Operating Vibration Levels Near Mine Utility Vehicle Lithium-ion Batteries

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Presentation topics

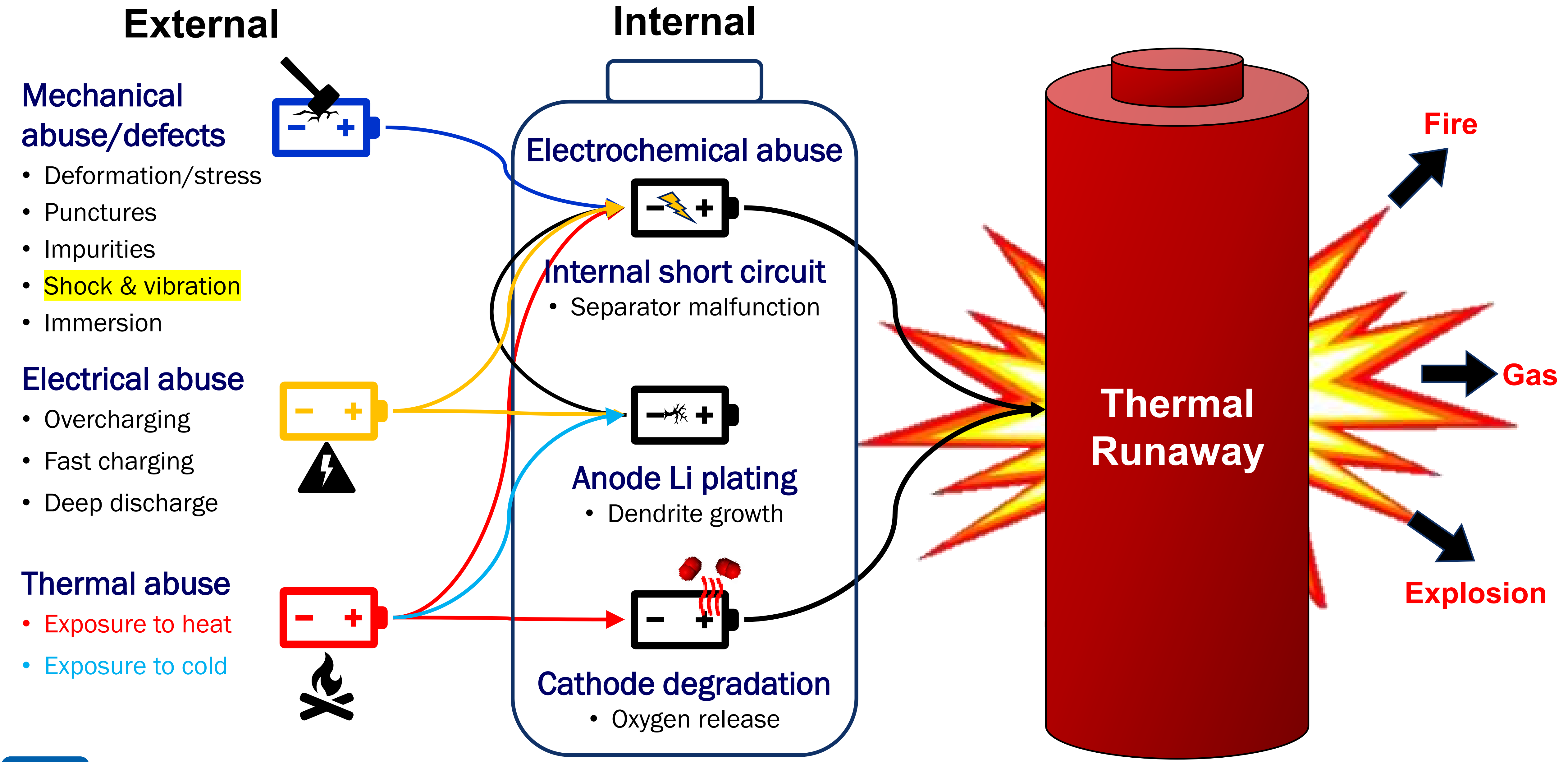
Background and LIB environment test standards

