

# **Bearing Health Economics and the Energy Management Information Gap in North American Freight Rail**

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## ABSTRACT

This paper analyzes the physical and financial impacts of bearing degradation on the efficient operations of Class I freight railroads. Current energy management systems are examined and their reliance on static nominal parameters is identified as the source of the gap.

Experimental data from Lopez et al. is analyzed and applied to larger scale consists; the mathematical modeling demonstrates that a representative freight consist operating at a 25% bearing defect rate experiences a 9% reduction in fuel efficiency at operating speed, culminating in an estimated \$71.1 million in wasted annual fuel expenditure across Class I railroads.

Undetected bearing degradation also presents acute catastrophic risk, as demonstrated by the 2023 East Palestine derailment, where escalating bearing temperatures went unaddressed due to alert routing failures. These findings establish the economic and operational justification for an onboard condition-monitoring architecture designed to supply real-time bearing health data to the energy management layer, a framework fully detailed in a companion paper.

## INTRODUCTION

The rail industry operates on an economy of scale; AAR estimations place the total number of active freight locomotives at around 25,000 - 26,000 units in just the class one railroads alone, the freight car fleet dwarfs this number with over 1.63 million revenue generating units as per 2023 railinc. With such a large quantity of mass to move across the country, conservative estimates from the AAR electrification study published in 2025 states that the total U.S. line-haul diesel consumption in 2023 was over 2.89 billion gallons [3].

With so much capital expenditure funneled directly into fuel, it is no surprise that over the last several decades a variety of measures to increase fuel efficiency have been implemented in the industry. Trip Optimizer, software that interfaces with the locomotive's main computer, is deployed on more than 12,000 locomotives and EPA-certified at 10% fuel savings versus manual operation, calculating throttle

commands from route topography and nominal consist weight. Other methods include SmartHPT, which is an intelligent cruise control platform developed by Wabtec; this enables the trip computer to send precise throttle commands to maximize engine efficiency whilst preserving the desired average velocity. This system also has a confirmed efficiency increase of 5%.

While these measures certainly have a genuine impact on fuel conservation and therefore capital expenditure savings, they are restricted by their reliance on topographical mapping and nominal weight to dictate their decision making. This leaves a distinct blind spot in their methodology, that being material wear and tear in both the locomotive and the entire consist of rolling stock. The trip optimization software receives the total consist weight, but weight does not tell you anything about how effectively those bearings are converting tractive effort into motion. A degraded bearing does not weigh more, it resists more.

A consist with degraded bearings or other minute structural discrepancies can cause excess friction to build in those sensitive areas which contributes to increased rolling resistance that compounds across all rolling stock. Experimental bearing power consumption data from Lopez et al. demonstrates that a 59-wagon consist operating at a 25% bearing defect rate requires 271 additional gallons of diesel per 10,000-mile trip compared to a fully healthy consist — a penalty invisible to current optimization systems [9]. These inefficiencies that are not taken into account are simply considered to be the cost of doing business in this industry.

This paper aims to quantify the frictional penalty of degraded bearings at fleet scale by utilizing mathematical modeling. It will also establish the economic case for the development of a system that can bridge this gap, as well as a preliminary architecture for the condition-monitoring system required to close it, with full treatment deferred to a companion paper.

Section 2 establishes the physical and mathematical baseline for rolling resistance and bearing degradation mechanics. Section 3 presents the worked quantification of the fuel penalty at consist scale using experimental bearing power consumption data. Section 4 analyzes the gap between current energy management system inputs and the actual mechanical state of revenue service consists.

### FRictional MECHANICS OF BEARING WEAR

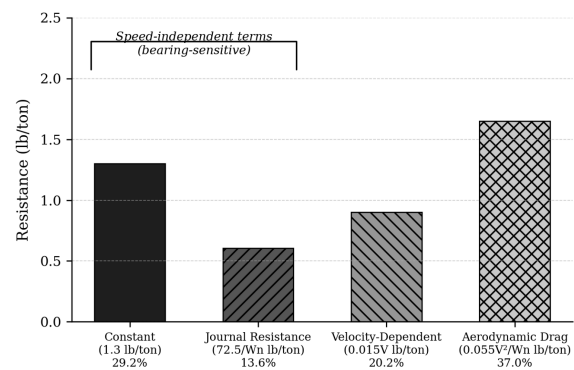
Bearing degradation can be characterized by the Davis equation. The Davis equation is a mathematical model that

enables the analysis of tractive resistance of locomotives and cars on straight and level track. The Davis equation was originally developed by W.J. Davis in 1926 [6] and has since been modified by the Association of American Railroads in its Manual of Standards and Recommended Practices RP-548 to reflect heavier equipment and roller bearings rather than journal bearings [7]. Field studies benchmarking these published coefficients against locomotive event-recorder data have found that real-world resistance values can diverge meaningfully from the RP-548 constants, though the equation's underlying structure remains the standard framework for resistance calculation in the industry[12].

