Adverse Outcomes Associated with Occupational Exposures to Whole Body Vibration:

Making a Health, Safety and Business Case

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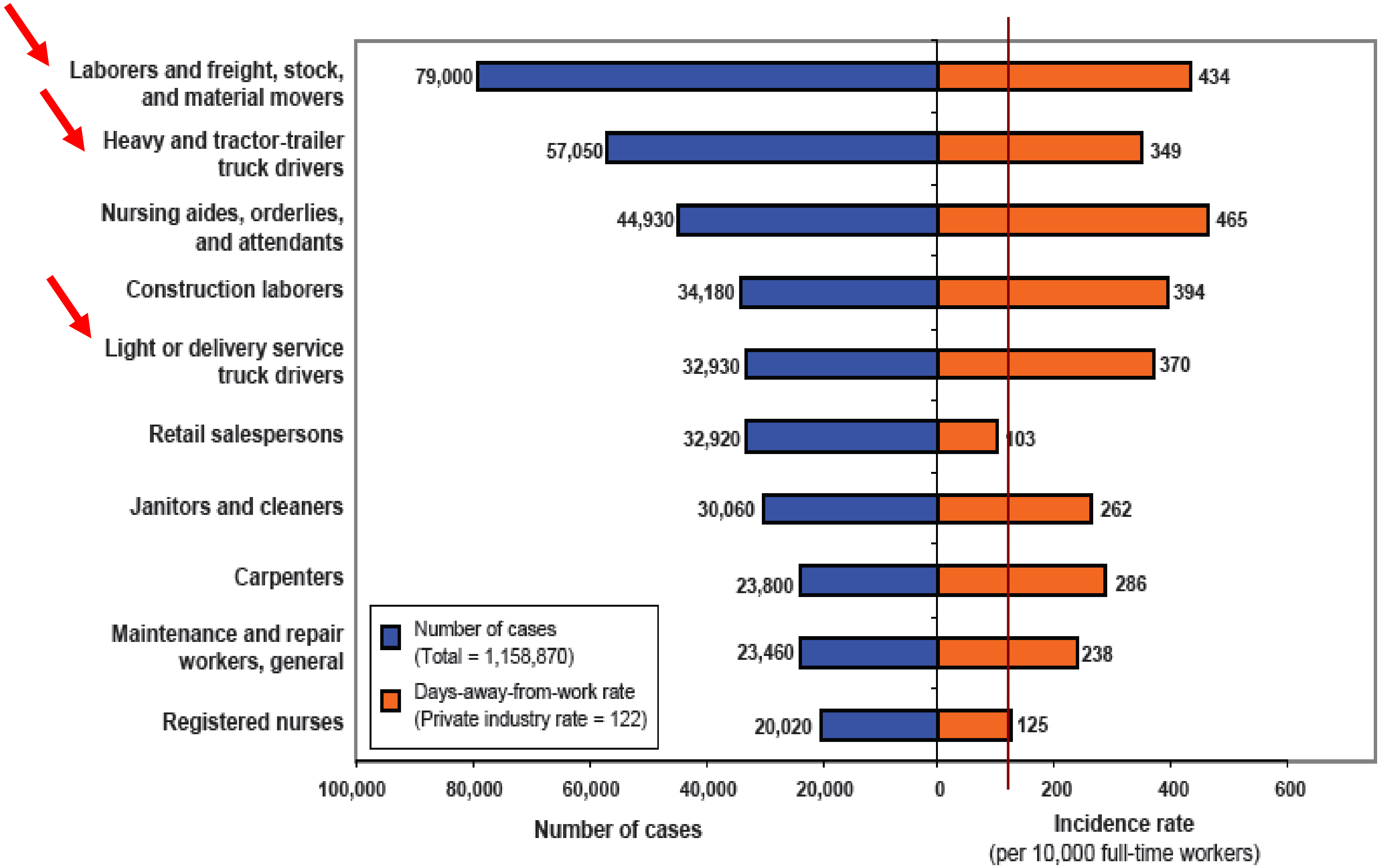
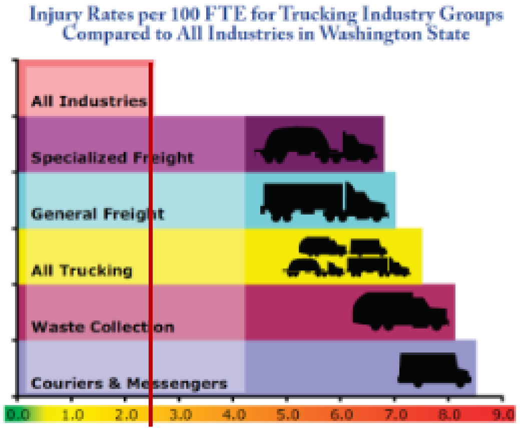
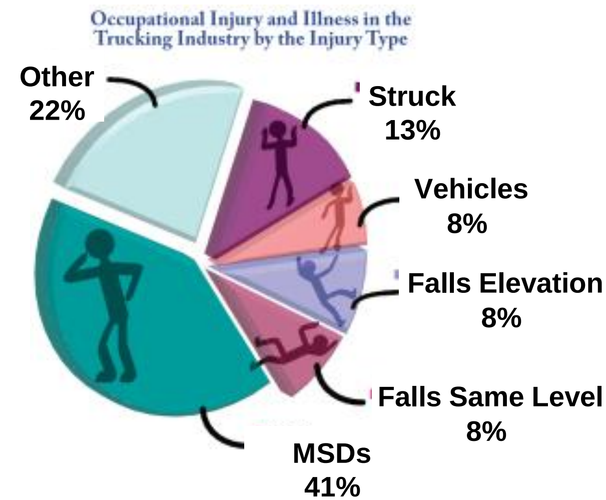
Number and incidence rate for occupations with 20,000 or more injuries and illnesses



