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HEAVY MOVABLE STRUCTURES, INC.
TWENTIETH BIENNIAL SYMPOSIUM

October 7-10, 2024

Movable Bridge Friction Review: Lessons in Measured Friction from Decades of Strain Gage Recordings

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Introduction

One of the benefits of using strain gage recordings to evaluate movable bridge imbalance is that it provides a measurement of the dynamic friction of the system during bridge operations. Experience demonstrates that there are significant variations in movable bridge system friction from bridge-to-bridge and sometimes from test-to-test. This paper presents an analysis of dynamic friction from movable bridge strain gage recordings to illustrate variations in dynamic friction and to provide a comparison of the measured friction with the AASHTO prescribed calculated dynamic friction used when sizing prime movers for movable bridges.

Strain Gage Testing Overview

Strain gage results were compiled from hundreds of historical strain gage balance tests for movable bridges. Gage installations were consistent with best industry practices and procedures; they were installed as close to the end of the drive train as practical and they were installed with full Wheatstone bridge arrangements to measure torsional strain and to discount bending. The measured torsional strain is then converted into shaft torque, then either to leaf torque for a bascule bridge, or rope load for a vertical lift bridge, accounting for additional drivetrain reductions and efficiency factors.

With some exceptions, the testing was performed to determine the imbalance of the bridge, through construction services or as part of an inspection. Although the tests were done at different temperatures, they were typically done with minimal external loads from either wind or precipitation, as this is best practice (and a typical construction requirement), to accurately determine imbalance and friction.

The measured loads were converted to imbalance and friction. Data points that were affected by acceleration and deceleration were omitted from the analyses, leaving recorded loads solely due to imbalance and friction. The imbalance and friction calculations were based on the assumptions that friction always opposes the direction of motion, and that the friction was equal in both directions of motion. Given these assumptions, the imbalance load was determined by summing the opening and closing loads at a given bridge angle or lift position and dividing the sum by two. Similarly, the friction load was determined by subtracting the two measurements and dividing that result by two.

In general, accurate results require that there are no significant external loads acting on the bridge during operation (weather loading, abnormal or varying friction, or other sources such as unidentified construction or maintenance materials). On a rolling lift bridge the data may also be affected by variations in the radius of curvature of the curved treads, out-of-level or waviness at the flat tread plates, or interference between lugs and pockets. The compiled strain gage testing results were reviewed for accuracy on a test-by-test basis.

Analyzed Bridges

The compiled data included results from rolling lift bascule, trunnion bascule, and vertical lift bridges. The trunnion bascule and vertical lift bridges were then separated into groups with plain trunnion bearings and rolling element trunnion bearings. For this review, multiple bascule leaves were treated as separate "bridges." This review included results from 123 bridges from over 370 tests, with records dating back to 1996.

Analysis Methodology

The strain gage friction measurements were compared to the anticipated friction based on the 2023 *AASHTO LRFD Movable Highway Bridge Design Specifications (AASHTO).* The basis of the comparisons was the friction factors provided in AASHTO Table 5.9.2-1, which are summarized in Table 1. Note that the friction factors provided are similar in *American Railway Engineering and Maintenance-of-Way Association (AREMA).*

Table 1: Summary of AASHTO Friction Factors Considered

Bearing Type	**Friction Factor For Motion**
Plain bearings with one or more rotations – used for vertical lift bridges with plain counterweight sheave bearings	0.09
Plain bearings with less than one complete rotation – used for trunnion bascule bridges with plain trunnion bearings	0.12
Rolling element bearings – used for trunnion bascule bridges with rolling element trunnion bearings – used for vertical lift bridges with rolling element counterweight sheave bearings	0.003
Rolling friction – used for rolling lift bascule bridges	0.006
Rope bending loss calculated as a friction factor (range of calculated values for plain bearing vertical lift bridge data set)[1] – used for vertical lift bridges with plain trunnion bearings	0.015 to 0.027
Rope bending loss calculated as a friction factor (range of calculated values for roller bearing vertical lift bridge data set)[1] – used for vertical lift bridges with rolling element trunnion bearings	0.008 to 0.016

1. *A rope bending loss friction factor was calculated for each bridge based on the AASHTO coefficient of direct tension = 0.3 x rope diameter / sheave pitch diameter; this loss in tension at the ropes was then equated to a dynamic friction factor acting at the sheave trunnion bearings, allowing for a comparison of recorded data versus the cumulative effect of rope loss and bearing friction loss*

A comparison of the measured friction with AASHTO friction required additional information for calculations:

Bridge Weight	Bridge leaf or span weights were determined based on available information: Preferred - results of balance calculations for new bridges Alternate 1 - design drawings (balance tables and loading summaries) Alternate 2 - estimates based on rope tension measurements or using counterweight rope strengths assuming a factor of safety of eight on direct tension
Plain Bearings	The plain bearing radii were according to shop drawings or design drawings.
Curved Treads	The curved tread radii were according to shop drawings or design drawings.
Roller Bearings	Rolling element bearing details were based on shop drawings or design drawings. For these calculations, the “radius” was estimated to be the average of the bore diameter and the outer diameter (“d” and “D” in manufacturer’s literature).
Lift Bridge Counterweight Sheave & Rope Size	Lift bridge counterweight rope and sheave pitch diameters were according to shop drawings or design drawings.

The presented results included bridges with historical data ranging from a single balance test to eighteen balance tests performed over twenty-five years. Note that the results from each balance test were based on the average of multiple runs.

It is typical to present the average friction with the strain gage balance test results. These include the average friction as a leaf torque for bascule bridges and average friction acting at the counterweight ropes for vertical lift bridges. Using the average friction results, the measured dynamic bearing friction coefficient was determined. For bascule bridges, this calculation was the average measured friction torque divided by the product of the weight times the trunnion bearing or curved tread radius. For vertical lift bridges this calculation used the average friction force acting at the counterweight ropes to determine a torque about the trunnion shaft, which was then divided by the product of the weight times the trunnion bearing radius.

The strain gage measurements of system friction on vertical lift bridges are a combination of bearing friction and wire rope bending losses. The bending loss for each subject bridge was calculated in accordance with AASHTO 5.9.3 as [0.3 x (rope diameter) ÷ (sheave diameter)]. See Figure 6 and Figure 8. The calculated rope bending loss was combined with the calculated AASHTO dynamic friction to determine an equivalent AASHTO friction factor for each subject bridge. The range of factors was then used for comparison with the measured dynamic friction factor.

Compiled Results

Rolling Lift Bascule Bridges

The comparison of measured versus AASHTO friction for rolling lift bascule bridges included 35 bridges and 75 tests overall. See Figure 1.

