RAILROAD TRACKSIDE DEFECT DETECTION

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Introduction

- Everyone was shocked recently by the derailment of a Norfolk Southern freight train that caused a total environmental disaster
- Things rapidly got even worse, if that is possible, with stories coming out about deferred maintenance on hotbox detectors ….. Ummnn… What exactly is a hotbox detector?
- Once we open this Pandora's box, more questions rapidly arise: What exactly do they do? How do they do it? What benefits do they provide, and what idiosyncrasies do they have? How did we get to this point?

A brief history

- For thousands of years, every Ox-Cart, every Roman Chariot, every wheeled vehicle has had issues with getting a low friction way of solidly supporting the weight of something on wheels.
- Let’s jump forward a bit …. Say to the introduction of the first trains in the early 1800s.
- Several things were required to create the concept of the train. Of course the steam engine was critical, but there was a tremendous increase in the need to supporting heavy loads, and steel was just being developed. To this day trains use steel wheels on a steel rail. Of course they also use steel for a lot of other stuff. Sometimes it is Aluminum, but that is the exception.

Their father’s magic carpet made of steel – Arlo Guthrie

- Railroads mount steel wheels on a steel axle. A typical freight car in the US uses two axles on one “truck” (or “bogey” in some places) and two more axles on the other
- The center of the axle has a shoulder and then a spline on each side. Each side gets a wheel that has an internal spline
- The wheel is undersized so when it is heated the spline expands enough to allow it to be hammered on. As it cools, it holds together with a classic “death grip.”

Bearings

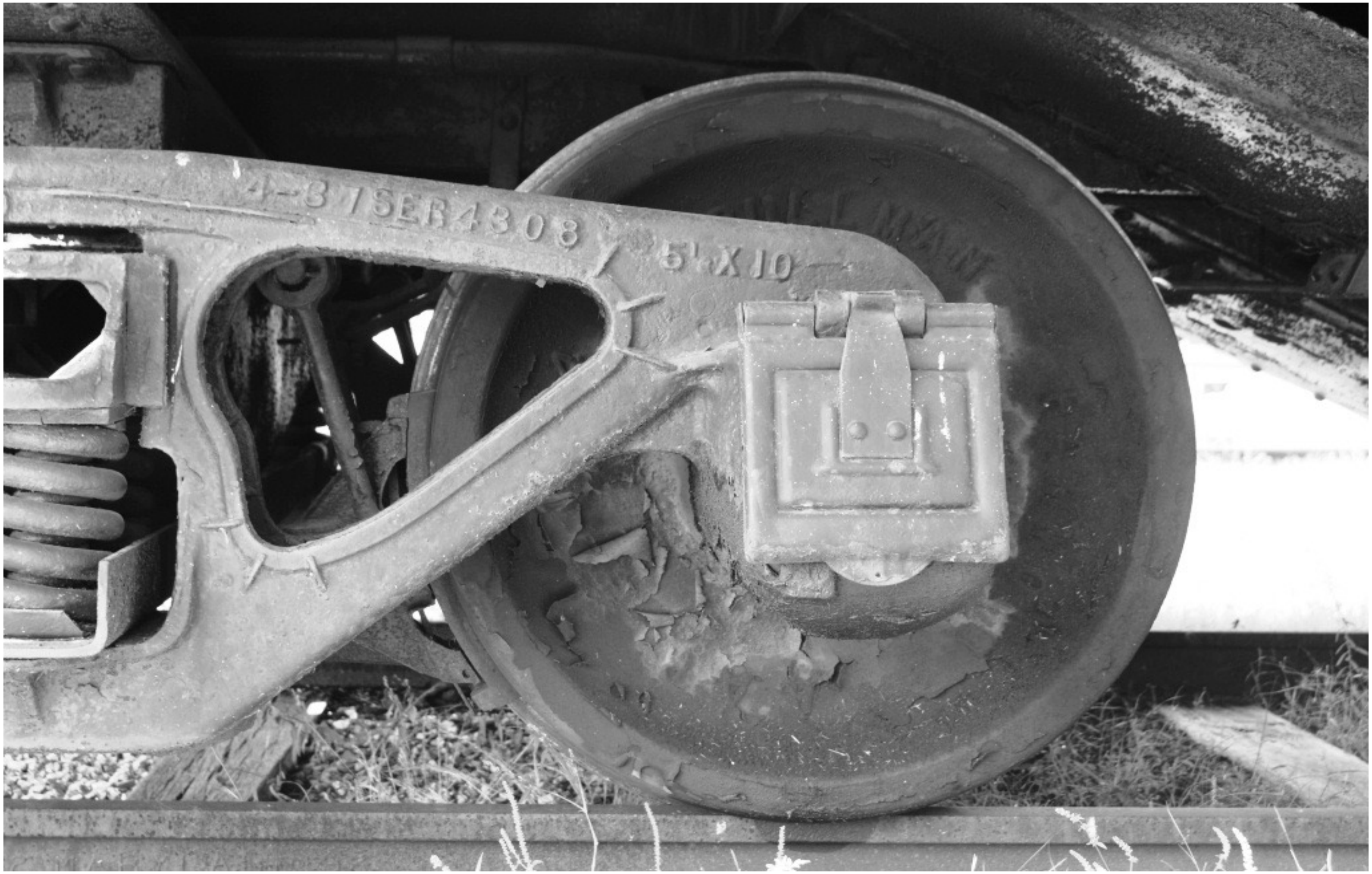
- Since ancient times wheels and axles have used some form of bearing to support the weight on the axle. Originally they were a loose fitting “donut” packed with grease. The grease had to be regularly refilled or the bearing would turn with a lot of friction.
- By the 1800s things had progressed to a polished steel shaft – the part of the axle extending past the wheel – and a pair of bronze pieces that clamped together for a close fit around the polished axle.
- The whole assembly has to be kept immersed in oil for lubrication
- Note that even today car engine crankshaft bearings are exactly the same