These 10 occupations have 20,000 or more cases of injuries and illnesses. Laborers and freight, stock, and material movers had 79,000 cases of injuries and illnesses and a rate of 434 per 10,000 workers. Nursing aides, orderlies, and attendants had a higher rate, 465 per 10,000 workers, but fewer cases.

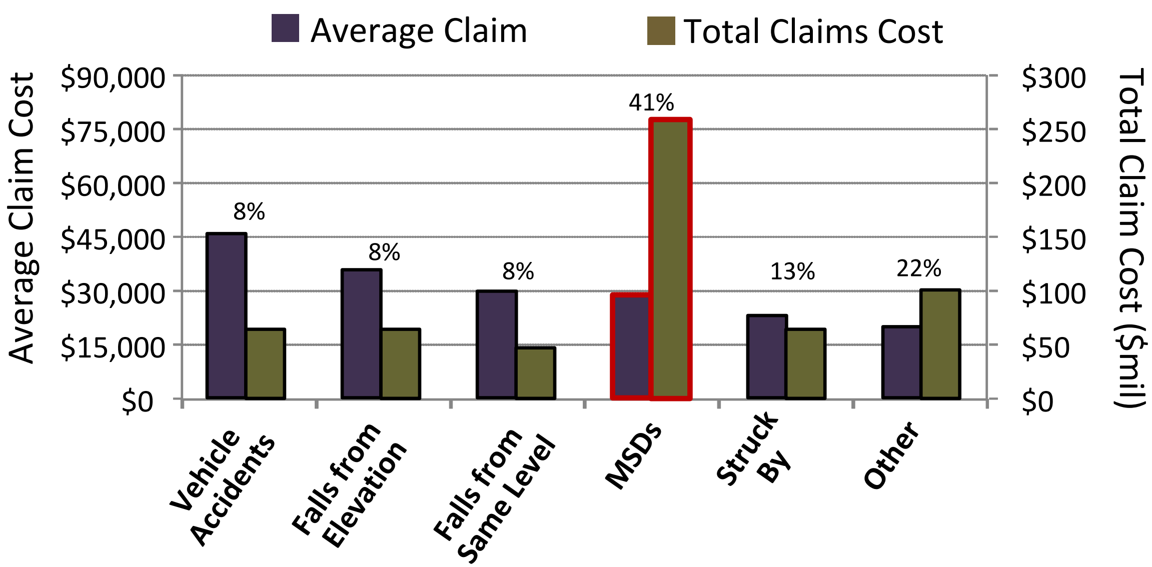




Injury rates in driving over 3x higher

Musculoskeletal disorders (MSDs) single largest component of claims

Average MSD Claim is $30k



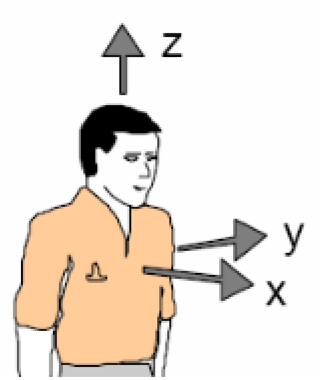
Whole Body Vibration (WBV) and Low Back Pain Development

- Back injuries are most significant non-lethal medical condition affecting the US workforce.
- Epidemiological studies have consistently linked WBV to low back pain/injury
- Dose response relationship established (~**5 years** of exposure)