SURFACE VEHICLE RECOMMENDED PRACTICE

NIOSH research project overview

MUV vibration measurements

Thermal runaway can be initiated by external or internal factors



Numerous LIB environmental testing standards exist, but the conditions specified may not be representative of mining conditions

- Mining environmental conditions may be more severe than other industries
  - Temperature/thermal shock
    - Transition from outside temp. to mine temp.
  - High in-mine humidity
    - Change from a colder outside temp. to a warmer in-mine temp. will lead to condensation that could enter the battery case
  - Dripping mine water
    - Conductive mine water can enter the battery case and cause short circuiting
  - Mechanical shock
    - Running into unexpected vehicles or bumping into the rib may occur routinely
  - Vibration
    - Rough travelway conditions with ruts, rails, and debris

Vibration tests specified by battery standards vary widely with different vibration types, frequency ranges and acceleration values

Standard	Test Parameters						
	Type	Freq. range (Hz)	Accel.	Disp. (mm)	Cum. test time (hr)	Sweep cycles	Application
SAE J3060	n/a	30 – 36	3.5 – 5.0 g_{RMS}		4 – 36		vehicle pb-acid and heavy-duty storage
SAE J2380	random	10 – 190	0.4 – 1.9 g_{RMS}		92.56		EV
IEC 60068-2-6	sinusoidal	0.1 – 5000	per spec.	per spec.	0.17 – 10	1 – 100	"Specimens"
IEC 60068-2-57	time-history, sine-beat	0.1 – 2000	0.1 – 5 g_{RMS}	0.4 – 200	*		"Specimens"
IEC 60068-2-64	random	1 – 5000	0.1 – 28 g_{RMS}		per spec.		"Specimens"
IEC 60068-2-80	mixed mode	1 – 5000	0.01 – 10 g_{RMS}	per spec.	per spec.		"Specimens"
IEC 62660-2	random	10 – 2000	27.8 m/s^2 (2.83 g)		8		EV
UNECE 100 & 180	log sweep	7 – 50 – 7	1.02 – 0.20 g		3	12	EV
UN 38.3 (T.3)	log sweep	7 – 200	1 – 8 g_{RMS}	1.6	0.25	12	Transport of dangerous goods
UL 1642, 1973 Annex E, 2054	sine sweep at 1 Hz/min	10 – 55		0.8	135 – 145 min		Cells/ Auxiliary/ Stationary
UL 2271	random	5 – 200	Vert 1.44 g_{RMS} Trans 1.23 g_{RMS} Long 0.96 g_{RMS}		1 sample: 21 hr/axis 2 samples: 15 hr/axis 3 samples: 12 hr/axis		Light duty EV

When comparing vibration, it is important to remember that

at low frequencies, small accelerations yield large displacements
at high frequencies, small displacements yield large accelerations

$$Disp = \frac{Accel}{(2\pi F)^2}$$

$$Accel = (2\pi F)^2 \times Disp$$

Displacement for 1 g acceleration	
F (Hz)	Disp. (mm)
1	250
2.5	40
5	10
10	2.5
25	0.40
50	0.01
100	0.025

Acceleration for 1 mm displacement	
F (Hz)	Accel (g)
1	0.0040
2.5	0.025
5	0.10
10	0.40
25	2.5
50	10
100	40

Shock tests specified by battery standards also vary widely with different peak acceleration values and durations