Sleeve Bearings

Bearings – cont’d

- On trains, the bearings were in “journal boxes” that were packed with what is basically rope that would keep the oil bath from splashing around
- Every time the train stopped a crew member would walk the length of the train on each side with an oil can to keep the journal boxes topped off.

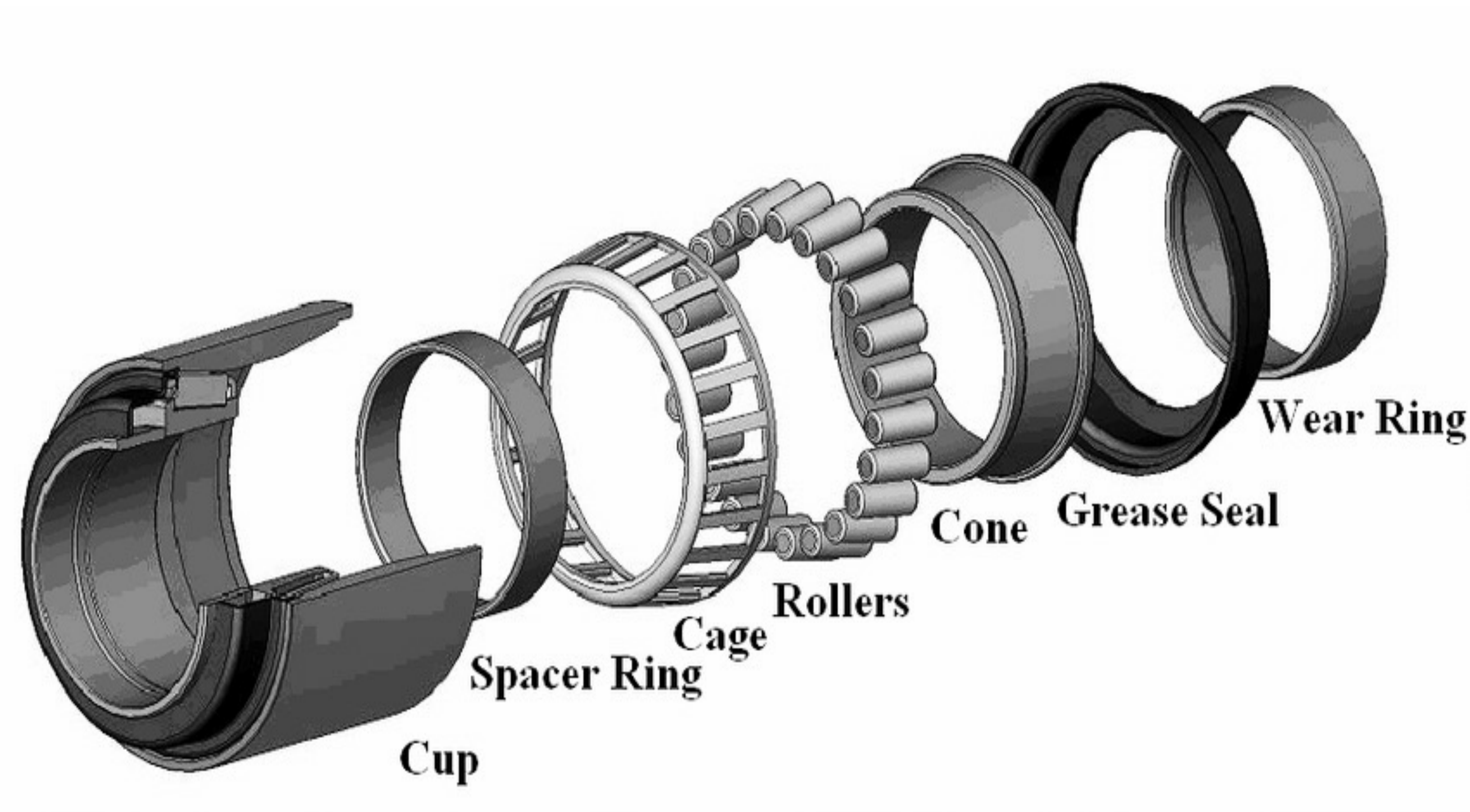
Journal Box



While we are on the subject of bearings

- By now you are likely trying as hard as you can to not yell out “Ball Bearings!”). Yes, you are correct.
- During World War 2, ball bearings were used for military hardware, especially airplanes. After the war, they rapidly became used everywhere.
- Railroads have thousands of units of various types of rolling stock that last for decades. Transitioning to anything new takes a long time. Journal boxes finally became historical artifacts around 1980.
- Trains actually use roller bearings, with cylindrical rollers rather than round balls. A typical bearing is about 18 inches diameter and 18 inches long.
- The roller bearings are lubricated for life. No longer does a crewman have to walk the train with an oilcan
- BUT … nothing lasts forever

Roller bearing exploded view



Truck with roller bearings

Trouble in Paradise

- If a journal box runs out of oil, the friction goes way up and the train is slowed
- More importantly, the bearing gets incredibly hot …. As in huge flames spewing out.
- When a journal box gets hot, it is no surprise that it is called a hotbox.
- If a passenger train gets a hotbox, it is hard to miss the undercarriage spewing flame and smoke. On the other hand, consider a hotbox in the middle of a mile long freight train, where – to steal a line from a horror movie – no one can hear you scream.
- Railroads had people actually watching for hotboxes. It was not a precise task. You couldn't miss it … you might even get your eyebrows singed.

Fun fact

- In the 1950s Broadway musical “Pajama Game” the female lead lives with her railroad engineer dad and talks to him about the events in the play. Kinda like a Shakespeare soliloquy.
- Probably to give him “street cred” with the audience, at one point he apologizes for being late to dinner because of a hotbox problem.
- A few years ago I saw a local theater performance where that line caught me by surprise. I was probably the only one who noticed.

