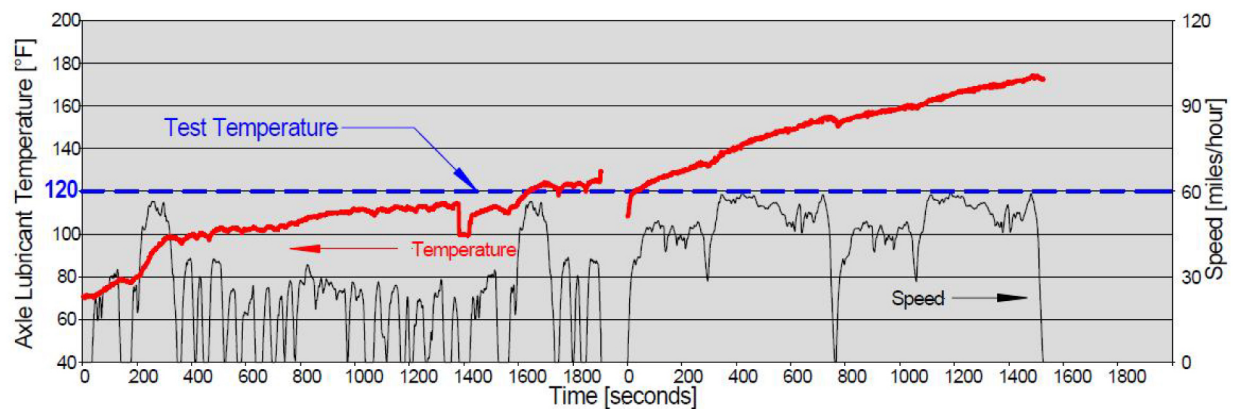


Figure 1. Axle gear sump temperature during the EPA Driving Cycles [8]

5, 6, 7, 8, 9]. Hobson [2] in 1979 proposed a procedure for laboratory axle efficiency test as part of the initial work of the SAE recommended practice [3]. He included test results with a variety of axles, lubricants and gear ratios and demonstrated that axle efficiency is very sensitive to lubricant selections and variations in load, speed and temperature. Porrett et al [4] developed a laboratory axle efficiency test using a torque sweep method. The test axle's differential was locked such that all the power from the driveshaft was transferred to one axle shaft. Axle power loss was calculated from measured input and output torque and speeds. Lubricant temperatures were controlled at each test point. Katoh et al [5] presented a calorimeter approach to measure the axle power loss where the axle was closed and immersed in an insulated water tank. The power loss was calculated by the measured inlet and outlet water stream temperatures and the flow rate under the assumption that all the axle power loss is converted into heat rejection. Ko and Hosoi [6] developed a method for measuring axle churning loss from the measured rise in lubricant temperature. In 1988, Winter and Wech [7] used a unique hypoid back-to-back test rig to investigate axle efficiency and illustrated the influences of hypoid offset and lubricant on the efficiency. They also reported that based on their tests, synthetic lubricants can increase the axle efficiency significantly at high torque conditions while low viscosity oil did not help to increase the efficiency at high speed range. There is a gap in the published literature on axle power losses until 2008 when Anderson and Maddock [8] developed a methodology for axle power loss and efficiency test. The authors proposed a loaded efficiency block cycle that was repeated 15 times to break in the axle, after which three additional cycles were run as the efficiency test cycles. In all these studies [2, 3, 4, 7-8], in order to compare the influence of various parameters, the operating axle oil temperatures were tightly controlled at pre-defined levels. However, in actual operation in a vehicle, the actual gear oil temperature could be quite different from the pre-defined levels and varies significantly depending on the driving conditions, such as load, speed and wind speed.

Axle lubricant rheological properties play an important role in axle thermal behavior, efficiency and life, and a number of studies on developing or testing axle fluid can be found [10, 11, 12, 13, 14, 15, 16, 17, 18, 19]. These studies are aimed at reducing axle operating oil temperature or improving efficiency. Using low viscosity oils can typically reduce spin loss and help improve axle efficiency but it results in higher temperature at high load that could be detrimental to gear and bearing life. It is reported that axle efficiency and life can be balanced or optimized through carefully developed multigrade lubricants that need to be tailored to a specific application or duty cycle. Leaving the lubricant and axle alone, in an experimental study on rear axle cooling performances, Ogino et al [20] concluded that leveling of the vehicle under floor to decrease the airflow resistance and prevention of the drop in the wind velocity under floor is an efficient method to reduce axle gear oil temperature.