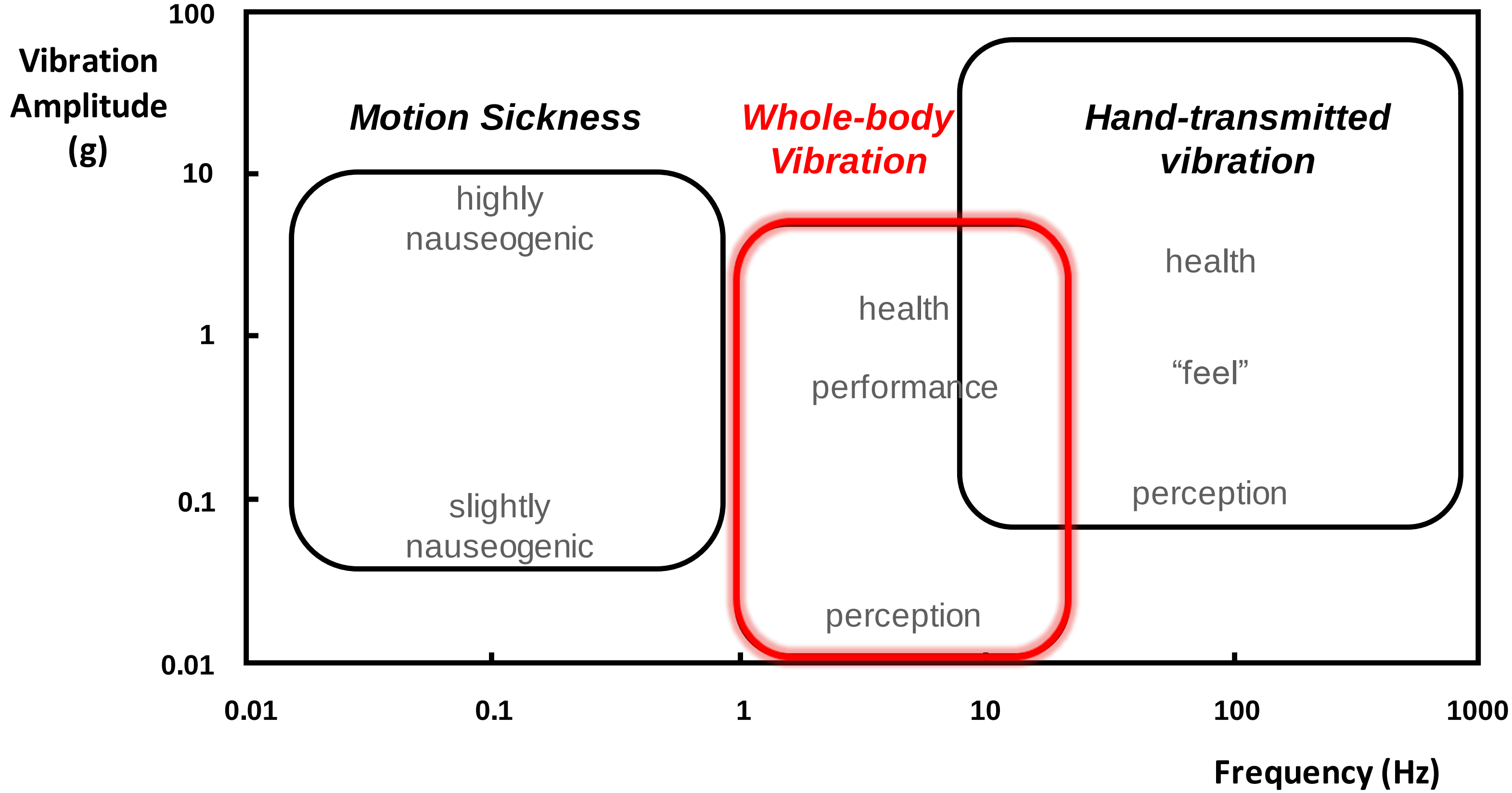
www.sflorg.com/spacenews/images/imsn091206_01_04.jpg

What Is Whole-Body Vibration?