Infrared

- During World War 2, a lot of research was done on the infrared part of the electromagnetic spectrum. Many classified devices were developed and used for the war effort
- After the war ended, much of that research was released to the public
- Railroads instantly recognized the potential for unmanned hotbox detection.   It was a no-brainer that instrumenting huge number of rolling stock with the technology of the day was out of the question.   Trackside was the way to go
- Even that had many issues with notifying the crew. Back in the day when trains had cabooses with crewmembers on board, they could be notified.
- That turned out to be less reliable than needed, and various methods were used. Once train crews started using radios, a reliable system became viable

An aside

- That is one reason why trains no longer have cabooses. An “End of Train Device” drops into the last coupler of the train with a battery operated blinking taillight and brake pressure monitor connected to a radio-based system to telemeter the data to the cab
- Watching the back of a train as it passes into the distance, slowly blinking out its lonely message to an indifferent world, always gives me a sad feeling.

Hot box detector

- An infrared sensor is mounted to the outside of the rail, low enough to have the bearing pass right over it without any interference.   A shutter closes to protect the optics except when a train is passing
- Wheel-detecting transducers are also installed inside the rail such that the wheel flanges pass right over a coil and a magnet
- Coils, magnets, movement – sound familiar? A generator. The sensor puts out an induced electrical pulse for every wheel that passes. Obviously, these sensors need only be on one rail.

Hotbox detector (cont'd)

- Two sensors are mounted about 40 feet out from the thermal sensor to provide a fraction of a second warning of an oncoming train.
- Two more sensors are two feet apart, bracketing the thermal sensor, for a measuring "gate".
- A trackside shelter contains all the necessary processing gear to calculate temperatures while tracking their location on the train (counting axles), and notifying the crew by radio. A typical message announces the location and usually follows it with "No defects. Have a safe day" Of course, a defect will produce a more elaborate message

Hotbox Detector

Trackside Detector Installations

- A trackside shelter contains all the necessary processing gear to calculate temperatures as a function of location on the train (counting axles) and notify the crew by radio
- Over the years, railroads have dabbled in more sophisticated methods to identify the problematic car, but until recently the sheer numbers of old cars and the lack of maintenance has been an issue
- Today, a variation on the E-Zpass devices on our cars has become the standard, providing more information. However, they are not perfectly reliable, and axle counting provides backup.

Everybody talks about the weather but nobody does anything about it

- In the tropics, solar powered hotbox detectors are quite viable; not so much where the infrared sensors can get buried in snow. At 40 below, you need connection to AC mains or a ridiculously large solar array and a huge battery bank
- By the way, the wheel sensors are quite robust, and those wheel flanges going by an inch away just brush away the snow.

How far apart do you need hotbox detectors?

- Back when hotbox detectors were new, studies showed that it can take many miles for a defective bearing to heat up to dangerous temperatures
  -Eventually the proper distance between hotbox detectors was determined to be about 30 miles
- At first, railroads gagged at the expense.
- Then a few high-profile derailments due to hotboxes occurred, causing grievous injuries, extensive property damage, and environmental catastrophes
- The railroads responded to public outrage and installed networks of hotbox detectors

But, what about lubricated for life bearings?

- When lubricated-for-life roller bearings came out, it was supposed to be the death knell for hotbox detectors
- But, nothing lasts forever, and roller bearings will eventually fail.
- Turns out they get hot just like journal boxes, and in a tremendous surprise – when they break down, they heat up FASTER
- What was supposed to be the end of hotbox detectors actually turned into a marketing opportunity as hotbox detection went from every 30 miles to 20

Wheel Sensors

- A hotbox detector needs multiple wheel sensors. They bolt to the inside of the rail, neatly snuggled under the head of the rail, and have a sensing surface that detects a wheel flange passing immediately over it
- A horseshoe magnet with a large coil of wire is mounted such that the flange completes the magnetic path
- As the flange passes, it produces a positive peak immediately followed by a negative peak.
- The faster the movement, the higher the positive and negative peak voltages, and the shorter their duration.
- Note that for slow moving trains, the pulse amplitude is very low and hard to detect.