SDO standard	Test Parameters				
	Accel	Duration (ms)	Orientation	Number of runs	Application
SAE J2464	25 g	15	3 axes, both directions	3 repeats 18 total	Packs / use T.4 for testing cells
IEC 60068-2-27	5 – 10,000 g	0.2 - 18	3 axes, both directions	per spec.	"Specimens"
IEC 60068-2-81	per spec.	per spec.	Three axes	per spec.	"Specimens"
IEC 62660-2	500 m/s^2 (51 g)	6	six spatial directions	10 per direction	EV
UNECE 100	28/17/12 g 15/10/10 g	120	Longitudinal Transverse	1	EV
UNECE 180	28/17/12 g 15/10/10 g	120	Longitudinal Transverse	1	EV
UN 38.3 (T.4)	50 or 150 g	5 or 11	3 axes, both directions	18	Transport of dangerous goods
UL 1642, 1973 Annex E, 2054	125 – 175 g w/ avg of 75 g in first 3 ms		3 directions	1	Cells
UL 2271	≤12 kg: 50 g 12–100 kg: 25 g > 100 kg: 10 g	≤12 kg:11 ms 12–100 kg: 15 ms > 100 kg: 20 ms	6 dir. for prismatic or 3 dir. for cylindrical	3	Light duty EV
UL 2580	25 g	15 ms	3 axes, both directions	18	Module / pack

Battery vibration and shock testing should be based on the application

- Most vibration standards do not specify significant vibration levels at frequencies low enough—below 10 Hz—to capture vehicle suspension vibration modes
- Driving over rough mining travelways could cause
  - Low frequency vibration with amplitudes in excess of 1 g_{RMS} (1 g_{RMS} at 2.5 Hz = 40 mm_{RMS}), lower frequency and higher level than specified by standards
  - Shocks with peak accelerations much less than 25 g with durations on the order of 100 ms, lower level and longer duration than what most standards specify
- Bumping into the mine ribs or other vehicles could cause shocks that greatly exceed 25 g and with durations under 100 ms
- Vibration and shock loading for mine-vehicle batteries should be based on machine-specific measurements with real world conditions

The US mining industry is beginning to implement lithium-ion batteries (LIBs) on mine utility vehicles (MUVs) and rubber-tired mantrips (RTMs)

https://www.pillarinnovations.com/solutions/emu

https://johnsonindustries.com/index.php/mining-vehicles/dc-electric-mining-vehicles

https://www.damascuscorp.com/mac-12-ac-96v-electric-transporter

NIOSH is conducting mine utility vehicle (MUV) and rubber-tired mantrip (RTM) lithium-ion battery (LIB) research in three areas

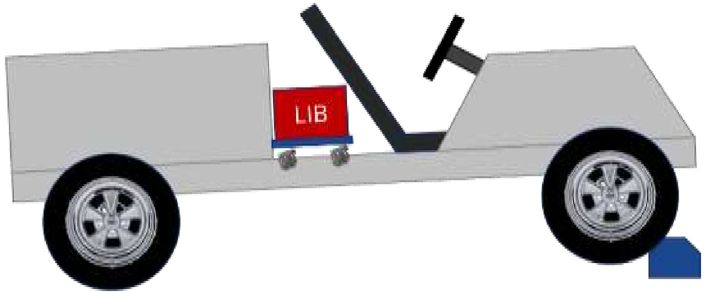
In-house/field LIB environmental testing

- Assess environmental conditions for MUVs/RTMs across US mines
- Measure shock & vibration (S&V), temperature (T), and relative humidity (RH) near battery locations
- Measure speed as allowed by mines
- Analyze collected S&V data to determine:
  - Peak shock and duration
  - Vibration frequency spectrum
- Determine T and %RH ranges
- Used to inform laboratory testing

LIB laboratory testing

- Review applicable environmental standards/guidance docs for LIBs
- Develop MUV/RTM-specific test procedures
- Conduct laboratory testing on MUV/RTM LIBs to
  - Determine their susceptibility to the mining environment
  - Establish maximum allowable vibration
- Used to inform LIB installation/isolation

LIB installation/isolation



- Determine how to mount LIBs to prevent damage from shock & vibration
- Develop multi-body vehicle dynamics (MBVD) simulation models
  - Conduct testing/analysis to determine mass properties, and tire and suspension stiffness & damping
- Validate MBVD simulation models using vehicle dynamics test data
- Use MBVD models to determine proper vibration isolators
- Fabricate, install, and test iso. systems

NIOSH performed "shakedown" vibration testing on a Pillar EMU MUV to inform our field measurement methodology