- **Objective measure to describe operator motion**
- **Vector quantity with:**
  - Magnitude or intensity of motion
  - Direction of motion
- **Usually characterized by:**
  - <u>Frequency:</u> How often the operator vibrates (units: Hz)
  - <u>Acceleration:</u> How motion of the operator changes over time (units: m/s^2)

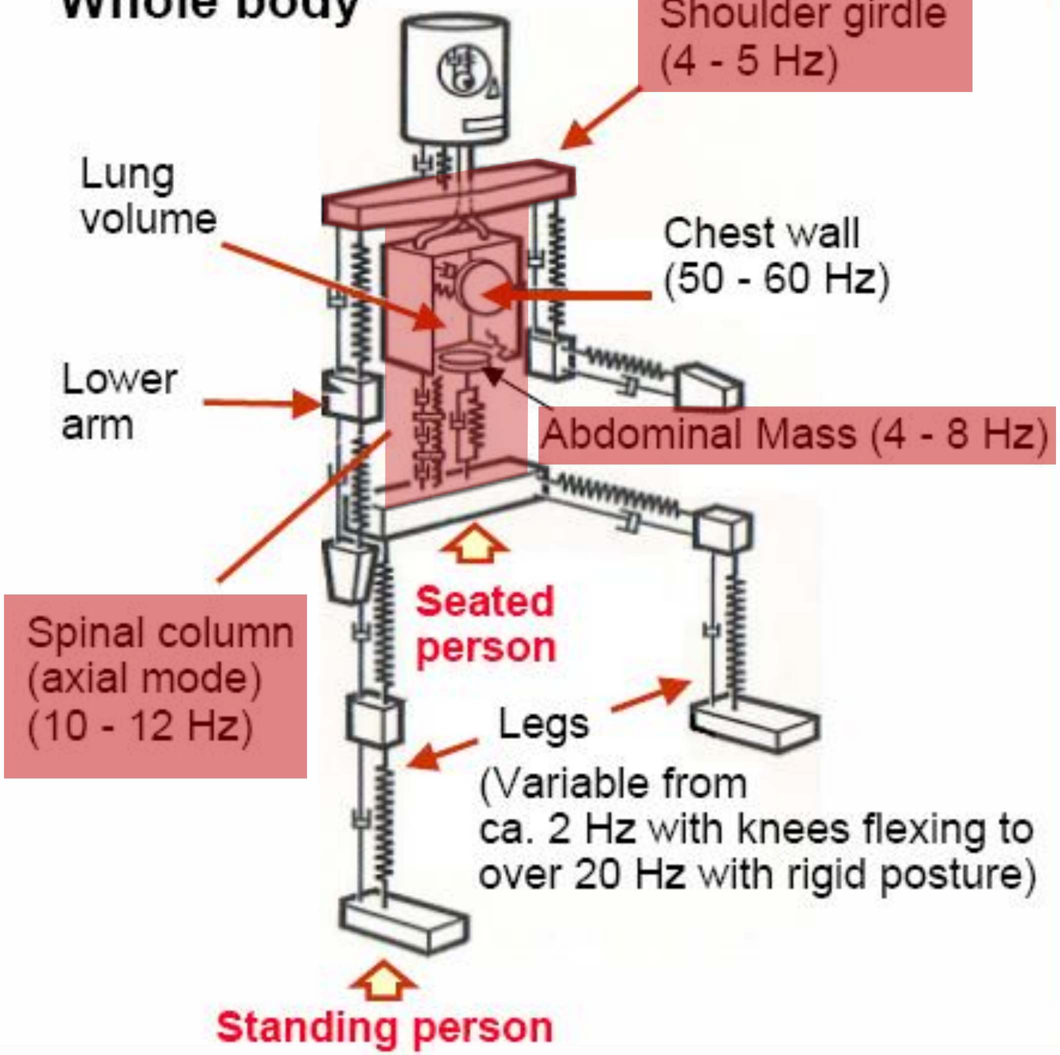


How Vibration Affects Humans

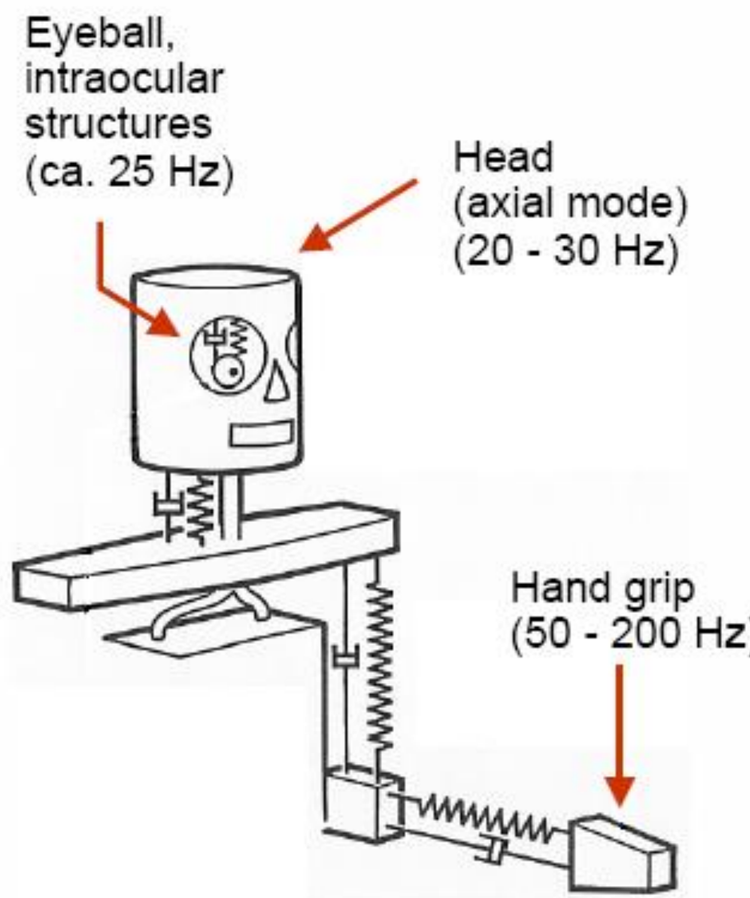


Source: Derived from Neil J. Mansfield, Human Response to Vibrations, CRC Press, 2005, p.7.

Whole body



Hand-arm



Why is Frequency Important

- **Parts of the body have different masses and stiffnesses**