These fore mentioned research work have limited their scope in the axle power loss or efficiency and oil temperature. The temperature variations of axle components, such as gear and bearing temperatures, are not addressed. Axle oil temperature varies significantly through EPA driving cycle as shown in Figure 1 [8]. Figure 1 indicates that gear oil temperature started at around 70°F (about 21°C) at the beginning of the EPA city cycle and it reached around 120°F (about 49°C) at the end of the city cycle. During the high way cycle, gear oil temperature continued to climb up and reached over 170°F (about 77°C). Consequently, large temperature variations at gear and bearing locations can be expected during the EPA driving cycle. These temperatures will get even higher at fully rated axle capacity under certain real world driving conditions and this will be important not just from a power loss perspective but also from a durability perspective. It is therefore important to understand the temperature variation in the automotive rear axle as a function of operating loads and speeds.

In this paper, we will explore the thermal characteristics of an automotive rear axle with the goals of understanding the

temperature distributions in the different parts of the axle, the steady state lubricant temperatures reached at given operating conditions and identifying major sources of power losses in the axle. An automotive rear drive axle will be used to experimentally investigate the thermal behavior and power losses under a range of speed and load conditions developed from a typical EPA fuel economy driving cycle.

TEST METHOD

Previous studies on developing a standard test procedure [8] were focused on efficiency measurement under tightly controlled constant gear oil temperature. The study in this paper is an extension of the previous work and the same dynamometer configuration is adapted here with an exception that the oil sump temperature is allowed to rise. A schematic view of the dynamometer configuration is shown in [Figure 2](#). As seen in the figure, three blowers are added to simulate wind cooling. These blowers are placed in front of the test axle and facing the differential carrier. The blowing speeds are set to simulate the vehicle under floor wind speeds. The oil temperature is allowed to rise until steady state conditions are reached. For the purpose of this study, steady state is defined by a 0.1 slope of the temperature curve, i.e. a rise of 1°F (about 0.56°C) every 10 minutes. The test then continues running for one additional minute to verify that steady state condition has been reached. The external cooling system is then turned on to cool down the oil before starting the next test point. The external hydraulic system is not used during these tests.

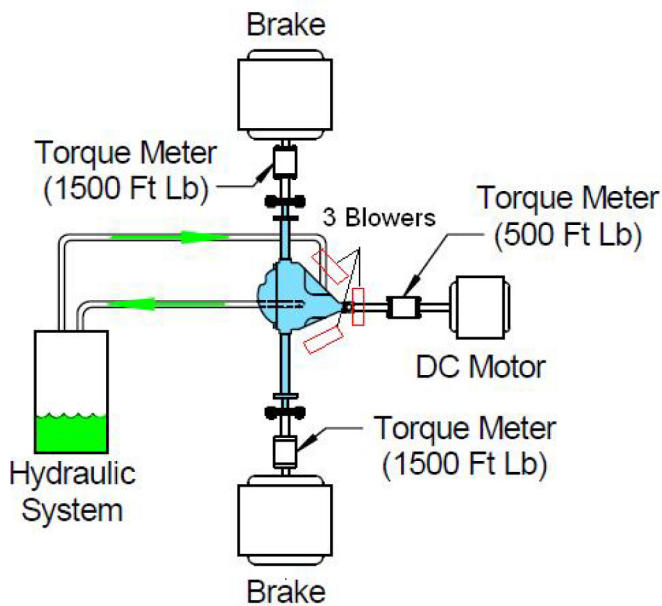


Figure 2. Axle thermal mapping test dynamometer

The rest of the test methodology utilized in this study is the same as proposed in [8] and so is only briefly described here. Axle thermal mapping and power loss tests were conducted

on a dynamometer in a “T” configuration with an open differential and an electric motor in order to obtain an accurate evaluation of axle thermal mapping. An open differential is used to mimic more realistic axle operating condition and the absorber controls were tuned to limit the speed difference to much less than 1 rpm. Precision digital torque meters are used on all three shafts to facilitate accurate torque measurements. The accuracy of the system has been studied and found to be sufficient to evaluate the potential power loss reductions due to proposed axle improvements. Details of the test stand configurations, measurement accuracy and repeatability can be found in [8]. In case of no load spin loss tests, the two axle output shafts were set free and a lower capacity torque meter was used to accurately capture smaller spin torque loss variations.