- Four-wheel independent suspension
  - Front: MacPherson strut w/ 8" travel
  - Rear: Dual A-Arm IRD w/ 9" travel
- Two passengers w/ a payload of 1,000 LB
- Wheelbase of about 9 ft
- Maximum speed of 25 mph
- Max tire pressure of 20 psi

NIOSH performed "shakedown" vibration testing on a Pillar EMU MUV to inform our field measurement methodology

- Ensure instrumentation is capable of measuring expected vibration
- Check which direction has highest levels
- Determine if location affects measured vibration levels
- Find out how travel speed, payload, and tire pressure affect vibration levels

NIOSH installed six enDAQ vibration data recorders, a radar-based speed sensor, and a speedometer on the EMU

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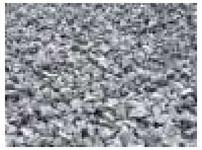
- The enDAQs incorporate triaxial accelerometers, batteries, and data storage
- Vibration was measured in three axes
  - Longitudinal – X-direction
  - Transverse – Y-direction
  - Vertical – Z-direction
- Vibration data were sampled at a rate of 2,000 samples/sec

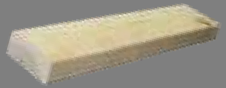
Testing was conducted on our ~900-ft-long MUV test track in our Experimental Mine with a driver and a passenger with speeds of 2.5, 5, and 7.5 mph

100’ gravel

10’ spacing 5’ spacing 15’ spacing 10’ spacing 5’ spacing 15’ spacing

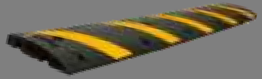
180’ full-width 2x4s



180’ staggered, half-width 2x4s

10’ spacing 5’ spacing 15’ spacing 10’ spacing 5’ spacing 15’ spacing

180’ full-width speed bumps



180’ staggered, half-width speed bumps

2 full-width and 2 staggered, half-width curbs

Our test track gives us a repeatable course to conduct in-house research

Beginning of MUV Test Track in Experimental Mine

The speed bump section of the test track represents rough conditions

Full-width Speed Bump Section with 10’, 5’, and 15’ spacing

The vibration at the front batteries was higher than the vibration at the rear batteries, and the vibration in the vertical direction was highest