- **The higher the mass the lower the resonant (vibration) frequency**
  - The stomach vibrates at 4 to 8 Hz (4 to 6 times a second)
  - Your spine vibrates at 10 to 12 Hz (10 to 12 ties a second)
- **The lower the mass the higher the resonant (vibration) frequency**
  - Your heart vibrates at 50 to 60 Hz
  - Your blood vessels and nerves vibrate at ~200 Hz
- **The vibration frequencies from the vehicle determine which body parts get vibrated**

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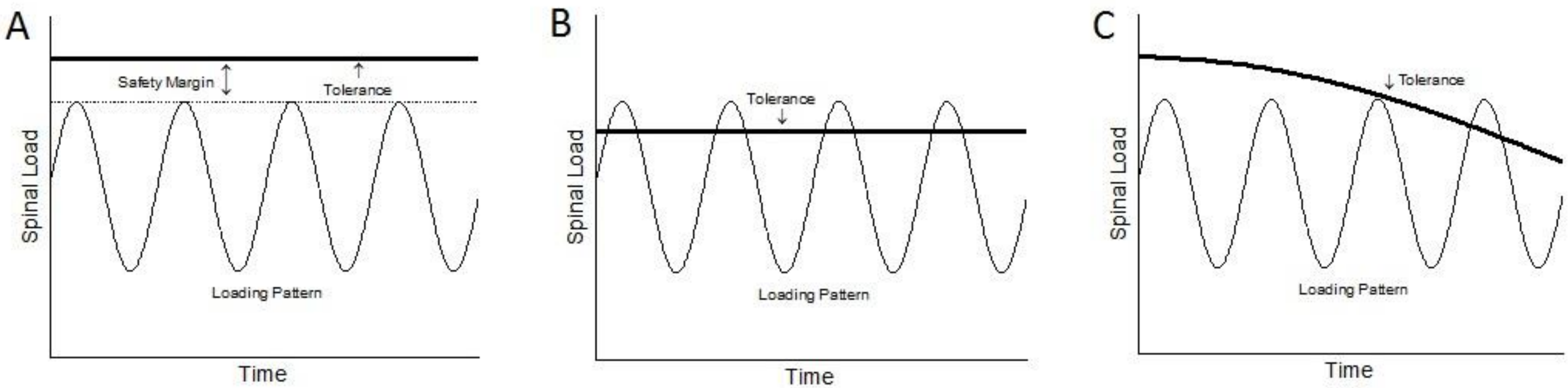
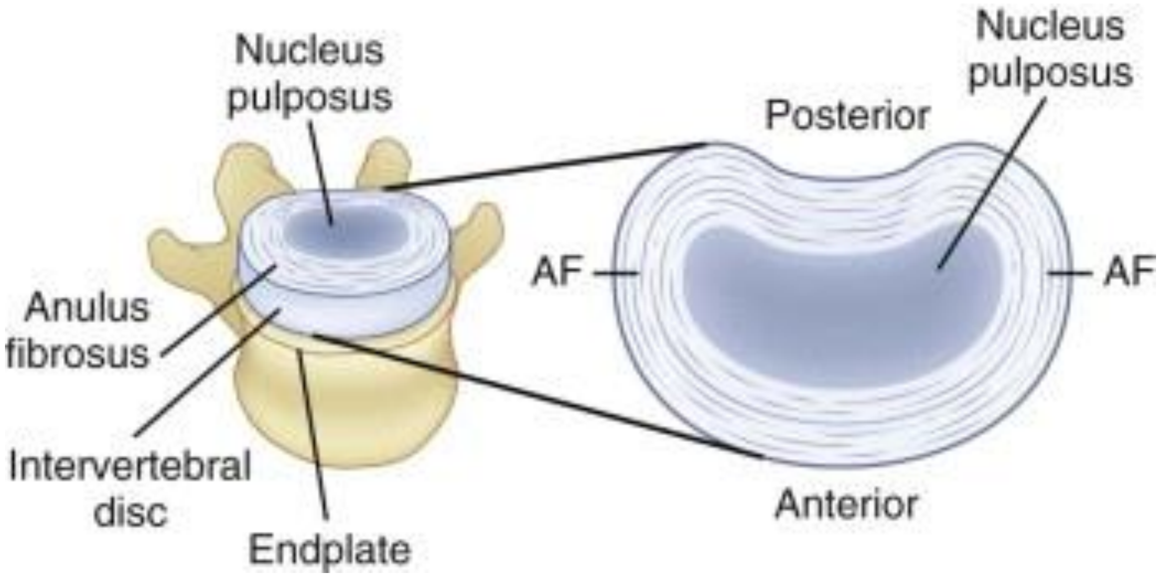
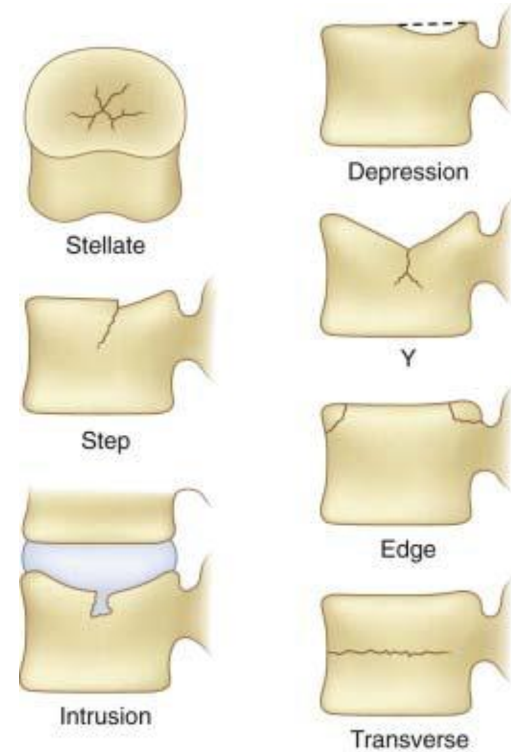
Load-Tolerance Relationship