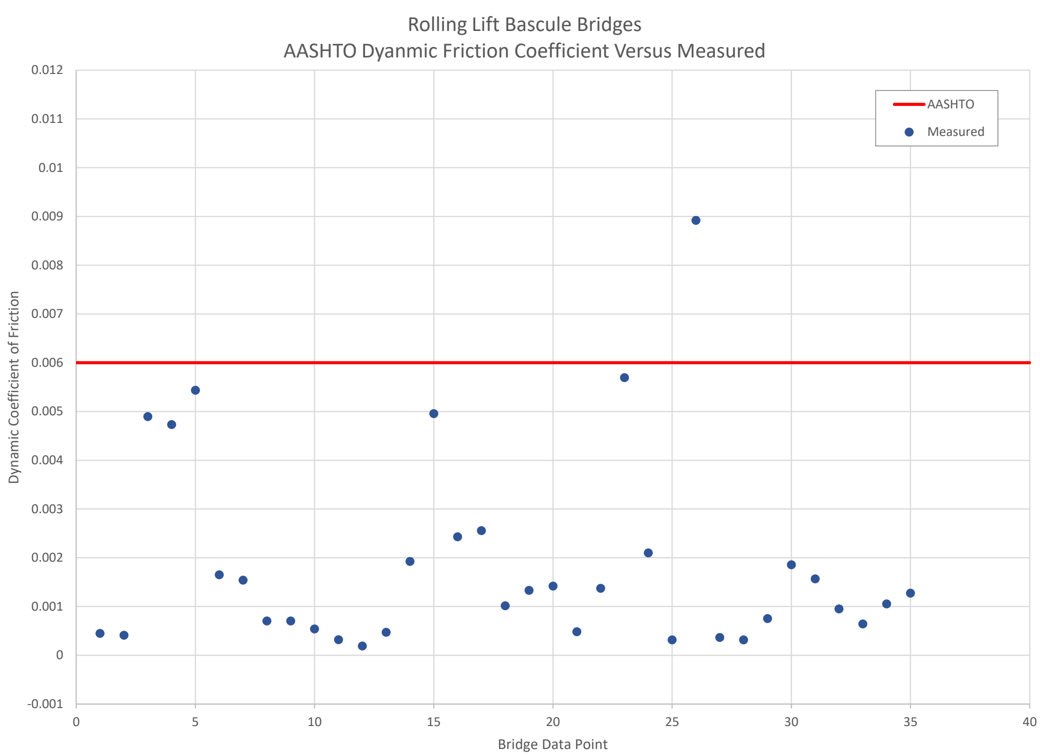

Figure 1: Rolling Lift Bascule Bridges – Measured vs. AASHTO Dynamic Friction

The measured dynamic friction was typically less than half of the AASHTO value, with some exceptions. The AASHTO friction factor is conservative based on this data set.

Trunnion Bascule Bridges with Plain Bearings

The comparison of measured versus AASHTO friction for trunnion bascule bridges with plain bearings included 48 bridges and 125 tests overall. See Figure 2.

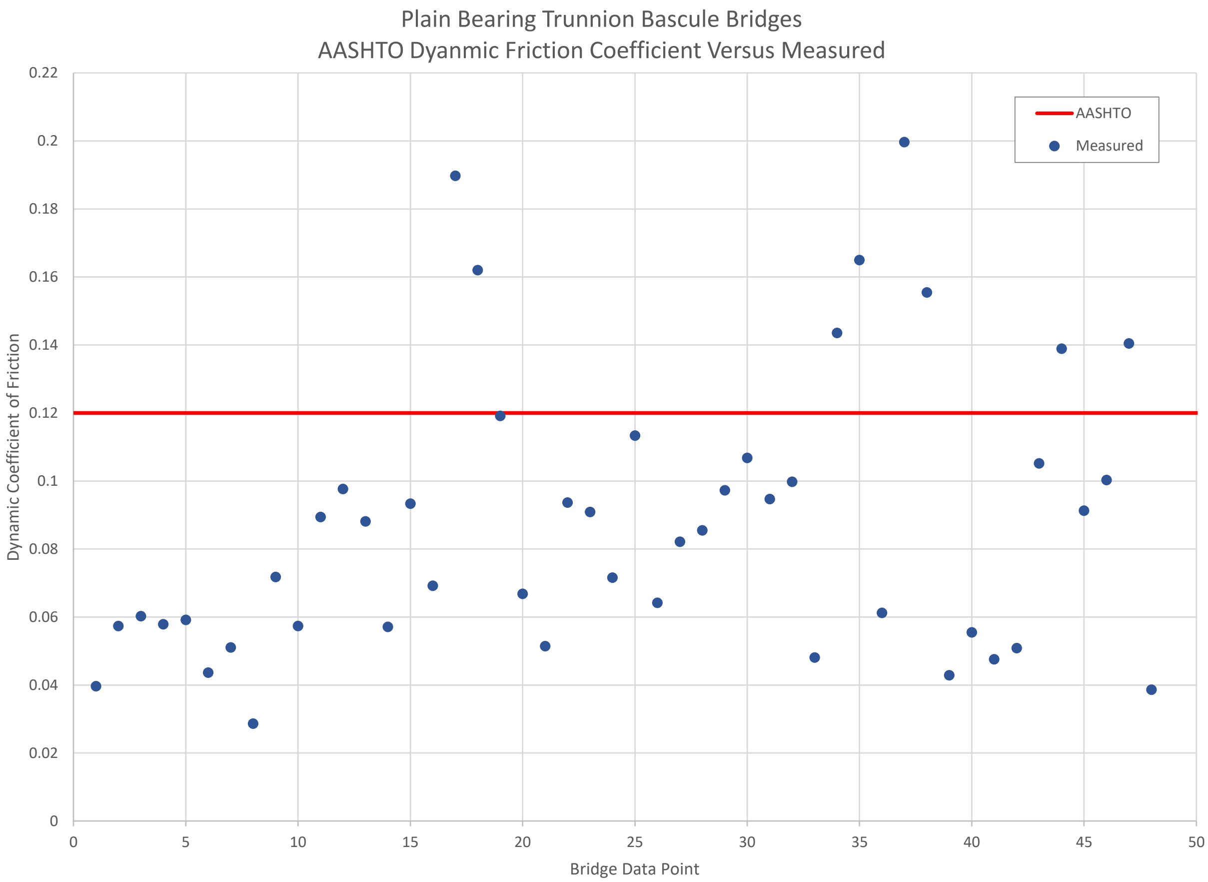

Figure 2: Trunnion Bascule Bridges with Plain Bearings - Measured vs. AASHTO Dynamic Friction

For most of the bridges, the measured trunnion bascule bridge plain bearing dynamic friction was less than the AASHTO calculation, though friction was higher at eight bridges.

Trunnion Bascule Bridges with Rolling Element Bearings

The comparison of measured versus AASHTO friction for trunnion bascule bridges with rolling element bearings was limited to 12 bridges (single test each). See Figure 3 and Figure 4.

