Shock and Vibration in Rail and other Transport Modes

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Acknowledgements

• AAR / TTCI
• ASF-Keystone, Union Pacific
• FRA
• Chicago Transit Authority
• Norfolk Southern
• Monsanto Company
• International Truck & Engine
“No, No, No...
That regular rock.
Me need Phillips.”
Broad overview of shock & vibration issues in railroading

- Vibration issues
- Typical mechanical shocks
- Various industry test standards
- Mitigation techniques
- Brief comparison of other transport modes to the rail shipping environment.

- Technical conclusions
- Future trends for S&V in railroading
SHOCK & VIBRATION ISSUES

• Overall car stability
• Component strength
• Human comfort
• Cargo damage
A closer look at the railcar environment: dynamic excitations

- **Vehicle**
  - 0 - 20 Hz

- **Bogie and Unsprung Mass**
  - 0 - 500 Hz

- Irregular running surfaces of wheel and rail
  - [Wheelflats, out-of-round wheels, wheel corrugation, rail corrugation, dipped welds and joints, shelling, etc]
  - 0 - 1500 Hz

- **Track components**
  - [Rail bending, railpads, tie bending, ballast and subgrade]
  - 0 - 1500 Hz

- **Wheel/rail noise**
  - [Rolling and impact noises from irregularities on wheel and rail, and squeal from stick-slip vibration]
  - 0 - 5000 Hz
At the low frequency end: rigid carbody motions

- Pitch & bounce, yaw & sway, twist & roll, lateral hunting... all under 4 Hz
Roll Input for AAR Chapter XI spec. (Left and right track vertical profiles)
0.6 Hz resonance -- Carbody roll
(constant amplitude cross-level deviations)

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Typical Twist & Roll resonance (generic tank car, 18 mph, 39’ cusps)
More low freq. behavior ~ 2 Hz
Wheelset Lateral Hunting
At the high frequency end -- potential fatigue of & on circuit boards

- Small mechanical fittings on a high frequency source (100-200 Hz)
- PC Board bending (70-150 Hz)
- Tiny cantilevered components (up to 1500 Hz if small enough)
A few peculiarities related to certain car types

- Covered hoppers – high CG, car rock-off
- Tank Cars – tors. stiff, track twist sensitive
- Conversion of 89’ flats to early car haulers
- Heavy duty span bolster cars (8+ axles)
- Lighter weight coal cars
Example project A: Infrequent top chord yielding of coal cars

Suspension bottoming, or component strength?
6000 miles later; several dozen data bursts in 5 general groups.
Vertical Bounce Detail ~ 1.9 Hz: Strain, neg(Accel.), Spring Deflection

![Graph showing vertical bounce details with axes labeled for strain, acceleration, and motion.](image-url)
Vibration issue: Over time, a little bounce leads to more bounce
Quasi-static event: Rotary Car Dumper
Coal Unloading ~ highest strains of test
Example project B: Development of a test spec. for aftermarket hardware

A TOR nozzle location at end of sand bracket
B Truck frame
C Electrical control cabinet
D Compressor room floor

(Note: Locations vary slightly with locomotive type)
Lab tests are always a compromise between reality and cost.

Over-the-Road Simulation, Whole Vehicle

Multiple Axes, Shaped Random

Single Shaker, Random Flat PSD

Sine Sweep or Dwell, Single Axis

Single Axis, Shaped Random

Cost / Complexity

Correlation with Field Environment

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Mid-cost & moderately real: Random Shaker Input With Same Frequency Content As Field

97th Percentile Data Records

Random shaker drive file with similar energy distribution; similar but more frequent peaks (e.g. Time Compression 250X)

\[ 250 = \left( \frac{1.80}{0.72} \right)^6 = \left( \frac{g_{RMS \, lab}}{g_{RMS \, field}} \right)^6 \]
Data collection on locomotive type A: Sander Bracket

Tri-axial access on sander bracket:

- at side frame (upper)
- at free end (lower)
Data collection on locomotive type B: Sander Bracket
Revenue Service Routes for Locomotive Vibration Tests
Overall Comparison – Peak Accelerations versus Location

- Controller
- Front Plow
- Lube Res.
- Side Frame
- Sander Resps.
- Journal Box

Max. Accel. (g peak-to-peak)
Field Data to Lab Test Conversion Process

- **Reduce field data**
  - Using all valid files, compute aggregate (damage-equivalent) side frame RMS accelerations
  - Envelope resulting shape of severe PSDs (power spectral densities)

- **Simplify PSD envelope, amplify to compress shake table time**
  - Select 10-20 breakpoints for PSD shape
  - Scale for 250:1 time compression vs. field

- **Augment 8-hour shaker period (per axis) with brief segments achieving similar g level extremes as found in field data**
Locomotive Bearing Box
Raw Vibration

- 251. g peak-to-peak, vertical direction
- Almost all energy around 500 Hz
- Estimated 0.01” double amplitude displacement
Locomotive Bearing Box
Same data in freq. domain (PSD)

Block length = ½ second
Bandwidth = 2 Hz
N=144 blocks
Most Severe Spectra from 2 loco. types and two service routes
PSD Envelope of Many Field Spectra and simplified shake table Breakpoints

