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Analysis of Wheel Deflection Causes and Effects

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Summary

As part of the Association of American Railroads' (AAR) Strategic Research Initiatives Program, the Transportation Technology Center, Inc. (TTCI) concurrently validated wheel profile monitoring systems (WPMS) and examined the causes of wheel deflection variations. Factors that were suspected to change the wheelset back-to-back measurement were ambient temperature changes on the axle, axle bending while the vehicle is loaded, and curved plate effects on rims heated by brakes. These factors were investigated using (1) linear expansion equation, (2) back-to-back measurements taken at the Transportation Technology Center (TTC), and (3) two finite element analysis (FEA) models of a wheelset with heat and load.

Based on measurements taken at TTC and FEA model analysis, deviation of wheel deflection was found to be influenced by variation in wheel temperature from braking operations, axle load, and axle temperature. The total differences between two detector passes with extreme cases due to each cause are listed below:

- The total difference in back-to-back measurement due to heated wheels (~550°F) from braking operations is 0.174 inch.
- The total difference in back-to-back measurement due to the axle load condition (between empty and fully loaded) is 0.042 inch.
- The total difference in back-to-back measurement due to axle expansion or contraction from operation temperatures (-20°F to 120°F) is 0.040 inch.

When acting all together, the change in back-to-back measurement between two detector passes could be as high as 0.256 inch. The AAR standards and recommended practices for shop maintenance of wheels and axles acceptable range for back-to-back measurements is 0.25 inch.[1] Loaded and heated conditions reduce the back-to-back measurement on the wheelset at the rail.

This is part in an ongoing effort to develop WPMS standards that include the following:

- Analysis of worn wheel profile variation
- A comprehensive survey of WPMS vendors
- Automated equipment identification matching
- Validation of vendor's detection technology

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INTRODUCTION

Automated machine vision wheel profile monitoring systems (WPMS) use cameras and/or lasers to measure critical dimensions on wheels and wheelsets. In the effort of validating WPMSs the within wheel variation of each measurement taken by the detector was investigated. This was done by taking multiple measurements of critical dimensions on free rolling wheelsets which had been used in revenue service including flange height, flange width, maximum tread hollow, tread hollow position, back-to-back gage, and rim thickness. This investigation into the back-to-back variation was initiated considering that axle bending could have an effect on back-to-back measurements. A small change (1/16 of an inch) in back-to-back could push the measurement out of tolerance. Figure 1 shows the difference between the AAR *Manual of Standards and Recommended Practices* (MSRP) lower limit (shop maintenance) and AAR *Interchange Rules* (IR) lower limit for back-to-back measurement.[1,2]

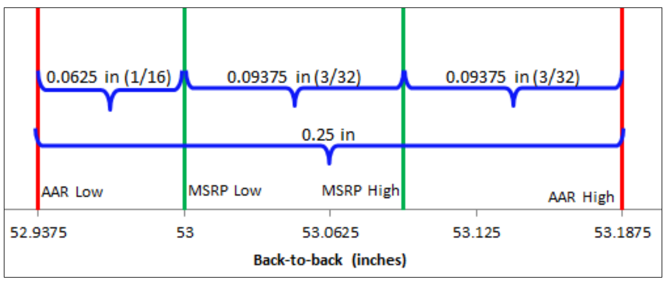

Figure 1. AAR MSRP and AAR Interchange Rules Lower and Upper Limits for Back-to-back Measurement

To better understand the variation of the back-to-back measurement for the WPMS, additional factors are considered as follows:

- Curved plate effects on rims heated by brakes while the vehicle is loaded and empty
- Axle bending while the vehicle is loaded
- Ambient temperature changes on the axle

Curved Plate Effects for Heated Rims

In order to estimate the wheel deflection caused by curved plate effects for heated rims and axle bending under load, a finite element analysis (FEA) model of a wheelset with typical properties was made. The wheelset is made up of an H-36 Class C wheel and a Class K axle. The axle was modeled with 88 kilo-pounds per square inch (ksi) tensile strength and 50 ksi yield strength.[1] The wheel was modeled with 166.8 ksi tensile strength and 108.9 ksi yield strength.[3] The model was placed into two configurations: with thermal and without thermal. Configurations with thermal applied represent the heat caused by a braking operation.