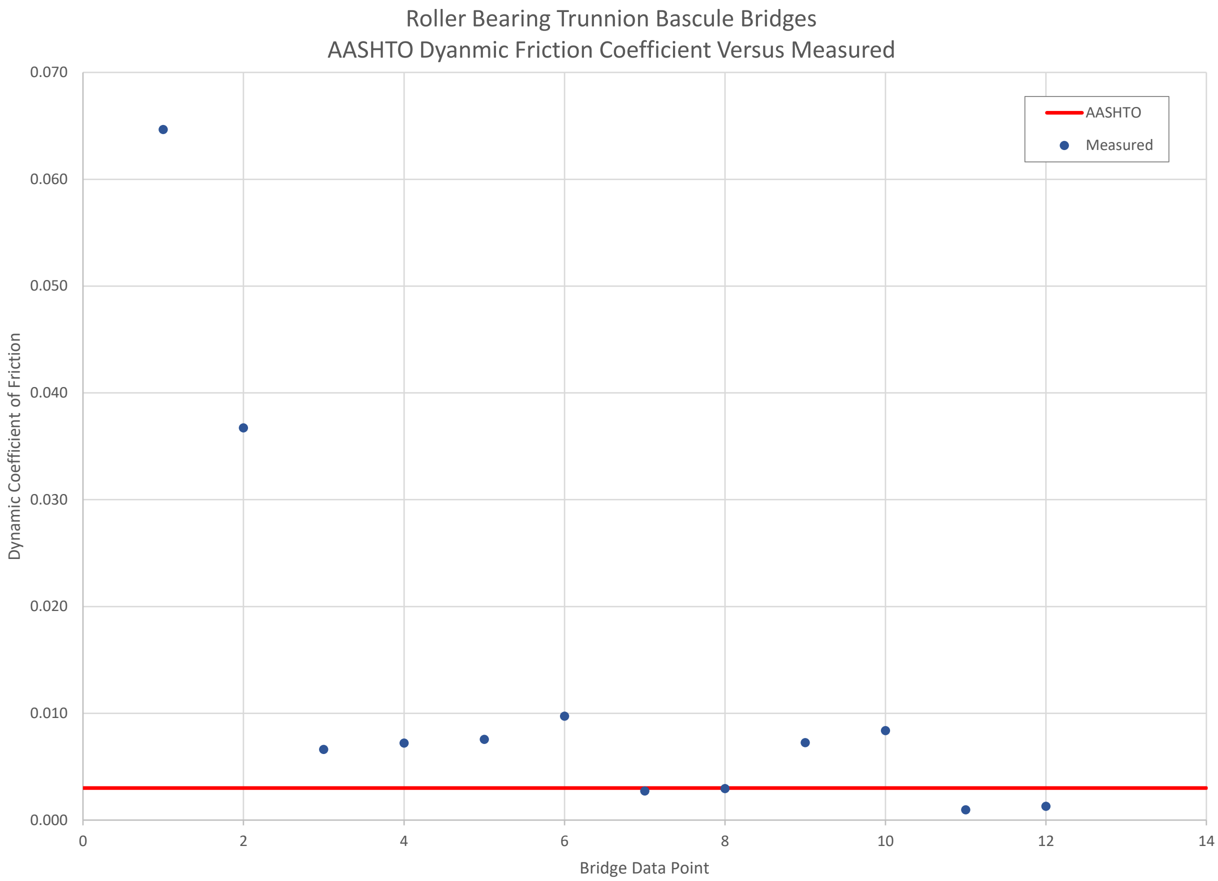

Figure 3: Trunnion Bascule Bridges with Rolling Element Bearings - Measured vs. AASHTO Dynamic Friction – Twelve Bridges

Although a limited sample size, measured trunnion bascule bridge rolling element bearing dynamic friction varied significantly compared to the AASHTO calculation. The first two data points in Figure 3 had significantly higher friction and is data from two leaves of a single bridge. An assessment of the bearings at that bridge noted poor lubricant quality, with water and significant wear particles noted. In addition, possible damage was noted at one of the bearings through vibration testing. Figure 4 provides a chart that excludes the first two data points.

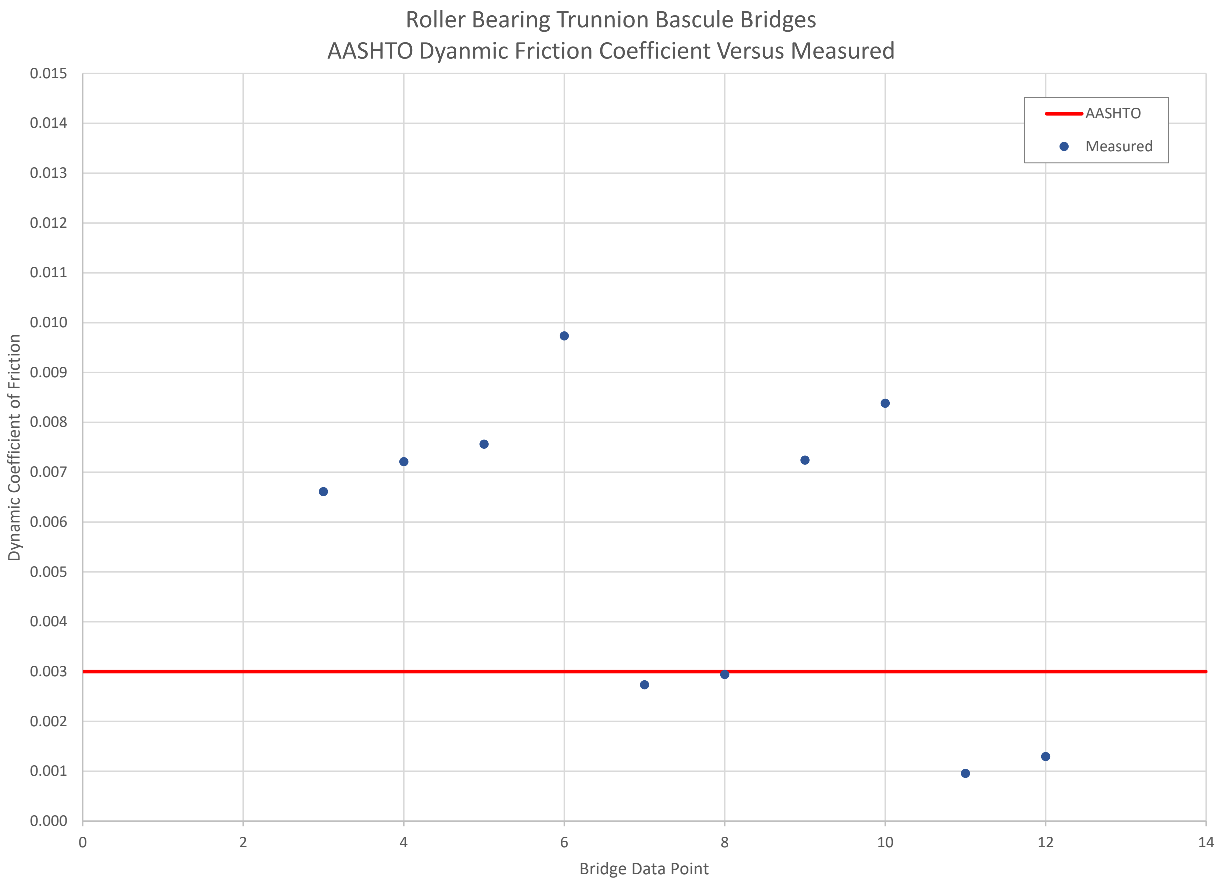

Figure 4: Trunnion Bascule Bridges with Rolling Element Bearings - Measured vs. AASHTO Dynamic Friction - Ten Bridges

Six of the ten bridges included in Figure 4 had friction that was more than double the AASHTO calculation.