My personal wheel sensor

Wheel sensor installation

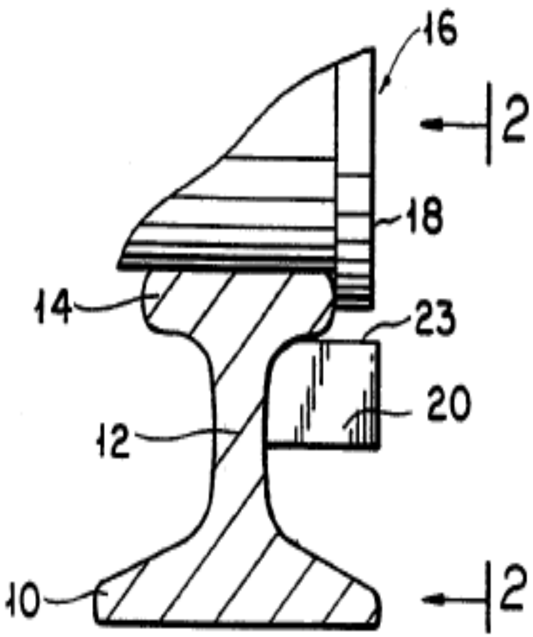


FIG. 1

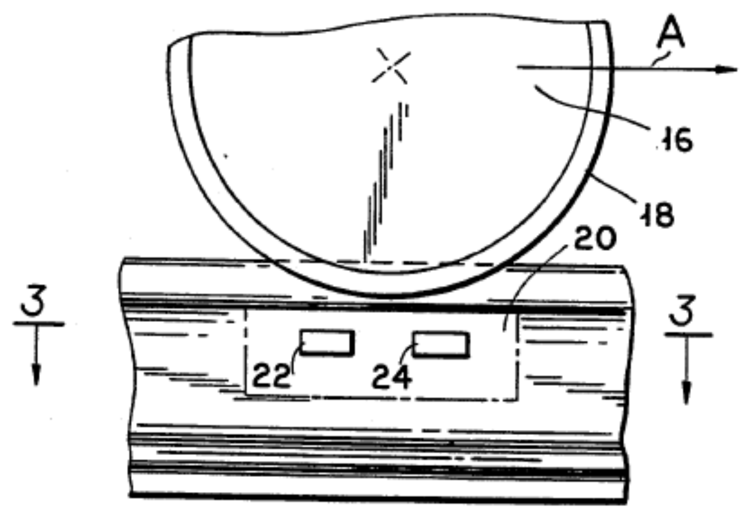


FIG. 2

Pure research – Acoustic Defect Detection

- Back around 1990, a Union Pacific yard supervisor in the North Platte yard was monitoring “Unit” coal trains coming in from the Powder Mill basin. He occasionally heard a funny noise and eventually was allowed “shop” a noisy coal hopper.
- He found a cracked roller in the roller bearing. It was obvious the noise was being generated when the weight of the train was borne by the crack.
- This developed a lot of interest and they let a contract to one of their hotbox detector manufacturers to follow up

Acoustic testing

- A team of two experts in acoustics (with their ridiculously expensive audio spectrum analyzers), and two engineers (me being one) went out to a test site they set up outside North Platte.
- One thing in our favor was that all the trains were the same – 108 fully loaded 100-ton coal hoppers, going 40 mph, with 36-inch diameter wheels and "AAR Class F" roller bearings.
- So, here we are out in the rolling farmland of Nebraska, waiting for trains. Of course, just to make it more ridiculous, the trains mostly ran at night, so there we were, out in the boondocks on a pleasant summer night with a fantastic view of the night sky.

So, what did we do?

- A microphone was set up about three feet out from each track about 2 feet above the ballast. We made up two switches such that someone would stand on either side of the passing train, listening for the tell-tale ratcheting sound and press the button to mark the recordings of a likely defective bearing
- One thing to watch out for was imperfectly round wheels that resulted when a stuck brake caused a wheel to rub the track. The flat spot remains after the brake is repaired. These “flat wheels” were not considered dangerous or worthy of our attention, despite their really loud and regular, thumping noises. And of course, don’t forget the ubiquitous clickety-clacks (although welded rail helps hold that down)