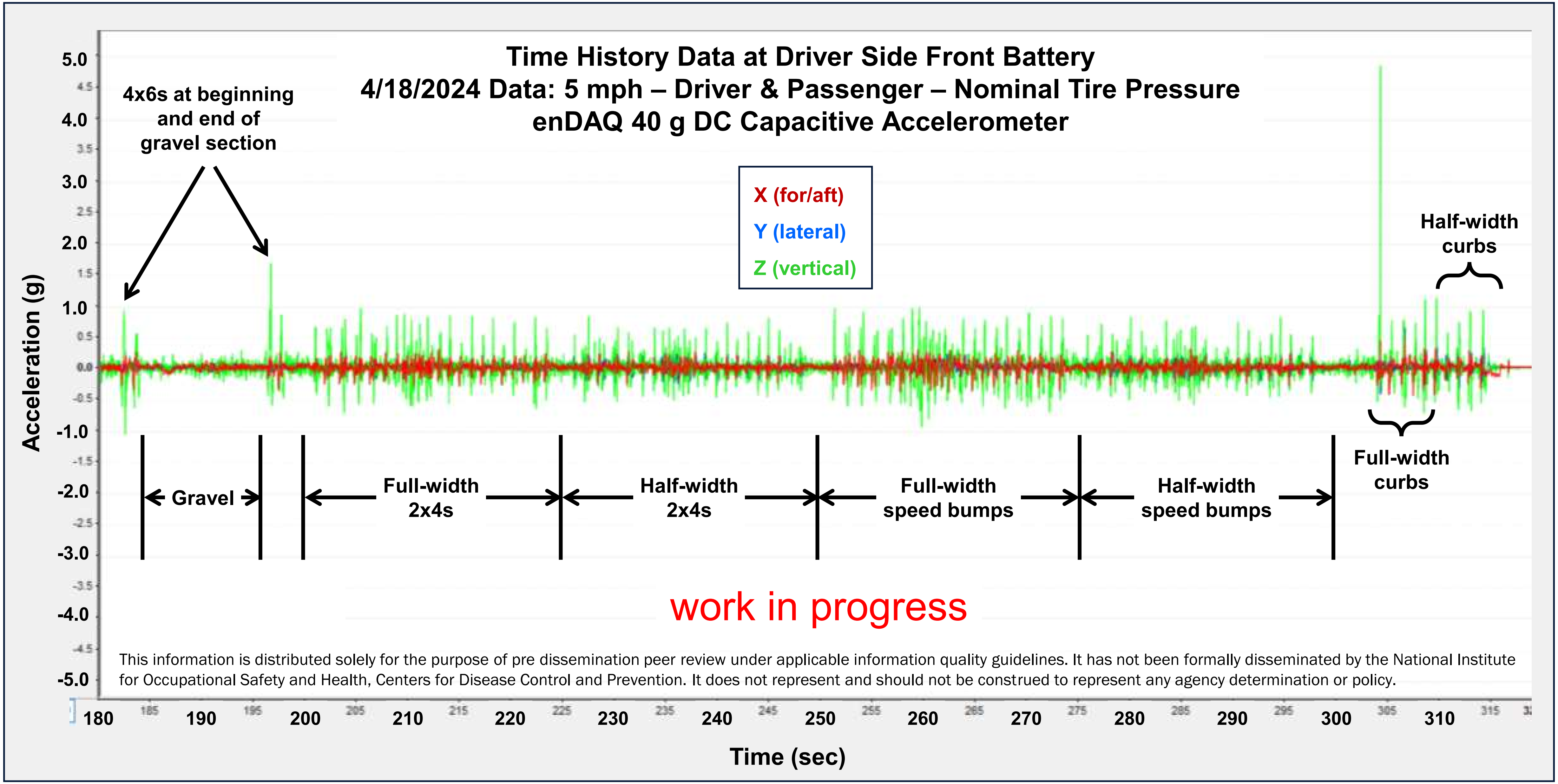
Peak Vibration from Run 2 on Full-width Speed Bump Section from 7.5 MPH Tests

Location	Front-to-back: X-dir (g)	Side-to-side: Y-dir (g)	Vertical: Z-dir (g)
Driver Side, Front	1.2	2.3	5.8
Passenger Side, Front	1.0	1.3	5.7
Driver Side, Rear	1.3	0.6	2.5
Passenger Side, Rear	1.1	0.5	2.7