Vertical Lift Bridges with Plain Counterweight Sheave Bearings

The comparison of measured versus AASHTO friction and rope bending loss for vertical lift bridges with plain bearings included 14 bridges and 108 tests overall. See Figure 5.

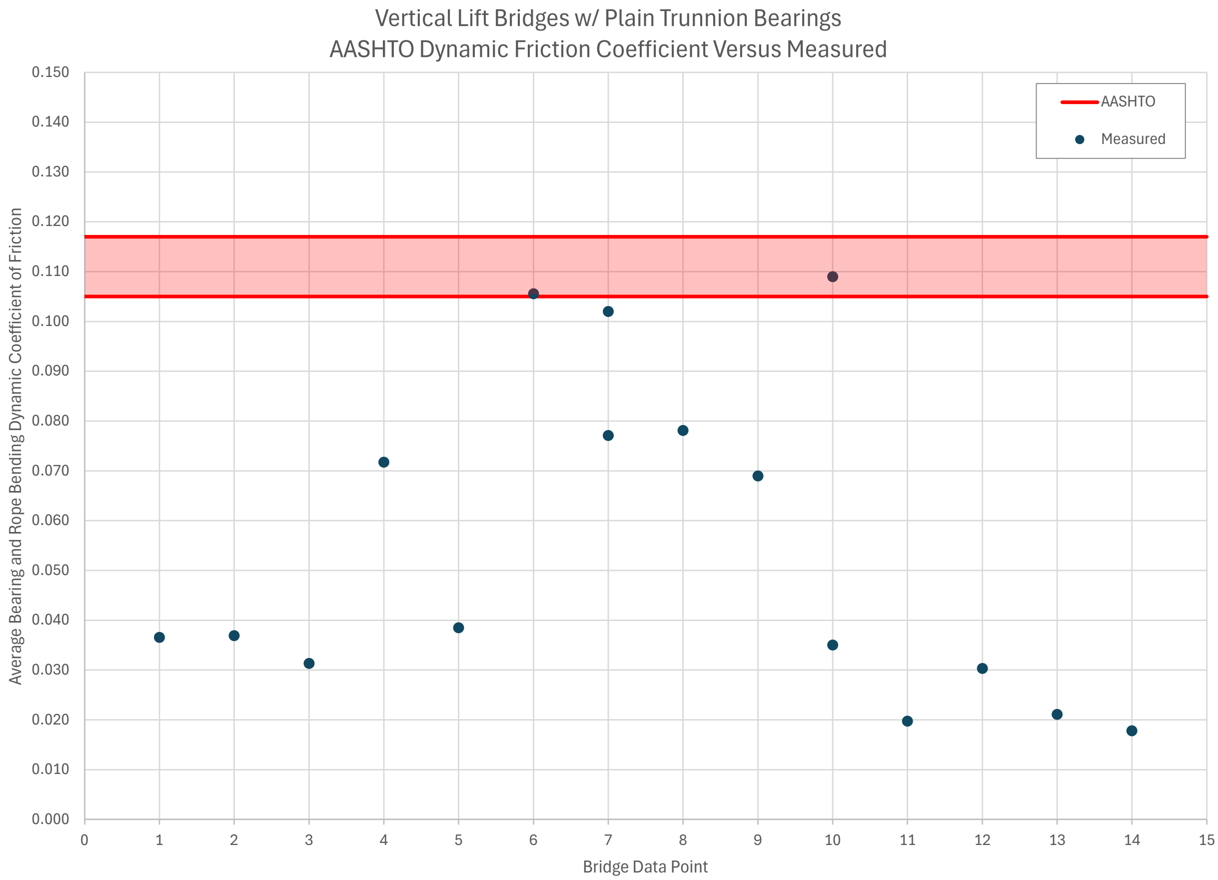

Figure 5: Vertical Lift Bridges with Plain Bearings – Measured vs. AASHTO Equivalent Friction Factor – 14 Bridges

The equivalent dynamic friction combining the bridge rope bending loss and trunnion bearing loss was calculated to have a range of 0.105 to 0.117 for the vertical lift bridges with plain trunnion bearings. See Figure 6 for a chart that describes the magnitude of the calculated rope bending loss and friction loss compared to the measured dynamic friction.

All vertical lift bridges with plain bearings had measured friction that was at or below the equivalent friction factor range. Nine of the fourteen vertical lift bridge plain bearing cases resulted in measured friction that was significantly less than the theoretical friction loss from rope bending and trunnion bearing friction loss. Note that bridge data points 7 and 10 each include two results. For each of these two bridges, the trunnion bearings were identified as damaged and were rehabilitated, resulting in a decrease in the measured friction. Measurements before and after the rehabilitations are included.

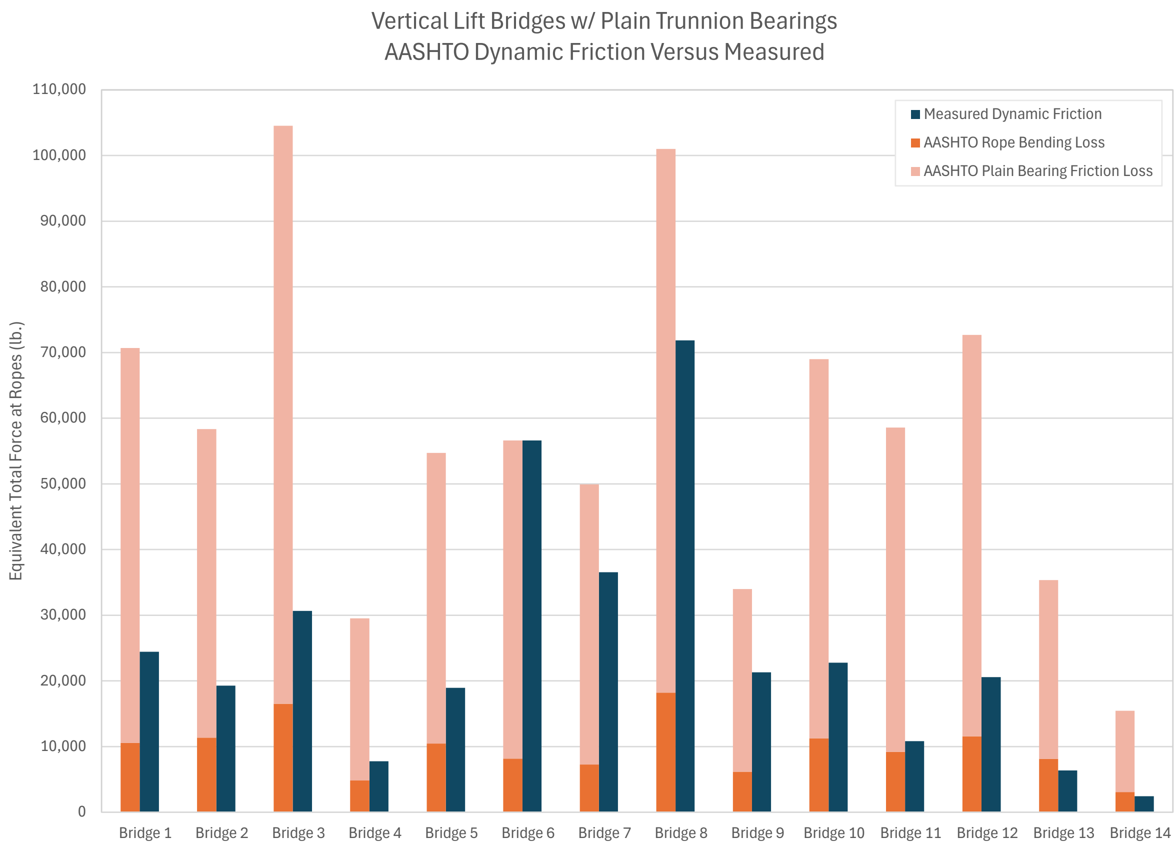

Figure 6: Vertical Lift Bridges with Plain Bearings - Composite Presentation of Dynamic Friction Loss vs Measured