The AAR RP-548[7] equation is written as such...

$$R' = 1.3 + \frac{72.5}{Wn} + 0.015v + \frac{0.055v^2}{(Wn)}$$

Where R' is the resistance in pounds per ton, Wn is the weight per axle (total car weight in tons divided by number of axles), n is the number of axles, and V is speed in miles per hour.



AAR RP-548 Modified Davis Equation [7], as reproduced in Szanto [12]. Calculated at V = 60 mph, W = 30 tons/axle (120-ton car, 4 axles). Total resistance R' = 4.45 lb/ton. Bearing-sensitive terms (constant + journal) account for 42.8% of total resistance.

Fig.1–Davis Equation Breakdown  
The speed constant 1.3 represents the speed-independent baseline resistance that is always present regardless of speed; it

represents the inherent friction present in the wheel-rail interface and changes very little across equipment conditions[7]. The term  $0.015V$  is conventionally attributed to the speed-dependent mechanical resistance, derived from flange friction, track undulation response and the fluid resistance of air inside the axle journal housings at higher speeds[12]. For the purposes of this paper,  $1.3$  and  $72.5/W_n$  represent the mechanical resistance or journal resistance component of the equation. These can be directly related to rolling resistance as this speed independent component captures the bearing friction and wheel-rail contact deformation.

A newly constructed bearing rolls smoothly on the track with no disturbances, but as it accumulates miles, various mechanical defects begin to manifest. These defects fall into three general categories. Geometric defects occur when one or more components within the bearing fall out of tolerance due to inconsistencies in the manufacturing process, or through improper reconditioning or prolonged usage[8]. Localized defects include pits, cracks, or spalls which typically initiate close to the contact surfaces of the inner and outer rings; subsurface inclusions propagate to the raceway surface through rolling-contact fatigue, causing metal to flake off and creating spalls, while these metal flakes become enmeshed in the grease and create new dents and pits on the rolling surfaces[8]. Distributed defects occur when multiple bearing components develop localized defects simultaneously, or when a single component has multiple defects distributed across its surface; a common example is the

water-etch defect, which is a consequence of water entering the bearing through an open orifice or broken seal and degrading the grease, directly increasing metal-to-metal friction and causing the rolling surfaces to wear at an accelerated rate[8]. All of these defect types accumulate over time and compound one another, progressively compromising bearing integrity. In certain instances, a bearing's raceway can deteriorate rapidly enough to cause excessive roller misalignment, and the resulting frictional heating can weaken the axle in as little as 60–135 seconds, potentially leading to catastrophic derailment depending on train speed and carried load[8].

Now conventional means of tracking this process fall short as standard temperature detecting is incapable of monitoring these minute changes until it is far too late. With conventional temperature sensors mounted on the main consists, they detect that the temperature difference between a healthy bearing and one with early cup spalls at 60mph is only 2-3°C, a value which is far below any hot-box detection threshold[9]. The impacts of such discrepancies were made painfully obvious during the 2023 East Palestine Rail disaster. The NTSB final report documents a three-stage detection failure[11]. The first thermal detector displayed a reading of 38°F above ambient, this progressed to the second detector reading 103°F which exceeded the 90°F non-critical threshold but such failure information was routed to a desk analyst and not the crew itself[11]. At 253°F - the sensor's maximum reading- this was the point where the alarm was triggered but at

that point it was far too late as it triggered just seconds before derailment[11]. The bearings in the affected cars were never “nominal” ; they were detected and escalating but the alert routing and analyst workload meant that no one stopped the train in time[11]. Unlike conventional temperature monitoring, vibration analysis can detect surface spalls at predictable defect frequencies far before they produce meaningful heat. In one experiment conducted by UTCRS (University Transportation Center for Railway Safety) , loaded freight cars that had sat idle for three years had 10 bearings removed and compared against freshly assembled healthy bearings on a test rig sized to appropriate maximum freight service conditions (66mph, 34,400lbs load per bearing), the test was terminated early at 93,554 miles due to impending bearing failure as they began indexing under load[10]. Starting at around 36,000 miles the abnormal bearings’ vibration levels rose continuously above the established threshold for a healthy bearing, while the temperature readings stayed within normal range throughout, usually below 50°F above ambient, which is not significantly different from healthy bearings, and far below the 170°F HBD alarm threshold[10]. This study was initiated specifically because the East Palestine bearing had two prior long idle periods — 565 days and then 216 days without use[10].