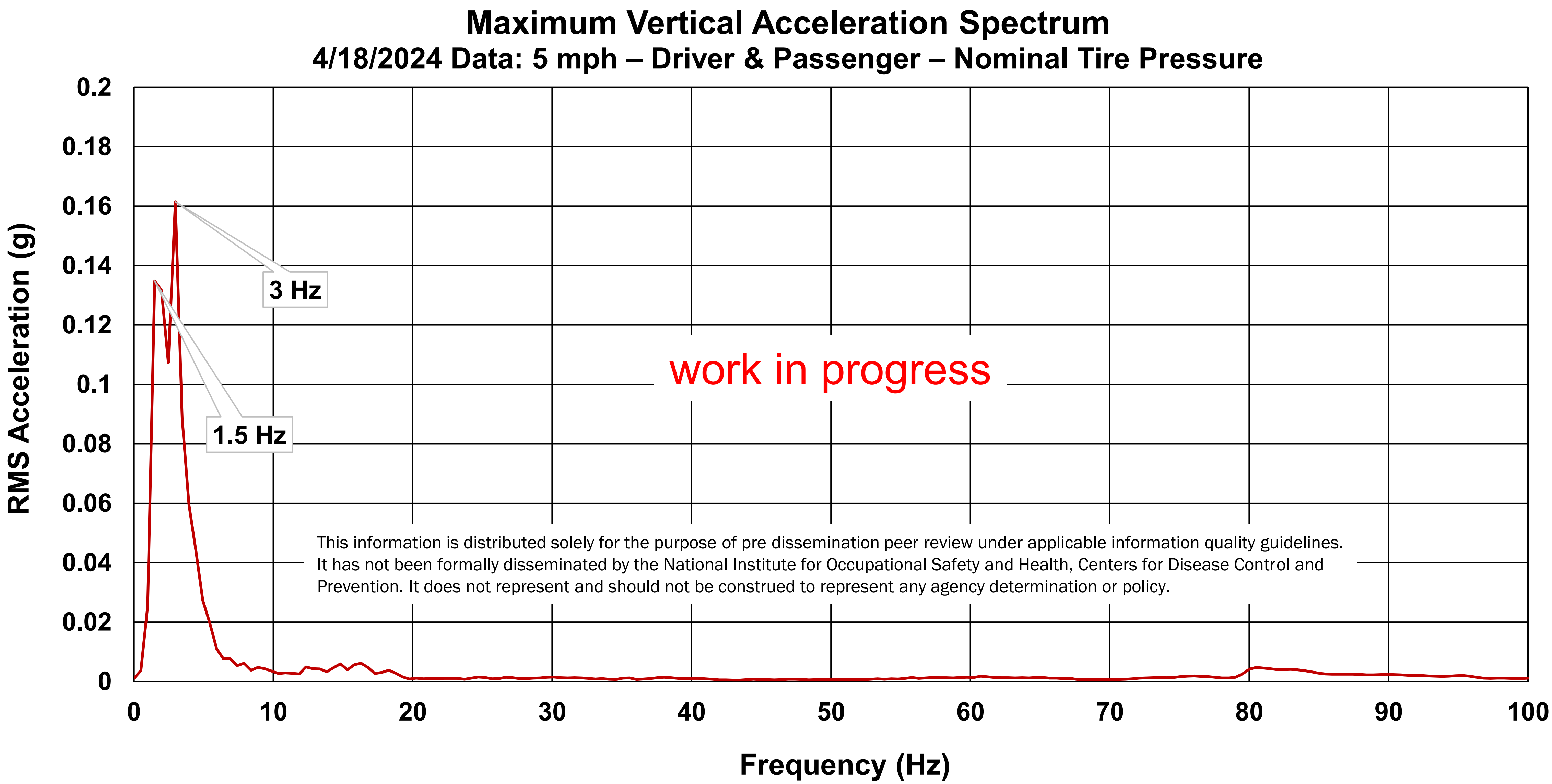
work in progress

Note: The MUV CG is close to the rear battery location. Therefore, pitching motion adds to the vertical vibration at the front batteries more than it does to the rear batteries

The data show that the vibration routinely reaches 1 g when driving at 5 mph



The highest accelerations are at frequencies below 5 Hz



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The findings from our in-house tests will be used to guide our field data collection methodology and laboratory testing of LIBs

- Field data will be collected on a variety of mine utility vehicles and rubber-tired mantrips at surface and underground mines across all commodities
- enDAQ vibration recorders will be used to measure vibration near the batteries that are furthest from a vehicle's center of gravity
- To date, we have completed two trips to underground coal mines with measurements on four MUVs at one mine and three MUVs at the other
- Shakers for battery testing will have to be capable reaching frequencies as low as 1–3 Hz

Summary and conclusions

- The initial vibration testing on an EMU MUV shows that
  - The front battery vibration is about 2x higher than the rear battery vibration (due to distance from CG)
  - Vibration in the vertical direction is highest
    - Peak vibration levels of over 5 g
    - Steady vibration of ~1 g
  - The predominant vibration energy for the tested EMU was at frequencies below 5 Hz with one peak at 1.5 Hz and one peak at 3 Hz
- Field vibration data should be measured at the batteries that are furthest from the expected vehicle center of gravity
- Laboratory vibration testing on MUV LIBs should focus on
  - sub-5 Hz frequencies
  - Vertical direction

Thanks for your attention!

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