As shown in Figure 6, the calculated theoretical AASHTO bearing friction loss is significantly greater than the rope bending loss. Nearly all vertical lift bridges with plain trunnion bearings had measured dynamic friction that was less than the combined AASHTO friction. Note that Bridge 7 and 10 present the post-rehabilitation measurements only.

Vertical Lift Bridges with Rolling Element Counterweight Sheave Bearings

The comparison of measured versus AASHTO friction and rope bending loss for vertical lift bridges with rolling element bearings included 14 bridges and 50 tests overall. See Figure 7.

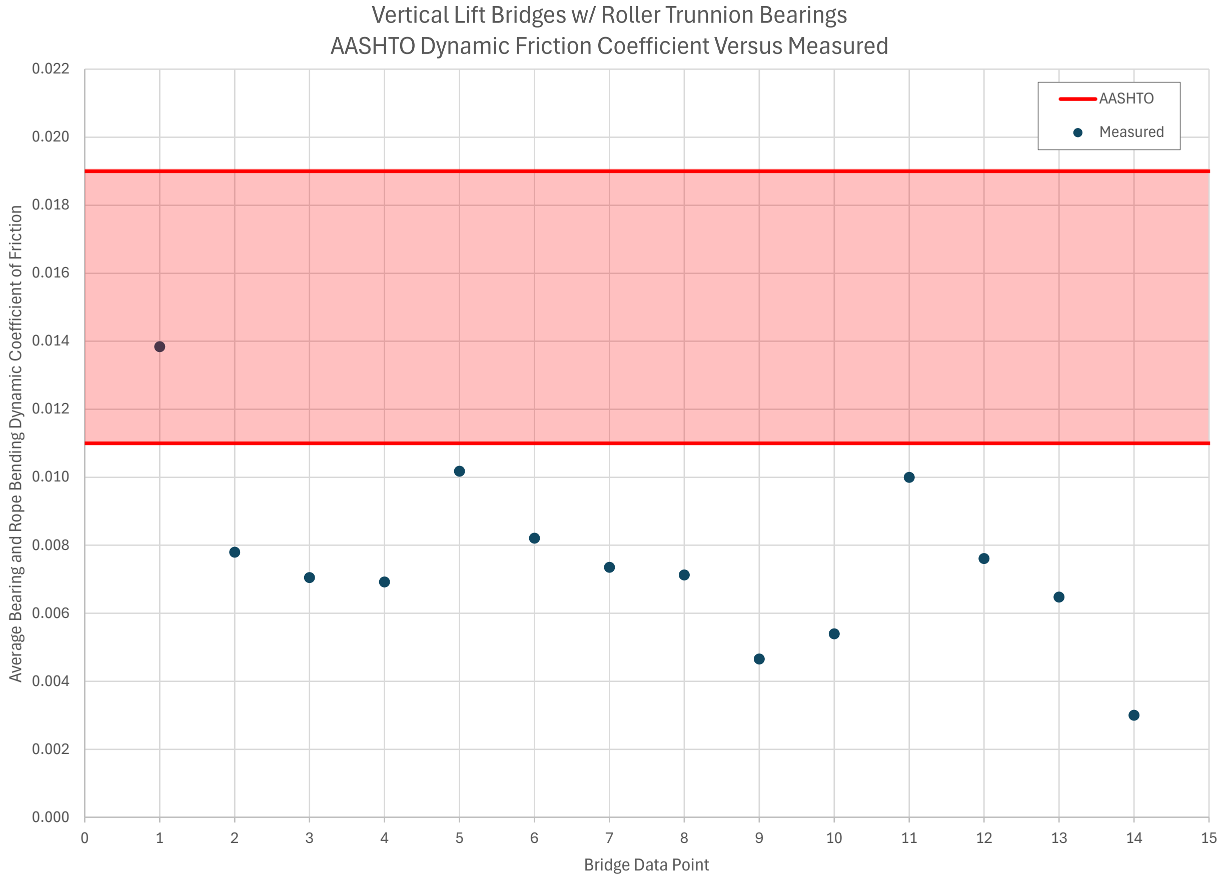

Figure 7: Vertical Lift Bridges with Rolling Element Bearings – Measured vs. AASHTO Dynamic Friction – 14 Bridges

The equivalent dynamic friction combining the bridge rope bending loss and trunnion bearing loss was calculated to have a range of 0.011 to 0.019 for the vertical lift bridges with rolling element trunnion bearings. See Figure 8 for a chart that describes the magnitude of the calculated rope bending loss and friction loss compared to the measured dynamic friction.

All of the vertical lift bridges with rolling element bearings had measured friction that was at or below the equivalent friction factor range.