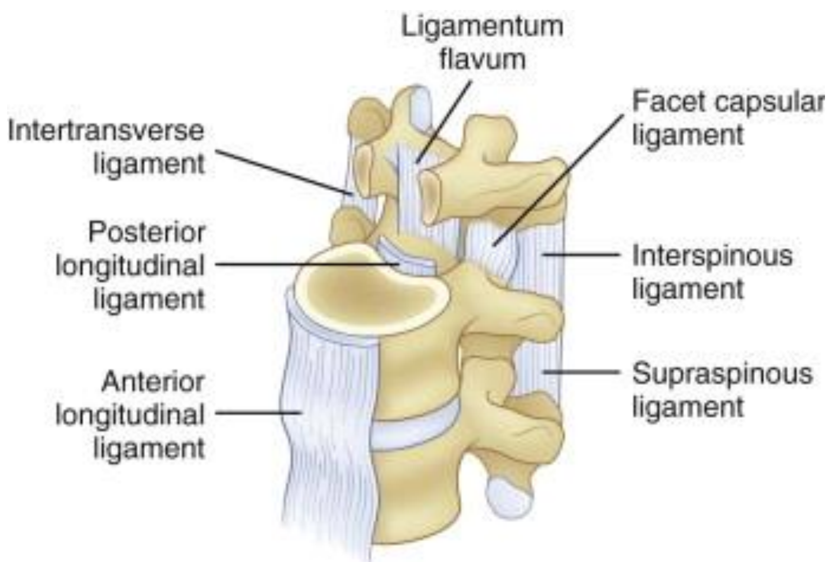
- Spinal tolerance to loading is believed to decrease over time
  - Similar to cumulative trauma disorders
  - One single impulsive event can cause injury