Figure 2 shows the arrangement of the FEA model. The wheelset was anchored at position C. An elastic support was placed at position B to represent the rail. Forces applied at position A were 39,000 pounds for loaded and 8,750 pounds for empty configurations. The thermal load applied to the model was about 550°F (287.78°C), and it was only applied to the rim of the wheel.

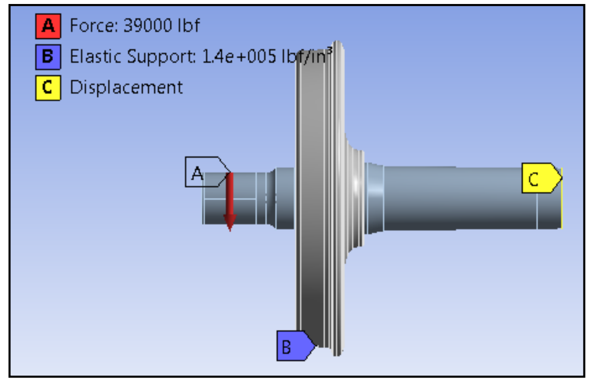

Figure 2. FEA Wheelset Model Arrangement

Figure 3 shows the results of the FEA for the loaded wheelset without thermal, and Figure 4 shows the results with thermal. The displacement at the bottom of the wheelset in Figure 3, when doubled to represent the change in back-to-back, is consistent with the measurements taken on the test vehicle discussed in the next section, because it is within the confidence interval of the mean difference between unloaded and loaded.

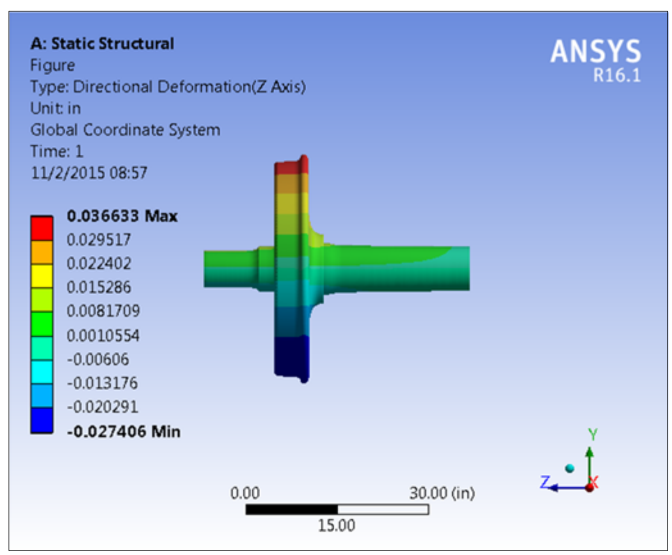

Figure 3. FEA Results of Loaded Wheelset without Thermal

The difference between displacements at the bottom of Figures 3 and 4 after being doubled is 0.174 inch. This value represents the decrease in back-to-back based on the curved plate effects from the rim heated during braking. The same difference of 0.174 inch was found in the analysis of the empty configuration when comparing the back-to-back measurements from thermal and no thermal configurations.

