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Development of a Truck Warp Index

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This Technology Digest (TD) describes the basic development of a truck warp index for truck performance detector data. It complements a second TD, TD-07-011, which describes the relationships between warp index and truck gage spread force, track curvature, friction, and axle load.

Summary

A truck warp index (WI) was developed to identify poorly performing trucks using truck performance detectors (TPDs). It enables discrimination between substantially unwarped and warped trucks. Consequently, it assists in the determination of performance bounds for both warped and unwarped trucks, in conjunction with other TPD indices such as truck gage spread force.

This work was part of the process to develop algorithms to identify poorly performing cars using TPDs and to relate the poor performance to car and car component conditions by means of a series of teardowns of identified cars.

The developed WI utilizes the fact that the lateral forces developed by the trail wheelset of a warped truck approach those developed by the lead wheelset; whereas, the lateral forces developed by the trail wheelset of an unwarped truck are approximately zero.

This WI is dependent on track curvature and possibly on the friction coefficient between wheel and rail at a given TPD site. It is relatively independent of axle load; consequently, poorly performing cars can be identified at any load status. These relationships are presented in TD-07-011.

This work was sponsored by the Association of American Railroads as part of its Strategic Research Initiatives Program.

INTRODUCTION

Transportation Technology Center, Inc. (TTCI) was tasked by the Association of American Railroads, as part of its Strategic Research Initiatives Program, to:

- Analyze TPD data
- Develop algorithms to identify poorly performing cars using TPDs
- Relate this poor performance to car and car component conditions by means of a series of teardowns of identified cars

TTCI began by investigating and reporting on TPD data and performance indices.[1] One of the indices was a truck warp factor (WF). WF attempted to discriminate between substantially unwarped and warped trucks. However, it tended to not be reliable, with a substantial quantity of negative values or values approaching infinity.

Further analytical and experimental studies were undertaken to develop a new performance parameter referred to as a truck WI. The WI has improved differentiation between trucks that are substantially warped and those that remain unwarped. Negative values and values far beyond 100-percent warp have been eliminated. It is believed that this index is thus more reliable. This development has:

- Highlighted that a main cause for poor curving performance of loaded cars is truck warp
- Enabled the examination of other TPD performance indices and the determination of performance levels for unwarped trucks (in other words, normal truck behavior) as opposed to that of warped trucks (degraded truck behavior)

These have been facilitated by the fact that WI:

- Is relatively independent of axle load (as opposed to many other indices)
- Is a single indicator of performance using the vertical and lateral loads imparted by all four wheels of a truck as they pass a detector

WI is a function of track curvature. The relationship between WI and track curvature is essentially linear for the ranges of track curvatures found at TPD sites.

WI for warped trucks may also be a function of the friction coefficient ($\mu_{site\ friction}$) between wheel and rail at a given TPD site. This relationship is less noticeable for unwarped trucks, attributed to the fact that warped trucks utilize creep forces closer to saturation than unwarped trucks.

The relationships between WI and track curvature, $\mu_{site\ friction}$, and axle load are discussed in TD-07-011.[2]

TRUCK PERFORMANCE DETECTOR

Nearly all TPDs comprise at least six instrumented cribs in a section of track with reverse curves in close proximity. A crib is the section of track between adjacent crossties. Each instrumented crib is equipped with strain gages applied to each rail and oriented to measure the vertical and lateral forces of each wheel that passes. TPD sites typically have three sets of instrumented crib pairs, one pair located in each curved section and another pair in the tangent section between curves, as Figure 1 shows. Paired instrumented cribs are spaced approximately 6-feet apart.