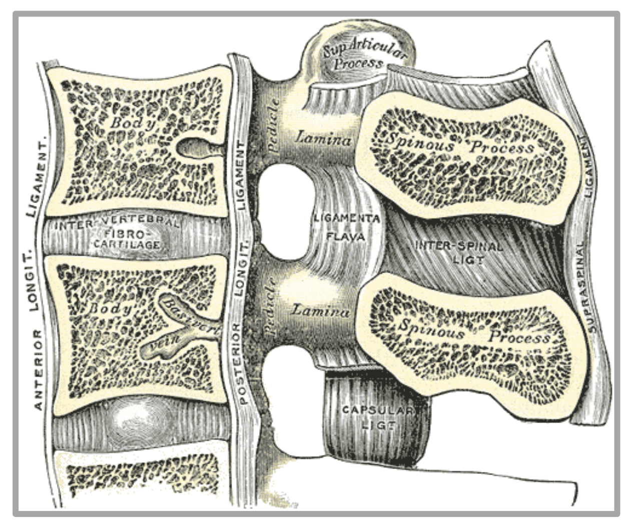
Intervertebral Disc





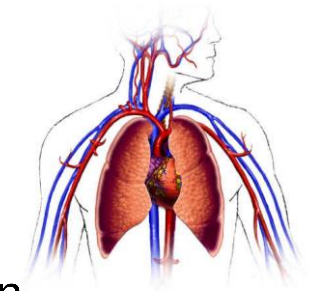
Bones and Ligaments





WBV Health Outcomes

Cardiovascular:

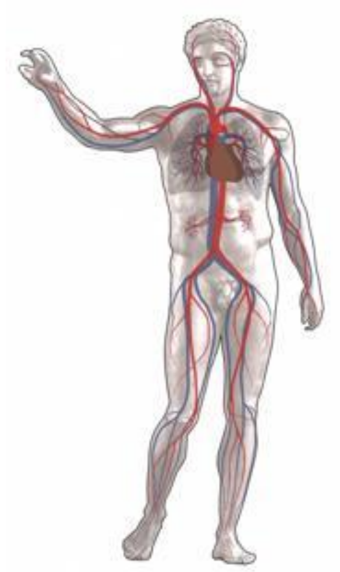


- ↑ Heart rate
- ↑ Sweating
- ↑ Pulmonary ventilation
- ↑ Oxygen uptake

Endocrine and Metabolic:

- ↓ Hypoglycemia (low blood sugar)
- ↓ Hypocholesterolemia (low cholesterol)
- ↓ Ascorbic acid levels

Motor Processes:



- Muscle Fatigue
- Reflex suppression

Respiratory System:

- ↑ Respiration (tensing muscles)
- Rapid breathing

Other:

- Kidneys
- Haemorrhoids
- Fertility

Whole Body Vibration Standards and Regulations

Peter W. Johnson [1] and Per Jonsson [2]

[1] University of Washington Department of Environmental and Occupational Health Sciences

[2] University of Gothenburg, Department of Occupational and Environmental Medicine

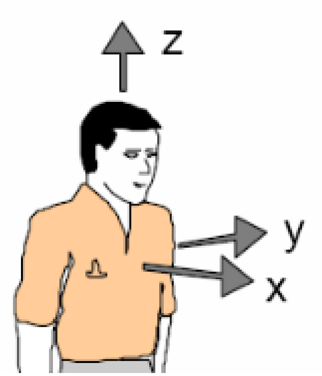
WBV Standards & Regulations

- **The international standard to measure vibration ISO 2631-1**
  1. Average vibration A_{eq} (rms) or A_w (running rms).
  2. Vibration dose value VDV – more sensitive to shocks and impulses.
  3. Standard for measuring most occupational vibration
- **The international standard to measure impulsive vibration ISO 2631-5**
  1. Standard for measuring more extreme vibrations (marine craft, rough off-road, etc.)
  2. Very difficult and not easy for non-technical people to measure and calculate
  3. Static Compressive Dose S_{ed} – for measuring shocks and impulses.

WBV Standards & Regulations

- **Europeans have to follow the EU directive**
  - Employer must assess (or measure) all exposed workers.
  - Lower limit, Daily Vibration Action Limit (DVAL)
  - Workers above DVAL must receive training.
  - Upper limit, Daily Vibration Exposure Limit (DVEL)
  - Workers jobs above DVEL must undergo some form of mitigation.
  - Employer must document exposure and implement a surveillance program.
- **The US and Canada have voluntary guidelines and standards**
  - ACGIH whole body vibration TLV (Threshold Limit Value)
  - US standard ANSI S3.18, 2002, nearly identical to ISO 2631-1

The Measurement of Whole-Body Vibration



Average Weighted Vibration

$$a_{eq} = \sqrt[2]{\frac{1}{T}\int_0^T a_w^2(t)dt}$$

Unit: m/s²

Average Vibration Exposure Measure "RMS" - Insensitive to Impulses

Calculation of A(8) :

$$A(8) = \sqrt{\frac{T}{8}} \cdot a_{eq}$$

8 Hour lower limit **0.43 m/s²**

- T is the expected exposure time [hours/day].
- a_{eq} is the value we measure in m/s^2
- Observe that the A(8) is not a dose
  It's the equivalent 8-hour acceleration value.