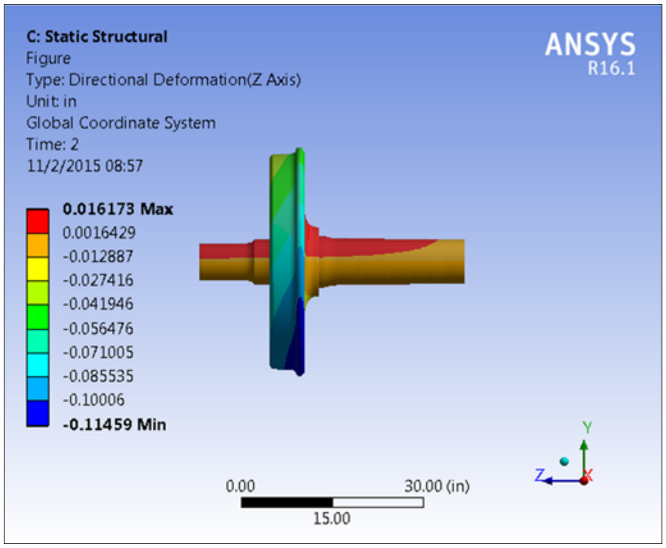

Figure 4. FEA Results of Loaded Wheelset with Thermal

The following effects could possibly have an influence on the wheel deflection caused by curved plate effects:

- Plate design
- Rim thickness
- Magnitude of heat
- Lateral forces

The wheel represented in the model was one plate design, and other plate designs could have an effect on wheel deflection. The magnitude of heat could cause more or less deflection. Additional lateral forces may cause a change in the back-to-back measurement as well.

Wheel Deflection from Load Condition

An experiment was designed to examine how much the back-to-back measurement would change while loaded versus empty. Using a back-to-back gage fit with a digital indicator, each wheelset on a single vehicle was measured in four equally spaced locations while loaded and unloaded. Each measurement was taken as close to the rail as possible, rotating the wheelset for each measurement position. This was done because, as shown in Figure 5, the hypothesized points of maximum back-to-back deflection are at the top and the bottom of the wheelset and WPMSs typically measure back-to-back near the rail. The loaded body weight was jacked up and the trucks rolled out from underneath the vehicle to take unloaded measurements as opposed to emptying the lading from the vehicle. The vehicle selected for measurements was a 286,000-pound coal car with K-type (6½ X 9) bearings. The vehicle represents a large percent of the freight population in both loading capacity and journal bearing size.

Figure 5. Points of Positive/Negative Wheel Deflection

Figure 6 is an individual value plot of all empty and loaded back-to-back measurements taken. From empty to loaded, there is a shift in the back-to-back towards lower values. When the wheelsets are loaded, some measurements come close to the AAR *Interchange Rules* lower limit.[2]

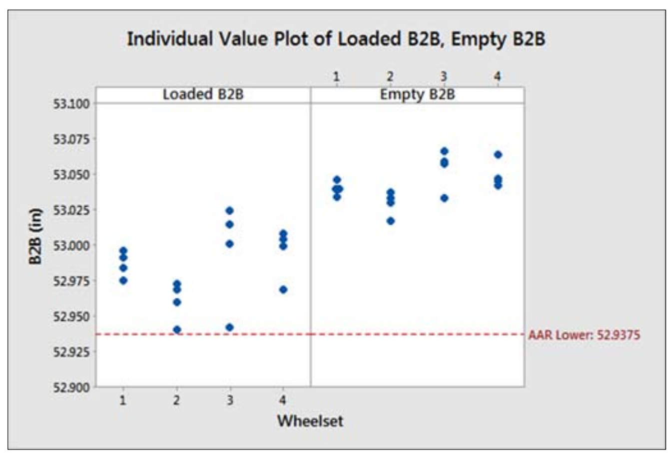

Figure 6. Individual Value Plot of Empty and Loaded Back-to-back Measurements

The goal of this test design was to take measurements and then complete a paired-t test. Figure 7 shows the results of the paired-t test, which found a statistical difference between loaded and empty back-to-back measurements. The confidence interval for the mean of the differences is -0.0666 inch to -0.0509 inch.