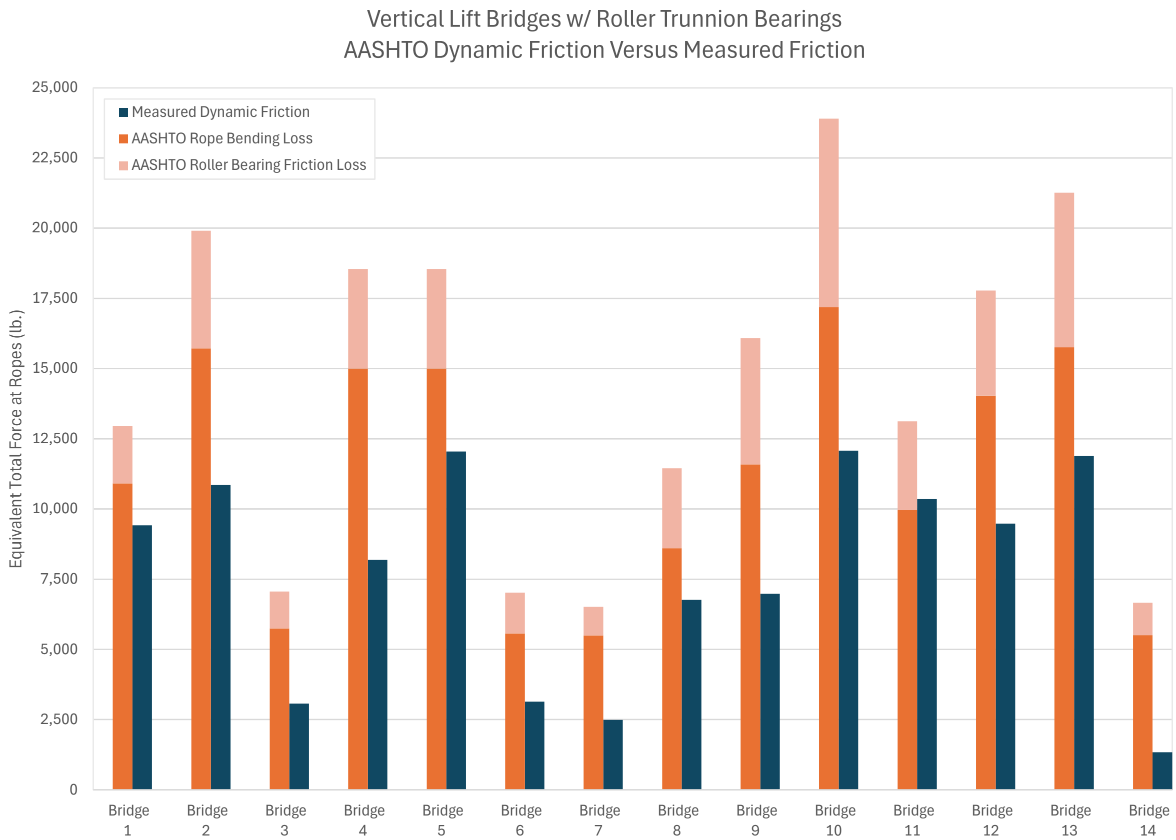

Figure 8: Vertical Lift Bridges with Rolling Element Bearings - Composite Presentation of Dynamic Friction Loss vs Measured

In contrast with Figure 6, the rope bending losses are greater than the bearing friction when considering rolling element bearings instead of plain bearings. Nearly all reviewed vertical lift bridges with rolling element trunnion bearings had measured dynamic friction that was less than the rope bending loss.

Other Dynamic Friction Trends

Review for Correlation of Rolling Lift Bridge Radius to Friction

For rolling lift bridges, the measured friction was charted along with tread radius to check for a possible correlation between the two. See Figure 9. The data points were arranged in order of increasing tread radii. Based on the chart the tread radius did not have an impact on the measured dynamic coefficient of friction.

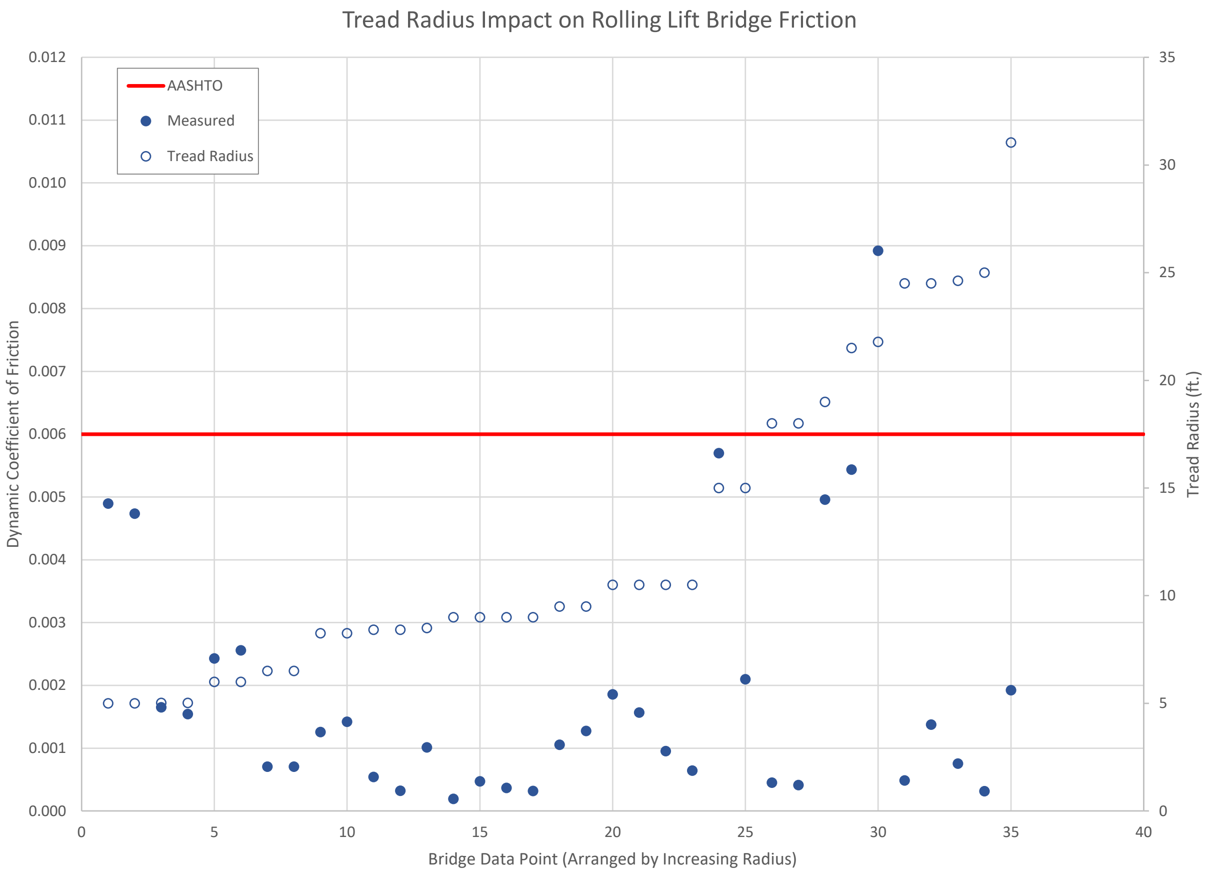

Figure 9: Rolling Lift Bascule Bridges – Effect of Curved Tread Radius

Variation in Friction from Test-to-Test

The compiled test results show that multiple bridges demonstrated significant variation of the measured dynamic friction over multiple tests. The Burlington Bristol Bridge is a span drive vertical lift bridge supported by plain trunnion bearings. Compiled tests show variations in friction over numerous strain gage tests. See Figure 10.