A very personal observation

- So there I am, on the far side of the track from the trailer. Thirty feet away, yet totally isolated. Might as well be on the moon.
- It is a pleasant warm summer evening. I have crossed the track and picked up my switch because the radio warned us of an oncoming train.
- Off in the distance a pinhole sized light appears. Shortly I start to hear the low throbbing of the exhaust.   Wub… ….wub…wub…wub
- Slowly it gets closer, the light gets brighter, and now the turbocharger whine chimes in   eeeeeeeeeeeeee…
- Now it is actually getting close and I can hear valve clatter added to the symphony. Braaaaaaaaap.   The headlight dominates the night and I make sure I'm properly holding the switch and ready

Personal Observation continued

- The train is getting very close. The headlight is blinding. The engine sounds all blend together in a deafening roar
- The earth is shaking under my feet. I cannot see anything. All I can hear is the roar. I just KNOW I am going to die here and now
- I raise my hand … the standard signal to let the train crew know that I know what I am doing and have no urge whatsoever to go in front of them.   They blow the horn. And now I realize the engine roar was just the prelude.
- As the pair of locomotives pass at 40 mph, I get a physical slap in the face of hot, smelly diesel exhaust.

Personal observation -3

- Actually, despite my conviction that I would die, nothing really happened.
- The sound of 108 fully loaded 100 ton coal hoppers passing by was deafening, but nothing compared to a few seconds ago.
- I occasionally heard what might be a bad bearing and pressed the button. Per direction, I ignored the clang-clang-clang of the more common but benign flat wheels
- After the train passed I went back into the trailer and was told how they got good data. Their quiet confidence was shocking in its incredible difference from the utter chaos I just went through
- There were strong hints of what was going on, but they said that they would have complete data after we got home and they processed all of the data properly

Data reduction

- Defective bearings generate a resonant impulse – like ringing a bell – when the defect bears the weight of the train.
- The ringing has a spectrum centered at about 11 kHz and the periodicity is dependent on the bearing rotation – dependent in turn on the wheel size and train speed
- They were able to replay the sound at 1/16 speed and it sounded exactly like the clanging sound of a hammer hitting a chisel. You could HEAR the shock

And then….

- A month later we were back.
- I got a pair of RadioShack horn tweeters and replaced the speaker elements with microphones to create a side-looking microphone focused on the passing bearings. They were mounted trackside at a safe distance, at the height of the bearings
- The microphones fed an 11kHz bandpass filter to optimize the carrier, and a tracking filter to match the envelope filtering to train speed. Cleaned up most of the clickety-clack and similar clutter.   To do this I monitored the processing gate from the two close-in wheel sensors. I also generated an audio tone during the gate and recorded all three channels on a tape recorder

So, what happened?

- We continued to work on the system and closed in on a practical detector system
- We got invited to a test at the US government Transportation Test Center outside Pueblo, Colorado. Some loaded coal hoppers with known defects were driven around their 18 mile loop track.
- Setting up the test went slowly. Finally, everything was ready, but it was bitter cold with icy, windblown snow. The decision was to go ahead before something else went wrong.

So what happened – cont'd

- But our prototype equipment was not weatherized. Each time the train approached, I went outside, stood on one rail then the other, inserting a pencil to brush the snow from the microphone elements.
- And THAT is how to play chicken with a freight train in a blizzard
- (never did find out what the test showed)

Eventual results

- After running tests and accumulating data for a while, it was determined that acoustic detection could reliably detect defective bearings approximately 10,000 miles before failure.
- The railroads felt this was unnecessarily too conservative and kept asking if we could instead give 1000 mile warning?
- More data gathering determined that it was going to be 10,000 miles unless someone figured out something completely different
- At that time, the company I was with divested the railroad product line to pursue other endeavors …. And the company went into a death spiral. I lost all contact with the players, with my understanding that the railroads weren't interested.
- Only recently I heard that there is some acoustic defect detection activity now. I have no idea if they ever resolved the thousand mile issue or decided to just go with 10,000.

March 2023 Update

- I was watching the news on television and they showed a clip of Transportation Secretary Pete Buttigieg speaking at the site of the major derailment and environmental disaster at East Palestine, Ohio.
- What caught my attention was when he said that there will be a push to improve existing defect detection systems including hotbox detectors and acoustic defect detectors
- Those few words really threw me for a loop. Suddenly, some original research I was involved with 25 years ago, only for it to fall into oblivion, suddenly has become a professed federal government priority? Heavy stuff.