This connects back to the Davis Equation as bearing degradation directly increases the speed-independent resistance terms such as the 1.3 value, which is technically supposed to remain constant, being overly inflated with these worn

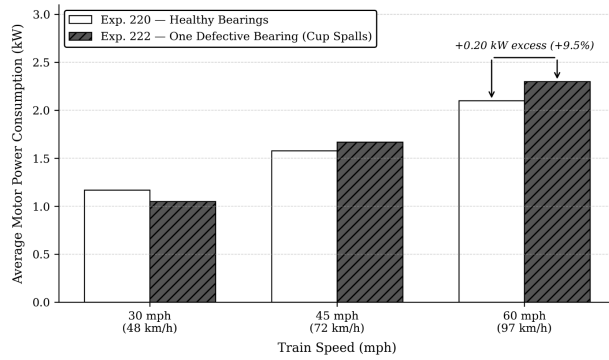
components. This means that the locomotive must produce additional tractive effort for every mile it travels no matter the topography, which causes significant fuel losses.

### **QUANTIFYING THE FUEL PENALTY**

Despite efforts by the rail industry to implement various detection methods and maintenance practices to ensure its rolling stock are operating at proper level of efficiency, current lapses in methodology contribute to decreased efficiency and unnecessary fuel burn. In the paper “Optimizing Power Consumption of Freight Railroad Bearings Using Laboratory Experimental Data.” by Lopez et. al. the penalties of these inefficiencies can be quantified using experimental data. Using a test rig capable of exerting 153 kN per bearing at full railcar load alongside a 22 kW variable speed motor simulating operational rotational forces, Lopez et al. quantified the power consumption of healthy and defective Class F and K tapered-roller bearings under controlled conditions [9].

Within the experiment itself, Experiment 220 was the control which used standard bearings to gain a baseline of efficiency. These results were to be compared against experiment 222 where bearing B2 had its outer ring replaced with a defective, spalled cup containing two significantly large spalls (10.2cm<sup>2</sup> and 9.97cm<sup>2</sup>). Both bearings underwent the same test and it was found that at 45mph and 60mph the defective bearing caused an increase in average motor power

consumption.



Data source: Lopez et al. [9], Tables 4 and 6. 100% load (153 kN/bearing). Exp. 222 contains one defective bearing (B2) with two cup

Fig.2 – Power Consumption, Healthy vs Defective

At 60 mph the average motor power jumps from 2.10 kW (healthy exp. 220) to 2.30kW (defective exp. 222).

These spalls caused the tapered roller to misalign creating abnormal friction and forcing the motor into higher power draw to maintain the same speed.

With this we can estimate the total power loss faced by a standard consist. Using the same experimental data as Lopez et. al. a 59 wagon rolling at 60mph with a 25% defect rate in the bearings requires 271 additional gallons of diesel over a 10,000 mile trip compared to an all healthy consist [9]. At \$3.80/gallon (EIA 2024 annual average) [13], 271 gallons x \$3.80 = \$1,030 in excess fuel cost per 10,000-mile trip. Extrapolating this result across the Class I freight car fleet, of which Railinc reports 1.63 million revenue-earning units [2], and applying the 25% defect rate modeled by Lopez et al. [9], approximately 407,500 cars carry bearings operating at defect-level conditions. At 59 cars per consist this represents approximately 6,906 affected consists in active service. Assuming a conservative 10 revenue trips per consist per

year — a figure well below documented Class I utilization rates and therefore a conservative lower bound — over a representative 10,000-mile route:

$$6,906 \text{ consists} \times 10 \text{ trips} \times 271 \text{ gallons} = 18,715,260 \text{ excess gallons annually}$$

At the 2024 U.S. average retail diesel price of \$3.80 per gallon [13]:

$$18,715,260 \times \$3.80 \approx \$71.1 \text{ million in excess annual fuel expenditure}$$

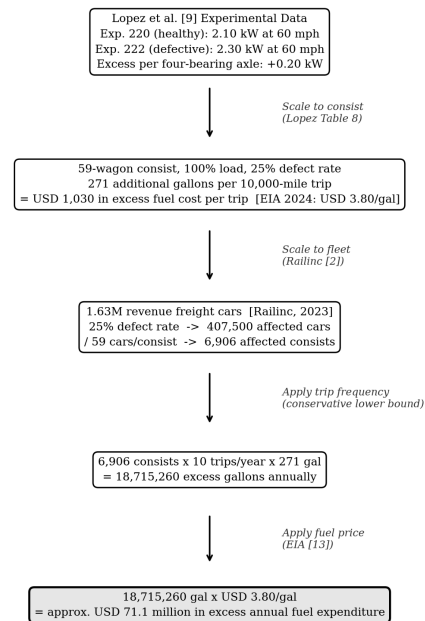


Fig.3 – Fleetscale Calculation Chain  
18,715,260 x \$3.80 = \$71.1 million annual in wasted fuel. While this is an impactful economic consequence of deferred maintenance, beyond fuel economics, the consequences of undetected bearing failure extend to catastrophic derailment events, as documented in East Palestine, Ohio in 2023