Overall lateral ampl. using breakpoints: 1.8 g RMS
## Summary of Shake Table Amplitudes (compared to MIL & Euro. specs)

<table>
<thead>
<tr>
<th>Location</th>
<th>120-day Simulations</th>
<th>Brief Field Extremes</th>
<th>IEC 61373 &quot;Long Life&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cab Vertical</td>
<td>0.26</td>
<td>1.32</td>
<td>0.81</td>
</tr>
<tr>
<td>Compressor Vertical</td>
<td>0.52</td>
<td>1.31</td>
<td>0.81</td>
</tr>
<tr>
<td>Plow Longitudinal</td>
<td>0.26</td>
<td>1.44</td>
<td>0.40</td>
</tr>
<tr>
<td>Sideframe Lateral</td>
<td>1.80</td>
<td>4.32</td>
<td>3.77</td>
</tr>
<tr>
<td>Unsprung Vertical</td>
<td>10.5</td>
<td>44.5</td>
<td>30.6</td>
</tr>
<tr>
<td>MIL-STD-810F Rail</td>
<td></td>
<td></td>
<td>0.49</td>
</tr>
<tr>
<td>Transport</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MIL-STD-810F &quot;Minimum Integrity&quot;</td>
<td></td>
<td></td>
<td>7.7</td>
</tr>
</tbody>
</table>
Finally Add Representative Thermal Cycling (-40 to 130 °F)

Record Vibr. and Sample Spray

Lateral Day 1
Long. Day 2
Vert. Day 3
Lat. Day 4

2-Minute Field Extremes

Vibration (g RMS)

Temperature

Time
Proof of test: freezing, shaking & baking a locomotive rail friction-modifier nozzle.

Electro-magnetic shaker with 15000 pounds of force

Heating/cooling source
Collection Grid Pans to check Spray Pattern and Application Amount
Final product: AAR spec. of minimum performance, before fleet installations

Clean nozzle

After build-up
Human Comfort Issues  ISO-2631
(empirical weighting of spectra)

Original Signal
0.83 g rms

Energy Spectrum

Vert. Accel. (g)

Time (sec)

PSD

Final Area 0.63 g weighted

Similar process for noise dBA
TYPICAL SHOCKS

• Car coupling
• In-train forces (slack action)
• Wheel imperfections
• Suspension bottoming out
• Rattling pieces
Coal Car  Project A -- revisited
Zero Speed Yard Data, Unattended (unexplained)

Vertical Car Body Accel.
Vert. Spring Defl.
Top Chord Strain
Train Speed

-4328 ue for 1/15th sec, then 2 hours at -2000 ue before relaxing
Shock events produce accelerations with energy into higher frequencies.
But unlike car bounce, the shock accelerations are not scaled duplicates of strains.
And thus, a common 4g Design spec. will be exceeded by high-freq. accel. data
One coupling shock: accel. filtered at 4 freqs., and coupler load cell trace
Similar sampling/filtering questions for various impacts related to passing wheels.

Original Data Lowpassed at 333Hz=$f_c$

After instead applying 10 Hz Lowpass filter

Revenue Train Sampled at 1000 Hz
Zoom in on only 6 seconds

Original Data 333Hz=$f_c$

After applying 10 Hz Lowpass filter
Max is 95%

Min is 41%, What’s going on?
Answer found by again zooming in on the original data…

Different frequency content!
A SAMPLING OF INDUSTRY STANDARDS (S&V and related issues)

- Car body stability & health
  - Track health
- Car component health
- Cargo stability & health
  - Longitudinal shock
- Human stability & comfort
- Locomotive specific issues
  - FRA 213 Track Geometry
  - AAR Chapter XI, and M-976 specs
  - Wheel Impact Detectors
  - AAR S-4200 ECP brake spec
  - pending AAR brake beam work
  - IEC-61373
  - MIL-STD-810
  - ISO-2631 ride comfort
  - AAR on-board rail lubricator vibration spec
Another recent example, AAR S-4200 ECP brake spec

Design to withstand:
- Vibrations 0.4 g rms 1-150 Hz (with +/-3 g peaks)
- Half-sine shocks of 10g peak (20 – 50 msec)
- If on car strength members, local resonances can raise levels to:
  - 15g (100-150 Hz)
  - 50g (200-500 Hz)
S & V MITIGATION TECHNIQUES

- Limit input energy available
  - Track geometry standards
  - Wheel flat limits, wheel impact detectors

- Interrupt transmission paths
  - Spring/elastomer isolators
    - between car components
    - between loco. structure & crew
    - track to ground

- Add damping, stiffness, mass
Limit the dynamic excitations to cars via geometry or speed limits
Title 49 CFR, Part 213
Track Safety Stds. (track geometry specs.)

Applicable and inspectors shall review the condition for compliance with other track surface parameters. Figure 6-7 illustrates a harmonic condition.
Inspectors shall carefully apply the provisions of this footnote. An acceptable remedial action is to raise and tamp one or two joints in the middle of the consecutive low joints. This will break up the harmonics.