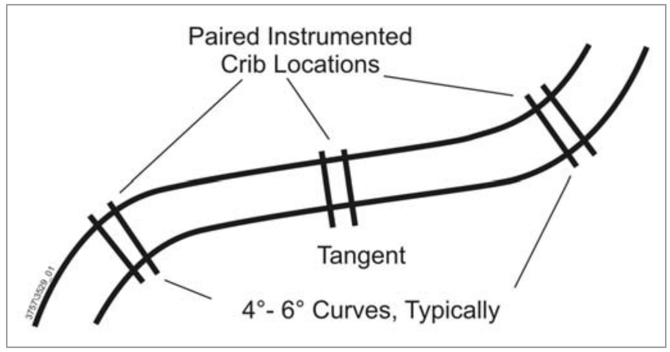

Figure 1. TPD Layout

Truck Performance Detector Data

TPD data comprises vertical (V) and lateral (L) loads at each crib for every passing wheel. Associated data identifies:

- Train
- Time and date
- Direction of travel across the detector
- Car identity
- Car orientation (leading end)
- Axle and wheel identity

Truck Performance Detector Metrics

Initial TPD metrics were based on metrics from AAR Specification M-1001 in the AAR's *Manual of Standards and Recommended Practices*.[3] These metrics include:

- Single Wheel L/V Ratio
- Axle Sum L/V Ratio
- Truck Side L/V Ratio

These metrics are valid but do not address:

- Acceptable performance limits at a TPD site given the prevailing track curvature and $\mu_{site\ friction}$
- How to deal with effects of different axle loads
- How to interpret performance utilizing the large number of metrics that can be developed on each crib pass

Subsequently, further metrics were developed:[1]

- Truck Gage Spread Force (TGSF)
- Rail Roll Index
- Various Wear Indices

Most of these further developed indices have not proven particularly useful, with the exception of TGSF, which gives an indication regarding increased stress state on equipment and track structure. It is, however, dependent on axle load and thus difficult to apply to fleets of cars with various axle loads. In addition, performance levels for normal and degraded trucks remained unknown using this metric. These problems led to the development of WI.

TRUCK WARP INDEX

Different lateral force footprints are produced by lead and trail wheelsets of warped and unwarped trucks in curves. Figure 2 shows the forces produced by an unwarped (square) truck as it passes through a curve. Lateral forces on the lead wheelset of the truck are appreciably higher than those developed on the trail wheelset of the truck.

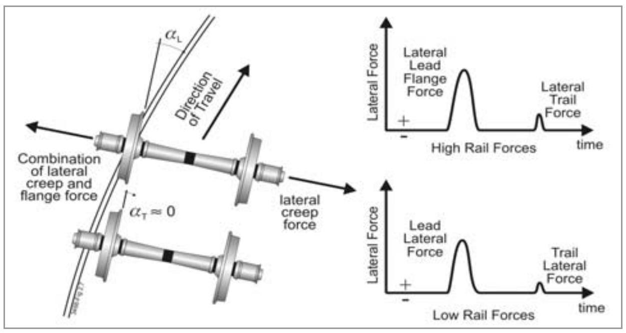

Figure 2. Model of an Unwarped Truck in a Curve

Figure 3 shows the forces developed by a warped truck as it passes though a curve. The lateral forces on the trail wheelset approach those of the lead wheelset. Also, although not easily visible, lateral forces on the lead wheelset are higher than those on the lead wheelset of an unwarped truck.

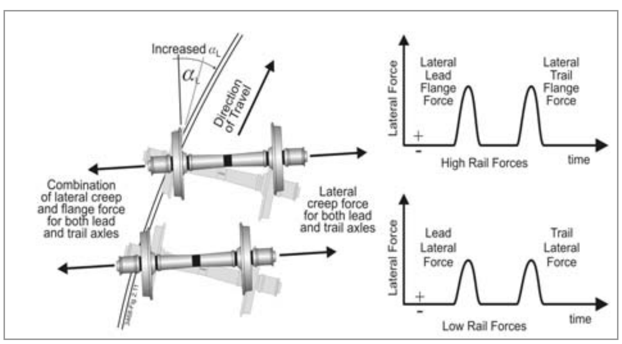

Figure 3. Model of a Warped Truck in a Curve

Figure 4 shows the relationship between Single Wheel L/V for the lead wheelset on the low rail and low rail Truck Side L/V for 11,000 trucks under loaded coal cars passing a TPD crib over a period of 5 days. Figure 4 shows that most of the data clusters along a line with a slope of:

$$(\text{Single Wheel L/V})/(\text{Truck Side L/V}) = 2 \qquad (1)$$

It is to be expected that unwarped trucks would exhibit this relationship since the lateral force exerted by the lead wheelset on the low rail approaches the total lateral force exerted by the truck on the low rail (the contribution from the trail wheelset being minimal). In symbols:

$$\text{Single Wheel L/V} = L_L/V_L \qquad (2)$$

(subscripts refer to lead wheelset on low rail)

and:

$$\text{Truck Side L/V} \rightarrow L_L/2V_L \qquad (3)$$

Some data approaches a line with a slope of:

$$(\text{Single Wheel L/V})/(\text{Truck Side L/V}) = 1 \qquad (4)$$

It is to be expected that warped trucks would exhibit this relationship since the total lateral force exerted by the truck on the low rail approaches twice the lateral force exerted by the lead wheelset on the low rail. In symbols:

Equation 2 still holds and:

$$\text{Truck Side L/V} \rightarrow 2L_L/2V_L \qquad (5)$$

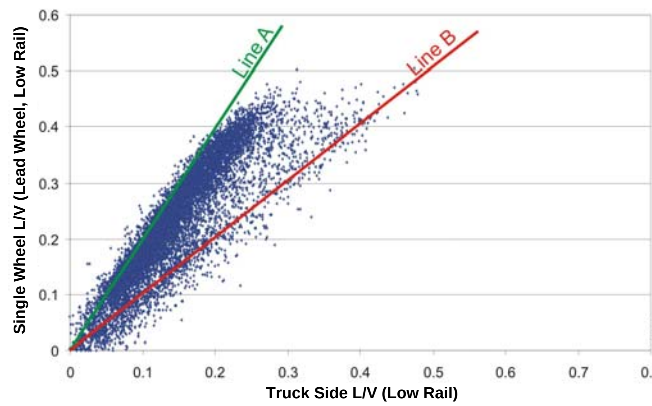

Figure 4. Lead Single Wheel L/V vs. Truck Side L/V for the Low Rail

Hence, Line A, with a slope of 2, represents unwarped trucks and Line B, with a slope of 1, represents warped trucks. This relationship can be transformed so that all data on Line B has an index of 100 percent and all data on Line A has an index of zero percent. Warp A index for the low rail is thus developed:

$$Warp\_A = [63.4 - ATAN(|\frac{Single\ \ Wheel\ \ L/V}{Truck\ \ Side\ \ L/V}|)] \times (Single\ Wheel\ L/V) \times C \qquad (6)$$

Where:

$$C = (\frac{1}{18.4} \times \frac{100}{0.6}) \qquad (7)$$

Constants in this transformation are as follows:

63.4: Arctangent (ATAN) of slope of 2 = 63.4°

18.4: ATAN(2) – ATAN(1) = 63.4° – 45° = 18.4°

0.6: Maximum expected low rail Single Wheel L/V (maximum assumed $\mu_{site\ friction}$)

Figure 5 shows the relationship between Single Wheel L/V for the lead wheelset on the low rail and low rail Truck Side Delta L/V[1] for the same 11,000 trucks under loaded coal cars passing a TPD crib over a period of 5 days. Figure 5 shows that most of the data clusters along a line with a slope of:

$$(\text{Single Wheel L/V})/(\text{Truck Side Delta L/V}) = 1 \qquad (8)$$

It is to be expected that unwarped trucks would exhibit this relationship since the difference in lateral forces exerted on the low rail between the lead and trail wheelsets approaches the lateral force exerted by the lead wheelset on the low rail (the trail wheelset contributing minimally). In symbols:

Equation 2 still holds and:

$$\text{Truck Side Delta L/V} \rightarrow L_L/V_L \qquad (9)$$

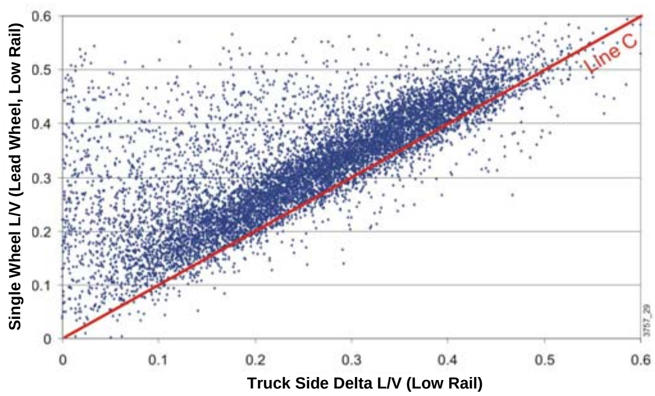

Figure 5. Lead Single Wheel L/V vs. Truck Side Delta L/V for the Low Rail

It is to be expected that warped trucks would exhibit a relationship in which the Single Wheel L/V for the lead wheelset on the low rail is significantly greater than the low rail Truck Side Delta L/V, which tends toward zero as warp and thus trail wheelset lateral force increase. Consequently, (Single Wheel L/V)/(Truck Side Delta L/V) → infinity.

Hence, Line C, having a slope of 1, represents unwarped trucks, and all data above this line represents trucks in varying degrees of warp. Data on the vertical axis represents trucks that are fully warped.

This relationship can be transformed so that all data on Line C has an index of zero percent, and all data on the vertical axis has an index of 100 percent. Warp B index for the low rail is thus developed:

$$Warp\_B = [ATAN(|\frac{Single\ Wheel\ L/V}{Truck\ Side\ Delta\ L/V}|) - 45] \times (Single\ Wheel\ L/V) \times D \qquad (10)$$

Where:

$$D = (\frac{1}{45} \times \frac{100}{0.6}) \qquad (11)$$

Constants in this transformation are:

45: ATAN of slope of 1 = 45°
0.6: Maximum expected low rail Single Wheel L/V (maximum assumed $\mu_{site\ friction}$)

Warp A and B indices may also be developed for data on the high rail. Experience with these two indices for both high and low rail in terms of data conditioning (round-off error resulting in either negative values or values in excess of 100%) led to the choice of:

- Warp A for the low rail
- Warp B for the high rail

Warp A and B indices are each designed to predict the warp state of a truck; however, there are certain instances where either may be indeterminate or produce a misleading result.

For example:

- If an unwarped truck enters a curve at an extremely high angle of attack, Truck Side L/V may be elevated; therefore, Warp A may be incorrectly high, while Warp B may be correctly lower.
- If a truck enters a curve lightly loaded, there may be insubstantial distinction between Single Wheel L/V and Truck Side Delta L/V; therefore, Warp B may be ambiguous while Warp A could be determined.

Bypassing such difficulties to determine a truck's true warp state, Warp A and B are combined as follows:

$$WI = \frac{\sqrt{Warp\_A^2 + Warp\_B^2}}{\sqrt{2}} \qquad (12)$$

Squaring eliminates negative values, while dividing by √2 factors the index, accounting for the sum of squares. WI has no units. It is expressed in terms of percentage.

CONCLUSIONS

WI has been developed for TPD data. Its relationships to TGSF, track curvature, $\mu_{site\ friction}$, and axle load are discussed in TD-07-011.

REFERENCES

1. Tournay, Harry M., et al. July 2006. "Interpreting Truck Performance Detector Data to Establish Car and Truck Condition." Research Report R-977, AAR, TTCI, Pueblo, CO.

2. Madrill, Benjamin, et al. April 2007. "Relating Warp Index, Truck Gage Spread Force, Track Curvature, Friction, and Axle Load." *Technology Digest* TD-07-011, AAR, TTCI, Pueblo, CO.

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