[11], underscoring that the economic exposure of unmonitored bearing degradation extends well beyond recoverable fuel costs into liability consequences of an entirely different order of magnitude. Both consequences, chronic fuel inefficiency and acute catastrophic failure, are expressions of the same underlying condition: bearing degradation advancing beyond recoverable states without generating actionable data for the systems responsible for managing consist performance.

### **THE INFORMATION GAP IN CURRENT MANAGEMENT SYSTEMS**

The inefficiencies present in the rail industry are not a result of negligence or a lack of trying, but rather a simple information gap. Currently there are a variety of software tools implemented to aid in reducing excess fuel consumption across the fleet. Trip Optimizer, produced by Wabtec, is an intelligent cruise control system which takes information about route topography, GPS positioning, Consist manifest data, real time sensor feedback and associated track restrictions to automate throttle and dynamic braking to produce the most optimal speed profile, reducing fuel burn in the process [4]. SmartHPT, another Wabtec product, is a power-management tool that focuses on optimizing the locomotive's power efficiency as opposed to purely tracking the physical trajectory of its path. Its goal is to optimize the Horsepower-per-ton (HPT) in real time[5]. It does this by analyzing which locomotives in the consist are drawing power and at what rate and distributing that power as necessary across all locomotives in the consist, ie,

shifting trailing locomotives into low-power or idle while forcing active units into higher, more thermodynamically efficient fuel notches. It achieves this by intaking, tractive effort demands, wheel slip metrics, consist topology, gross weight distribution, and terrain speed limits. Together, these systems represent the current state of the art in locomotive energy optimization — and yet both operate exclusively on parameters knowable at the yard before departure.

While these systems receive nominal consist weight, that is a static value assigned at the yard before departure and does not change en route regardless of what happens mechanically. Neither of these systems receives any data regarding the mechanical condition of the individual cars[4,5]. Bearing health, wheel condition, axle load distribution, none of it enters the optimization calculation.

This matters because as shown in section 3, a consist with 25% defective bearings of which said bearings could be in various stages of degradation, has a much higher rolling resistance than the nominal weight implies. The power consumption differential reported by Lopez et al. translates to a 9% reduction in fuel efficiency at operating speed. — a penalty that accumulates invisibly across every mile of the trip because no mechanism exists within current energy management architectures to detect or compensate for it [9]. Trip Optimizer calculates the theoretically efficient throttle profile for the consist it *thinks* it has. The consist actually requires more tractive effort at every mile. That gap between those two states is invisible to the system.

As for wayside detection, while the industry currently implements HBDs to track bearing temperature data from along the rail; as section 2 describes, temperature readings lag too far behind vibration to catch early stage defects [8,10]. Even if an HBD catches a bearing that is about to fail catastrophically, it does not provide the granular approach needed to track the progressive degradation of these bearings over time and adjust throttle commands as necessary based on the rolling resistance itself [10]. Detection and optimization are two different functions which require their own separate data architectures. While an HBD may tell you when to stop a train, they do not tell Trip Optimizer how hard to pull it.

This gap can be addressed through a purpose-built onboard condition-monitoring architecture capable of supplying bearing health data directly to the locomotive energy management layer — the design and implementation of which are presented in a companion paper.

## **CONCLUSION**

This paper examined the fuel penalty associated with the degradation of bearings on Class I freight consists, quantifying that penalty using experimental data accumulated by Lopez et al., and identified the shortcomings of the current platforms used in the optimization of freight transportation that prevent them from detecting or compensating for these gaps. The experimental data confirmed that a 9% reduction in fuel efficiency at the operating speed of an average length consist with 25% defective bearings yields approximately \$71.1 million in excess annual fuel

expenditure. Current energy management systems like SmartHPT and Trip Optimizer are incapable of detecting or compensating for this because they operate on static inputs that do not include bearing health data. This fuel penalty is a chronic symptom of an unaddressed information gap that could escalate into catastrophic disasters. With this knowledge building the foundation, the companion paper will closely analyze the architecture of the system designed to fill this gap. Implementation of such a system would enable energy management platforms to respond to actual consist mechanical state rather than nominal parameters, reducing both chronic fuel inefficiency and the risk of undetected bearing failure.

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