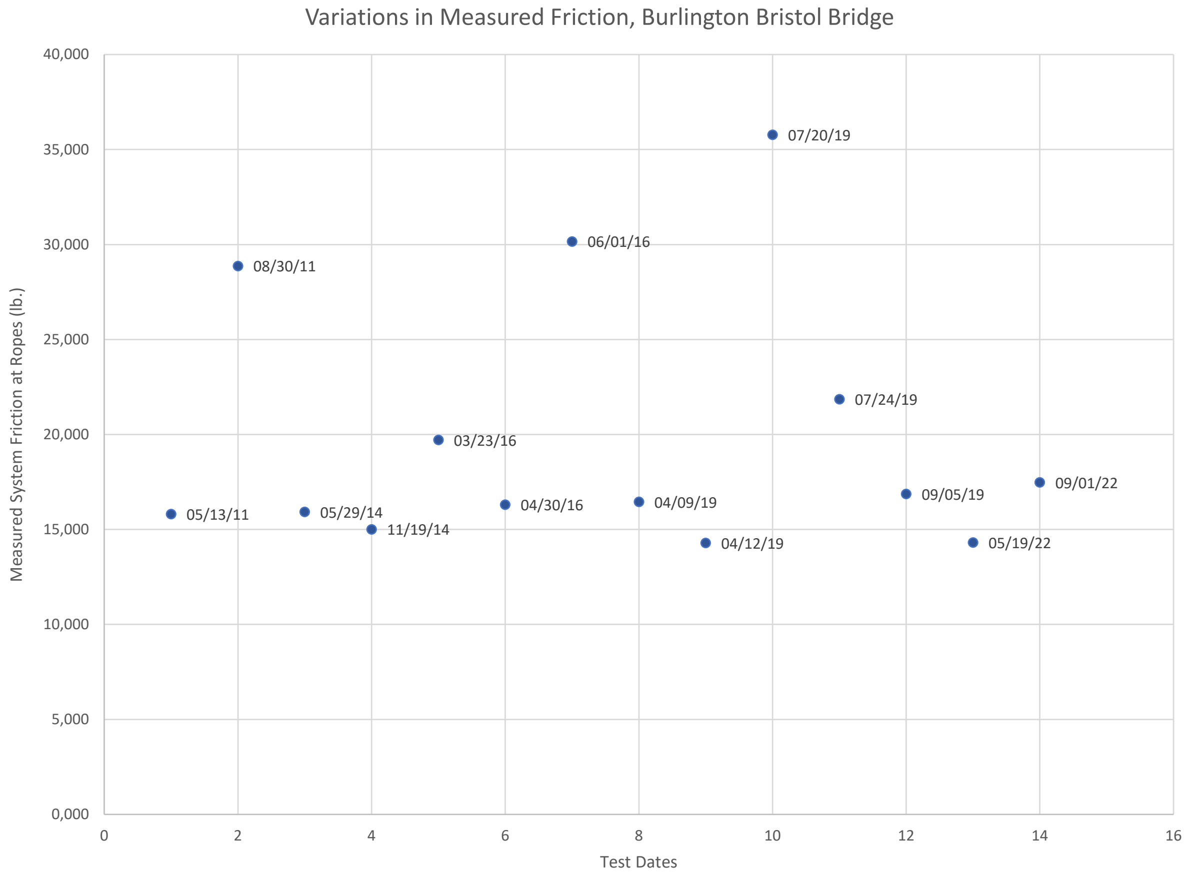

Figure 10:Variation in Measured Friction at a Single Vertical Lift Bridge

Figure 10 shows the significant variations in measured friction over many tests at the Burlington Bristol Bridge. The maximum delta between results was over 20,000 lbs. These tests were reviewed in greater detail to determine possible causes for these differences.

Trends Due to Operating Speed

One of the possible contributors to the variations in measured friction at the Burlington Bristol Bridge relates to the bridge operating speed. There are some small variations as the bridge control system is operator-dependent, but a more significant factor was the use of the auxiliary drive for some tests. The operating speed was compared to the measured dynamic friction to determine if there was a correlation. Figure 11 includes an overlay of the two parameters, with the tests arranged in order of increasing speed.

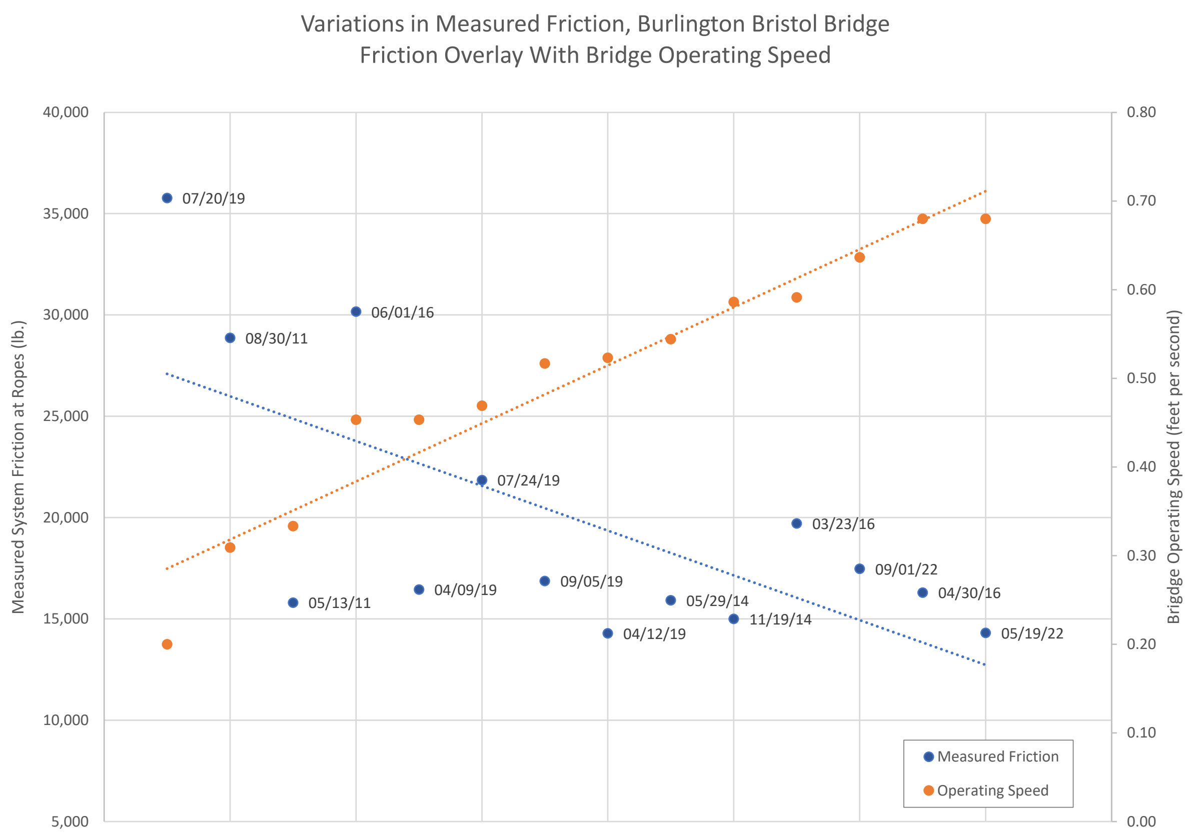

Figure 11: Burlington Bristol Bridge Dynamic Friction Comparison to Operating Speed

Note the poor fit of the measured friction trendline in Figure 11. Based on years of experience testing bridges, an inverse relationship between speed and friction was anticipated. However, there was a poor fit between many of the data points and the friction trend line for this data set. It is likely that other variables, such as temperature and machinery lubrication, affect the measured friction values that are presented in Figure 11.

Trends Due to Temperature

Another possible contributor to the variations in measured friction at the Burlington Bristol Bridge relates to the ambient temperature at the time of the test. Significant temperature changes are known to change the operating behavior of the bridge and to impact friction. The friction affect may be magnified if there are issues such as inadequate trunnion bearing thrust gaps. Figure 12 includes an overlay of the two parameters, with the tests arranged in order of increasing temperature at the time of testing.