The tests were carried out on an automotive rear axle. Four groups of thermocouples were mounted on the test axle [21] to measure the temperature variations at various rotating and stationary axle components. Seven rotating thermocouples were mounted on pinion tooth (P1-2), pinion shaft (P5) and pinion head and tail bearing inner race locations (P3-4 and P6-7) as shown in [Figure 3](#). There are also seven rotating thermocouples mounted on gear tooth (D1-2), differential case (D5) and differential bearing inner race locations (D3-4 and D6-7) as shown in [Figure 4](#). [Figure 5](#) shows nine thermocouples on carrier cover (L1-9), where L2 corresponds to the upper side of the carrier cover and L6 is at the bottom side. [Figure 6](#) through different views illustrates fifteen thermocouples on the carrier (C1-15), where C1-4 and C5-8 are mounted at the locations of outer races of differential bearings and pinion bearings, respectively. C9-12 are located at the top of the carrier while C13-15 are at the bottom. A wireless telemetry system was used to extract the temperature readings of the rotating thermocouples P1-7 and D1-7. The rotating thermocouples were installed by an instrumentation company. A High Speed Digital data collection system was used for the pinion thermocouples P1-7. The data collection system for the rotating thermocouples on the differential case and ring gear (D1-7) is a microwave based telemetry system. The instrumented axle is shown in [Figure 7](#). Detailed information about the axle instrumentation and data acquisition and processing can be found in [21].

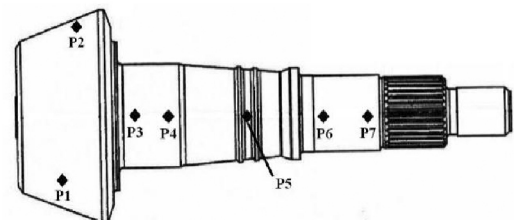


Figure 3. Rotating thermocouples on pinion (P1-P7)

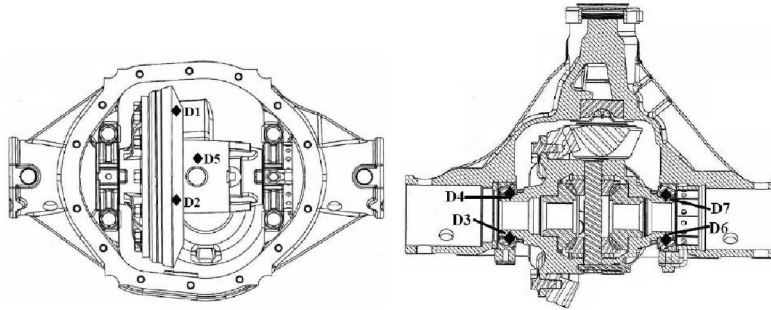


Figure 4. Rotating thermocouples on ring gear and differential case (D1-D7)

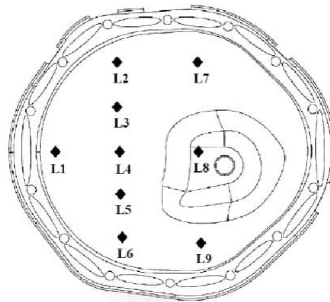


Figure 5. Stationary thermocouples on carrier cover (L1-L9)