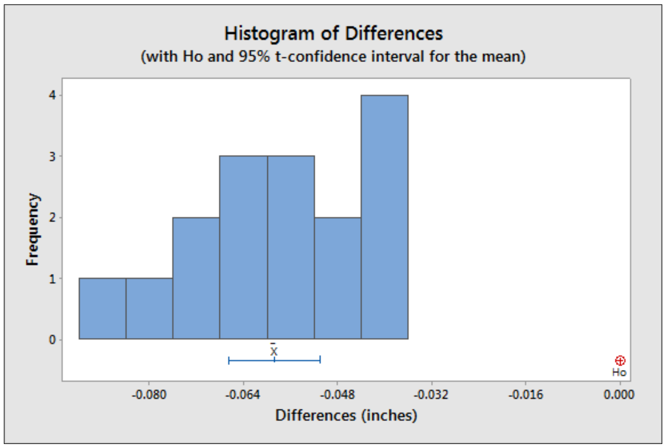

Figure 7. Paired-t Test Minitab Results

Wheel Deflection from Axle Temperature

The back-to-back measurement can be affected by expansion of the axle over an ambient temperature range. In order to estimate how much the axle length might expand with revenue service temperatures ranging from -20 to 120 degrees in Fahrenheit, the equation for linear thermal expansion was used. The steel used in the axle of a wheelset is equivalent to 1055 steel and has a coefficient of linear thermal expansion at 212°F of $6.1\text{x}10^{-6} in/in°F$.[4]

Equation 1, the equation for linear thermal expansion was used to calculate how much the distance between the nearest edges of the wheel hubs of 47.25 inches will expand over the difference of 140°F.

$$\boldsymbol{Length_{Final}} = \boldsymbol{Length_{Initial}}(\mathbf{1} + \boldsymbol{CTE} * \Delta \boldsymbol{T}) \quad (1)$$

The result, shown in Equation 2, is that the axle could expand as much as 0.040 inch.

$$\boldsymbol{Length_{Final}} = \mathbf{47.25}(\mathbf{1} + \mathbf{6.1x10^{-6}} * \mathbf{140}) = \mathbf{47.29}\ \boldsymbol{in.} \quad (2)$$

CONCLUSION

Table 1 shows the cumulative results from the effects considered in this digest. The value of -0.042 inch was calculated by finding the difference in the displacements from the FEA analysis between loaded and empty configurations. The total result of -0.256 inch is the amount the back-to-back measurement could change between two wheel profile detector passes in extreme opposing conditions. This is significant, because the overall acceptable range of back-to-back is only 0.25 inch.

Table 1. Change in Back-to-Back Summary

	Increase in Back-to-back (in)	Decrease in Back-to-back (in)	Difference
Operational Temperatures	Summer (from 50° to 120°) 0.025	Winter (from 50° to -20°) -0.025	-0.040
Load Condition	Empty 0.000	Loaded -0.042	-0.042
Wheel Heated by Brakes	None 0.000	Heated to 550° F -0.174	-0.174
		Total	-0.256

If trending analysis is to be done using the back-to-back measurement from WPMS, operational conditions should be considered. For example, a wheelset may be read as within tolerances when passing a WPMS, but if that wheel is loaded and has a braking operation occurring then it may appear out of tolerance. Once operational conditions have been accounted for, the back-to-back measurements should show a much steadier trend towards moving in or out of tolerance.

REFERENCES

1. Association of American Railroads. 1997. *Manual of Standards and Recommended Practices*, Section G-II, the Wheel & Axle Manual. Washington, DC.
2. Association of American Railroads. 2013. *Field Manual of the AAR Interchange Rules*, Rules 41. Washington, DC.
3. Hernandez, Francisco C. Robles, Semih Kalay, and Scott Cummings. January 2009. “Properties and Microstructure of High Performance Wheels,” *Technology Digest* TD-09-001, Association of American Railroads, Transportation Technology Center, Inc., Pueblo Colorado.
4. *Metals Handbook. Irons, Steels, and High-performance Alloys*. Vol. 1. Materials Park, OH: ASM International, 1990.