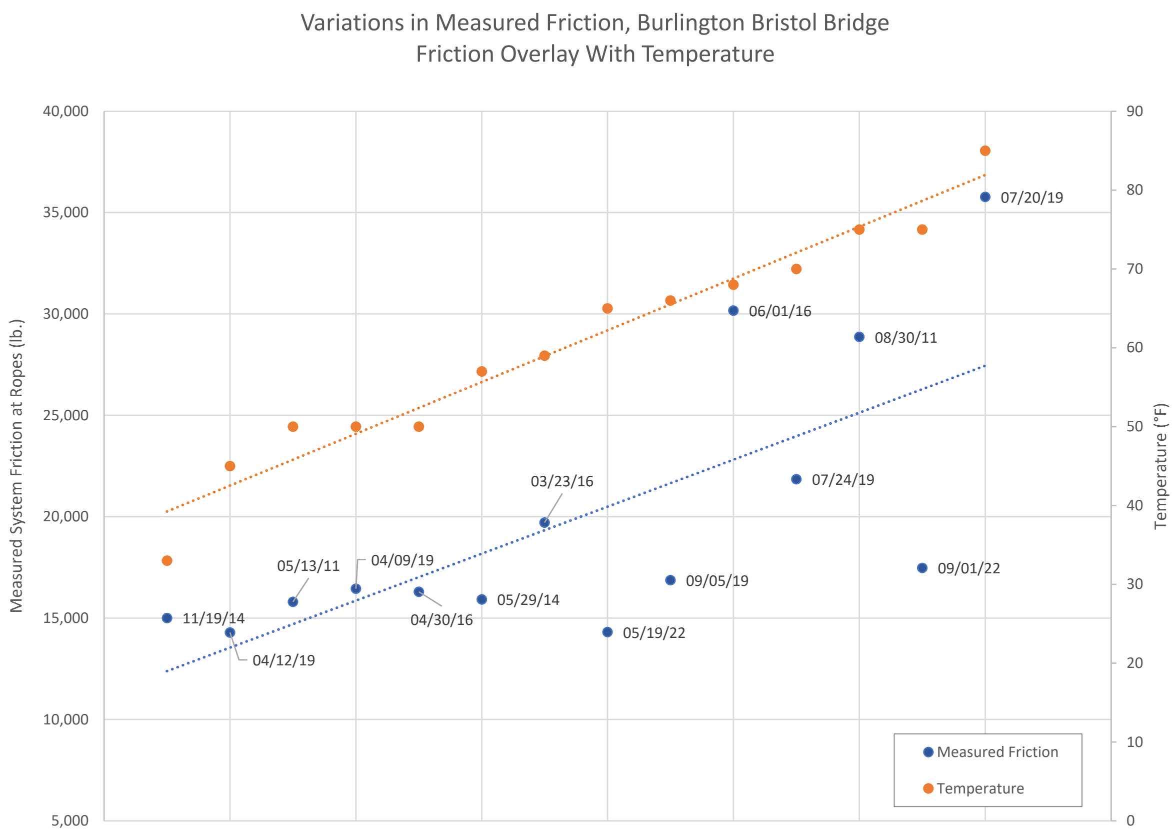

Figure 12: Burlington Bristol Dynamic Friction Comparison to Temperature at the Time of Test

Although there are some outliers, Figure 12 does appear to show a trend that correlates with temperature. Based on this data, it is likely that the temperature plays a role in the variations in friction at the bridge. It is also likely that the speed and temperature can combine to create high friction scenarios.

Summary of Findings

This review of the friction at bascule and vertical lift bridges yielded the following findings:

1. The measured friction at rolling lift bascule bridges was typically less than half of the AASHTO friction calculation, with some exceptions.
2. The measured friction at trunnion bascule bridges that use plain bearings was less than the AASHTO value for the majority of the 48 reviewed bridges, though the friction was higher at eight bridges.

3. Limited measurements were available for friction at trunnion bascule bridges with rolling element bearings, however more than half of the measurements exceeded the AASHTO friction calculation by 100% or more.
4. The measured friction at all vertical lift bridges with plain bearings was at or below the range of theoretical combined friction loss due to bearing friction and rope bending.
5. The measured friction at all vertical lift bridges with roller bearings was at or below the range of theoretical combined friction loss due to bearing friction and rope bending.
6. There was no correlation between the measured friction and the size of curved tread radii for rolling lift bridges.
7. When reviewing data for one vertical lift bridge with plain trunnion bearings, there was not a strong correlation in the data between speed of operation and bridge friction, though it is a factor worth evaluating when the measured dynamic friction changes.
8. When reviewing data for one vertical lift bridge with plain trunnion bearings, there was a fair correlation between bridge friction and the temperature at the time of the testing.

Conclusions

The comparisons of measured friction with AASHTO friction provides some insights which may be of use to owners and engineers in the future.

For bascule bridges, the data demonstrates that the AASHTO friction for rolling lift bridges is a conservative estimate, the AASHTO friction for plain trunnion bearings is a fair approximation, and the AASHTO friction for trunnion bearings with rolling element bearings is a low estimate. These differences will have a small impact on the sizing of prime movers for bascule bridges, as the prime mover requirements are dominated by wind loads acting against the bridges in the open position. However, the results may serve as guidance for applications when the selected new motor or the evaluation of an existing motor are marginal relative to AASHTO required motor capacity. If, for example, an engineer is selecting a prime mover for a new rolling lift bridge, they may consider that the friction will likely be lower than the AASHTO estimates, should they find that the motor power requirements are just over a desired motor size. For a trunnion bascule bridge supported in rolling element bearings, the opposite impact may be considered.

Some trends were also noted in the data for vertical lift bridges when comparing plain with rolling element counterweight sheave trunnion bearings. For the plain bearings, many of the data points were well below the AASHTO friction, though there was significant variation. For rolling element bearings, the AASHTO friction appears to be a conservative estimate. Unlike bascule bridges, friction is often a major contributor to power requirements for vertical lift bridges. As with bascule bridges, some consideration to these results may be given when evaluating machinery loads. Note that the impact of selecting rolling element bearings instead of plain bearings has a more dramatic impact than the difference in measured versus AASHTO friction for rolling element bearings.

For existing bridges, the data herein may be of value when reviewing the machinery and motor capacity, but best practice would be to directly measure operating loads, including friction loads.

The results of the investigations into the impact on temperature and operating speed were reviewed for one subject bridge, given its history of variations in measured friction. The evaluation did not yield a strong correlation between operating speed and measured friction, but there was a trend of higher friction at higher ambient temperatures. For the subject bridge, the temperature trend is likely attributable to temperature dependent thrust gaps between the counterweight sheaves and the counterweight sheave bearings. It is noteworthy that the effect of temperature on measured friction would not impact the measurement of imbalance, so long as the effect is similar in both operating directions. As for speed, it is best practice to operate at the same speed in the opening and closing directions to maintain the constant friction presupposition for imbalance measurement.

As the results of this review make clear, measurements of loads via dynamic strain gage measurements provide valuable data that owners and engineers can use to make informed decisions for existing and new movable bridge machinery.