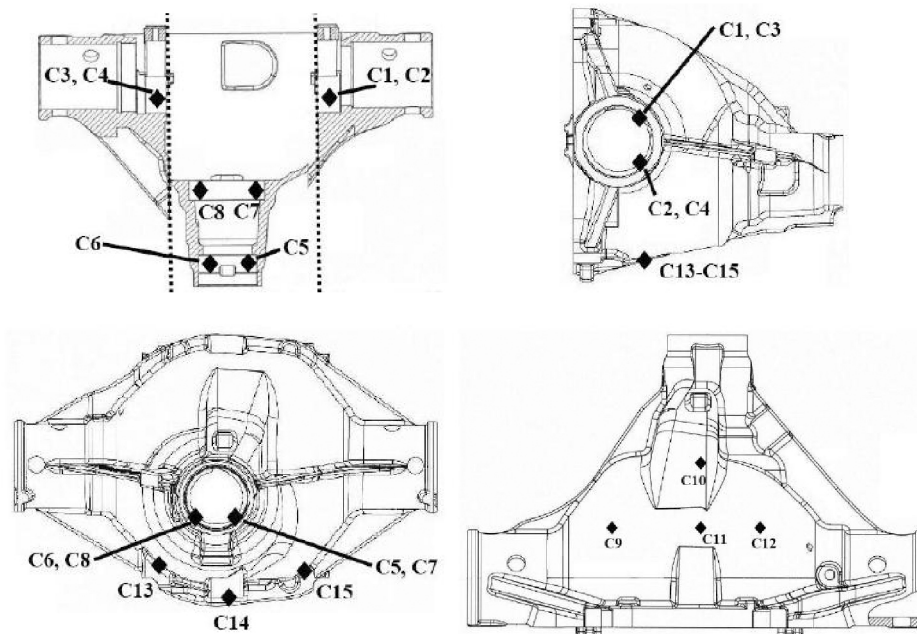


Figure 6. Stationary thermocouples on various carrier locations (C1-C15)



Figure 7. Stationary thermocouples on various carrier locations (C1-C15)

Both no load tests (also called spin loss test) and loaded tests (also called efficiency test) were performed with the instrumented axle. Under no load conditions, tests were conducted at four pinion speed levels, namely 500, 900, 1600 and 2900 rpm. For the loaded tests, the test schedule shown in Figure 8(a) was developed based on the standard 29/20 test schedule proposed in [8] shown in Figure 8(b). There are nine test points in total that is the subset of the 29/20 test schedule. The input pinion speed, torque and power at these nine points are listed in Table 1. Prior to executing the test schedule, this axle was broken-in by running through the standard 29/20 cycle multiple times.

Table 1. 9-point loaded test schedule

Test Point and Sequence	Pinion Speed	Pinion Torque		Input Power	
	[rpm]	[Nm]	[lb-ft]	[W]	[HP]
1	500	54	40	2984	4
2	1600	54	40	8952	12
3	500	298	220	15666	21
4	2900	54	40	16412	22
5	500	542	400	28348	38
6	1600	298	220	49982	67
7	1600	542	400	91012	122
8	2900	298	220	90266	121
9	2900	542	400	164866	221

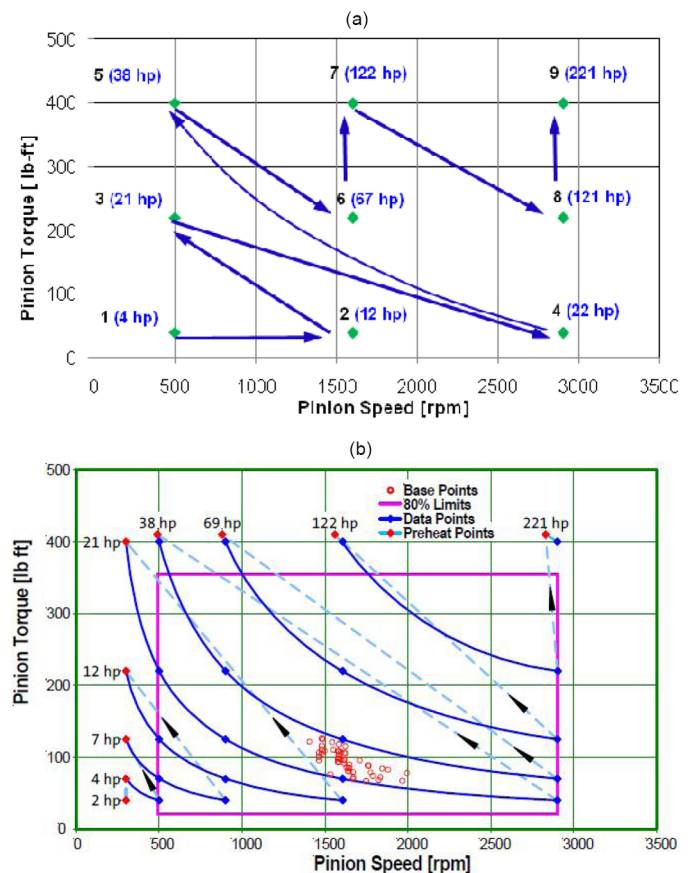


Figure 8. Test Schedule a) nine point test schedule in this study, and b) Standard 29/20 test schedule [8].