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So what’s the story behind the news?

- The area around the derailment in East Palestine, Ohio does have an extensive array of hotbox detectors that have been working well for decades.
- The railroad unions say that Burlington Northern has scaled the trackside equipment maintenance way back, and things have not been the same since
- Listening to a report of how the overheating of the bearing that failed progressed, it appears that the hotbox detectors were working, but not fully.
- Analysis showed the system detected problems early, but they did not meet the criteria to notify the train crew. Something is not quite right there

More details

- I heard that as soon as an overheat condition was actually reported to the crew, they tried to stop the train but it was already too late and the bearing let go and the train derailed.
- Now there is talk focusing on brakes. I have a problem with that. I think they did not have proper training in hotbox detectors
- My take is that if you have a wheel bearing on the verge of collapse, you want to absolutely minimize the stress on it
- Hitting the brakes – regardless of their design - puts tremendous additional stress on the bearings and I believed it was the braking that caused it to fail.
- They should have been trained to respond by cutting all power, but not using any braking at all; just let the train gently coast to an eventual stop.

New subject – Other systems

- Back when I was involved in acoustic defect detection, the hot topic of the day was Automatic Train Control
- ATC was to use computers to better track railroad rolling stock and improve monitoring and safety systems
- They were adapting the transponders used in E-Zpass and similar toll-collection systems to track every freight car in the country.
- As each train rolled into a yard, the staff would have an instantly generated consist list of exactly where every car is on the train, its cargo and eventual destination.
- Recognizing how difficult it is for maintaining rolling stock, the wheel sensors had a new task – to track passing axles to identify missing responses and identify their location.

Wheel sensors redux

- The new system needed to upgrade the ubiquitous wheel sensor.
- The classic wheel sensor does not really work at slow train speeds, as the voltage output is very wide and of low amplitude. What was needed is a wheel sensor that is totally speed independent
- At a “spitball session” I threw out a few ideas … and next thing I knew I was the lead on the zero-speed wheel transducer.

Spitballing ideas

- The iconic WW2 mine detector and the metal detectors that are still used for finding buried metal use two resonant circuits at the same frequency. One uses a large coil exposed to the elements, and the other is user-adjustable
- When the large sensing coil is placed near metal, the resonant frequency changes. If the other (isolated) resonant circuit is tuned to match the frequencies, there is a "zero beat." Any difference will cause an audio tone.

Zero-Speed Transducer

- Extending the idea, I had two resonant circuits with two exposed coils that the passing wheel flange would go over first over one and then the other. The presence of the metal would detune one or the other, in a sequence determined by wheel direction
- Fun fact: I expected the wheel to change the inductance of the coils, but tests did not show what I expected until I realized that the large hunk of a few hundred pounds of iron created eddy currents and lowered the “Q” of the circuit, greatly reducing the resonant peak sharpness. Works well; I’m good.

The circuit

- The two resonant L-C circuits are fed with the same waveform, separated by 90 degrees.
- The outputs were fed to a mixer (multiplier) circuit where the quadrature signals produced little output, but deviations from 90 degrees caused an output waveform like that of the classic transducers, only with constant peak amplitudes.
- It reliably indicated presence, speed and direction of passing wheels, including a dead stop.

Patent

- We filed for a patent on the zero speed transducer
- A patent search turned up an old patent that had used somewhat similar ideas to generate a speed independent wheel sensor, but why hadn't anybody in the business ever heard of it?
- At that time I discovered an upsetting situation. There was a drift problem and I needed to develop a calibration method. It is easy to calibrate when no train is present, but if a train stopped with a wheel over the transducer it would throw it completely out. We had a paradox
- I'll never know for sure, but I suspect that the older patent had the same problem and it was never resolved.