Figure 6-7

The worst single warp is 1-1/2” which is acceptable for Class 6 but six consecutive pair of joints have a difference that exceed 1-1/4” therefore the track must be reduced to Class 1.
WILD Detectors: maintain wheels based on revenue track impacts
Transmission and reflections of rail vibration are highly site dependent

Earth vibration due to freight trains
Noise, Squeal and Corrugation (A human perception problem)

- Potential Solutions
  - Grinding to remove corrugation
  - Improve curving via W/R profile
  - Lubrication
  - Reduce surface roughness of wheel turning and rail grinding

- Structural or surface changes to wheel (block or cut sound transmission path)
Chicago Transit Authority: Wheel screech damper
More costly transit N&V mitigation
Example project C: (rarely) we come across a beneficial use of vibration

- Civil engineers brought us “dynamic track stabilization” for after tamping operations
- Essentially a combination of
  - adding stiffness/strength via aggregate material change
  - delaying the time when small bounces will beget bigger bounces
Ballast Stabilization
(Use of vibration to control track settlement)
Track stabilization worth about 10-20 trains of otherwise slow ordered traffic
Thus, the desired vibration lessens chances of this: Lateral Track (Panel) Shift
Another potential beneficial use...

- From this campus, Dr. Weaver’s research on rail neutral temperature...
- Wavelength of high frequency rail vibrations changes with longitudinal stress on the rail
- Goal: Non-destructive determination of rail neutral temperature.
RAIL VIBRATION COMPARED TO OTHER TRANSIT MODES
(Example projects C & D)
First some antique video footage
Moving Cargo, Containers and Operators
Evolved from two projects involving weld failures on ISO tank containers
Unattended Container Shock Record
(Does/does not exceed 4g Design Std?)

Logged Event Values (g)

SN 13392 Event 39, Long.

Original extremum value: 20.4

Filtered Values (g)

-2.5g after 30 Hz lowpass filter

-20.4 g raw data?
“Well then, this is a much lower frequency event, surely it is abusive”

Integrating the accel. signal yields a velocity change of 102 mph in 1/3 second. Invalid data!
Vibration for many vehicles compared

(Bob Fries, N. Cooper-rider 1993)
The highway truck environment is generally more harsh on cargo & humans than rail. Shipboard environment is generally less harsh than rail. Ship environment is more like a factory floor.

Low frequencies (<15 Hz) strains ~ accels.
- Less true as frequency content increases
- Not true for raw shock data

Field data is incomparable to any other criteria or test without knowing the sampling & filtering

Ground borne vibrations—rules of thumb
- Twice the train speed ~ twice the vibration
- Twice the distance from track ~ half the vibr.
Observed & periodic opportunity for engineering confusion

Car Model

Load Measuring Axle

Travel along track

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Another test risk: small populations

Four strain gages at “same” locations on cantilever beam – next to fixed end.

(22” long, 3 ½” wide, 1/16” thick)
Strain variations, even with careful attention to similar gage placement

Variation in Peak-to-peak

13%

\[
g_3 = 543 \text{ue} \\
g_4 = 502 \text{ue} \\
g_7 = 477 \text{ue} \\
g_8 = 521 \text{ue}
\]
What about variations on a railcar?
Structural member strains, Left vs. Right

50% difference in amplitude.
Final reminder: accelerations vs. strains

Low freq. correlation, but not at high freqs.
Wrap-up: industry trends relating to S&V

- “Perfect engineering specification”
  - would fail 100.0% of latent bad designs or processes,
  - while passing 100.0% of the good.
- Actual specifications tended to promote certain dimensional tolerances, minimum design strengths, or perfunctory initial performance... not perfect.
- For about a decade, advances in technology have gradually begun to provide operational feedback, largely due to monitoring shock and/or vibration (or close cousins).
Implementation risks

This monitoring of S&V (or close cousins) can be infinitely more complex than the old visual inspection. Thus, there is much concern about the false positives or negatives.

Fortunately, the industry is gradually moving ahead:
- Wheel Impact Monitors
- Acoustic Bearing Signatures
- Excessive Railcar Bounce
- Peak Wheel Forces
- Yard Coupling Shocks, or desired lack thereof
- etc.
Two opinions about S&V work in railroading

**PLUS:** In an otherwise mature industry, further exploiting shock and vibration to assist business decisions holds great opportunity for rail engineers.

**MINUS:** Fostering adoption of these technologies requires great patience and persistence. (Railroads, suppliers, shippers, car owners, and the FRA have a complicated and symbiotic relationship. In some cases, these newer and more effective specifications redistribute costs. This may be unpopular.)
Example project E: 1994 brake beam tests. Adoption of standards is still in-process.
Give an engineer just a simple request…
And the engineer will aim to please...
AS AN ENGINEER,
I FEEL A PROFESSIONAL
RESPONSIBILITY TO
MAKE THINGS EASY
FOR PEOPLE.

...) CARRY
THE THREE.
Engineering Information is not the same thing as test (or analysis) data

Like Dilbert, we need to provide information, not just data, “Here is $7.14, you owe me five & a quarter.”