Patent - continued

- The path forward became clear when I learned some nominally useless trivia. The knuckle-couplers that connect rail cars have a sloppy fit and as a train starts you can hear them sequentially engage as the train starts one car at a time.
- The effect becomes resonant at speeds of around 3 miles per hour and the cars slam together and apart continuously
- Unsurprisingly, trains are NEVER operated at those speeds. If you can't go 5 mph, you stay put until you can.
- This gave me the opportunity to develop a calibration scheme. Calibration stopped when a wheel was stopped over the transducer…. But it could be corrupted at 3 mph. Not to worry …. ain't gonna happen.

Patent - 3

- US Patent 5,395,078 was issued for a “speed independent wheel transducer with calibration.”
- During the earlier mentioned implosion of the company, I learned that some of the new keepers of the faith were not interested in pursuing it. I never got a good explanation
- I have no idea what happened after that, but I am proud of it anyway.

Positive Train Control

- A number of horrific passenger train accidents caused by train operators not reducing speed where necessary attracted a lot of public and government attention
- A system in development, Positive Train Control (PTC), suddenly found itself as the holy grail in this issue and it was pushed to become standard
- Positive train control is a complex system that inter-links computers on the train, trackside, and at a central office. While PTC does a lot more, the one aspect that caught everyone’s attention is that train speed and local speed limits are monitored and it prevents the train from exceeding the local speed limit
- The federal government passed laws requiring all passenger rail systems to use PTC. When many railroads missed the end-date, a new end-date was developed with a series of fines for missing the new date.

I have a personal PTC story too

- Since Northrop Grumman skipped town, and declared me retired, I have been trying to un-retire ever since with varied success
- A few years ago there was some activity with me possibly going to work for an outfit that had the contract to install PTC on the Long Island RR and Metro North. Sounded perfect for me.
- I was informed that they instead decided to bring in someone with recent hands-on experience with PTC
- Hmm. When everyone is under the gun to produce on schedule, is that the time to job hop? Why did the other company not fight it?
- Anyway, 18 months later, the news had an item that caught me up short. The newly installed equipment had been factory tested without calibrated equipment and everything had to be pulled out and sent back for retesting. The completion date slipped months.
- NOOOOOOOOO! What a rookie mistake. I have to ask if it is related?

Let's talk about brakes a bit

- For hundreds of years, brakes used a form-fitting shoe that rubs against the rim of the wheel to stop it. Usually the brake shoes have some kind of a material that does not abrade the wheel, but they do wear and require occasional changing
- In the earliest days of railroads, freight trains were quite short, and trains had a brakeman at each end whose job was to run on the catwalks on top of the freight cars to turn cranks to engage the brakes
- This all changed when a young George Westinghouse made a name for himself by developing brakes that used compressed air.
- At first, compressed air was sent down the line to stop the train. Soon it was realized that not being able to start the train was far better than not being able to stop it, so compressed air was then used to RELEASE the brakes.

More on brakes

- Freight car brakes really haven't changed in well over a hundred years. There have been some changes though.
- Subway trains and the like have been using their motors as generators while slowing down with resistors to dissipate the energy until the speed is reduced and friction braking finishes the job
- However, this involves parts that are not used on freight cars and would involve major changes to thousands of freight cars
- In recent years there has been some government pressure to bring brakes into (at least) the LAST century
- There have been moves to mandate upgrades across the national rail system in a manner analogous to Positive Train Control on passenger trains, but the railroads have been fighting this due to the incredible costs, and taking cars out of service for extensive upgrades.

Stopping trains with wind

- When George Westinghouse first proposed air brakes, many missed the point and said it was folly to stop a train with wind
- Despite its success, stopping a train with wind does actually have some limitations
- With longer and longer freight trains, the propagation speed of the compressed air down the length of a train has meant that while stopping, brakes at the rear of the train can be seconds behind the front
- A proposal to carry data the length of the train would mitigate the lag. However, adding such a data link to those thousands of freight cars makes railroad executives blood run cold

Electronic Brake Control

- Actually, considering how long it takes a freight train to stop, a couple of seconds of delay is really pretty insignificant
- Some people have picked up on this and say it was influential in the East Palestine derailment, but there is no evidence for this
- However, if trains were to be instrumented, on-board defect detection would become viable and would provide a vast improvement to avoiding derailments
- <END>