Vibration Dose Value

$$\text{VDV} = \sqrt[4]{\int_0^T a_w^4(t)dt}$$

Unit: $m/s^{1.75}$

Cumulative Vibration Exposure Dose – Sensitive to Impulses

Calculation of VDV(8) : $\mathbf{VDV(8)} = \sqrt[4]{\frac{\mathrm{T}}{\mathrm{T_{meas}}}} \cdot \mathrm{VDV_{meas}}$

8 Hour lower limit **8.5 $m/s^{1.75}$**

- T is the expected exposure time [hours/day].
- T_{meas} is time we measured.
- VDV_{meas} is the value we measure in $m/s^{1.75}$
- Observe that the VDV is a dose

ISO 2631-1 Vibration Limits

Continuous Average

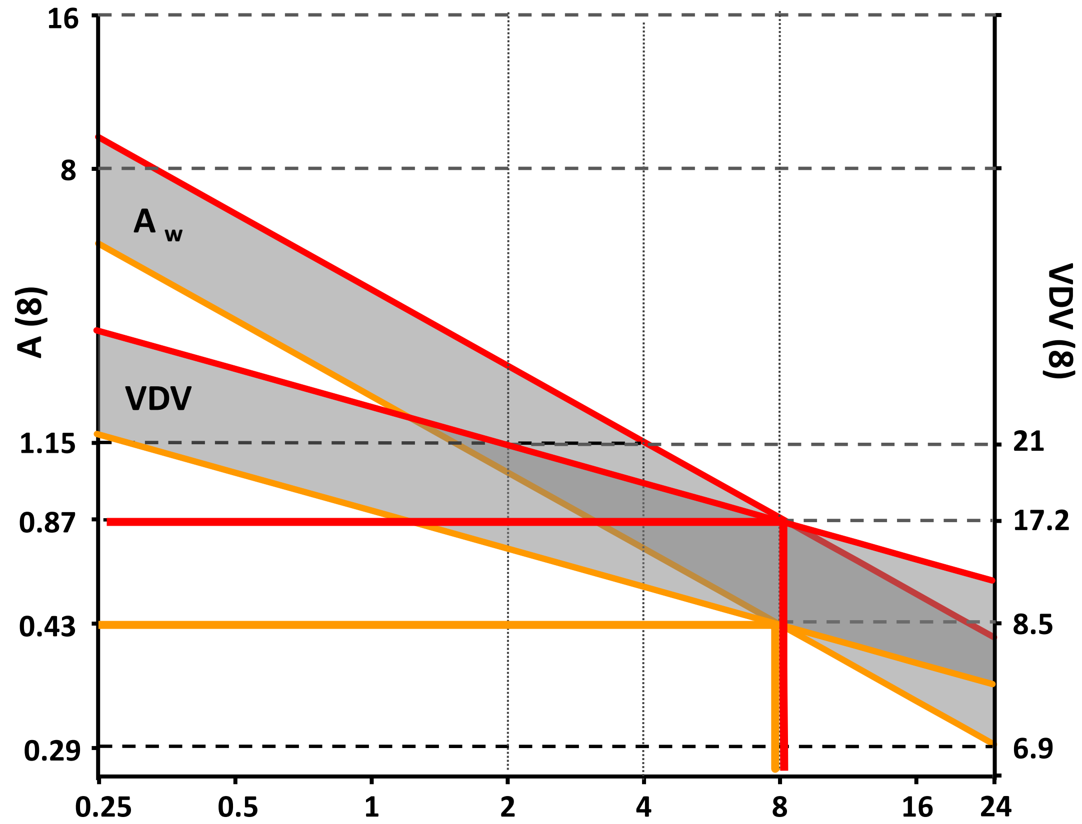
$$A_w = \left[\frac{1}{T}\int_0^T a_w^2(t)\,dt\right]^{\frac{1}{2}}$$

Impulsive Cumulative

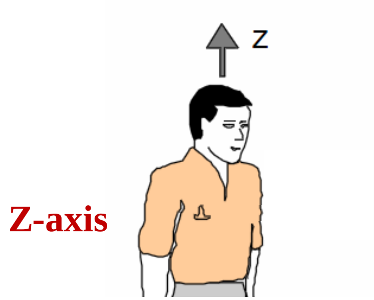
$$VDV = \{\int_0^T [a_w(t)]^4\,dt\}^{1/4}$$

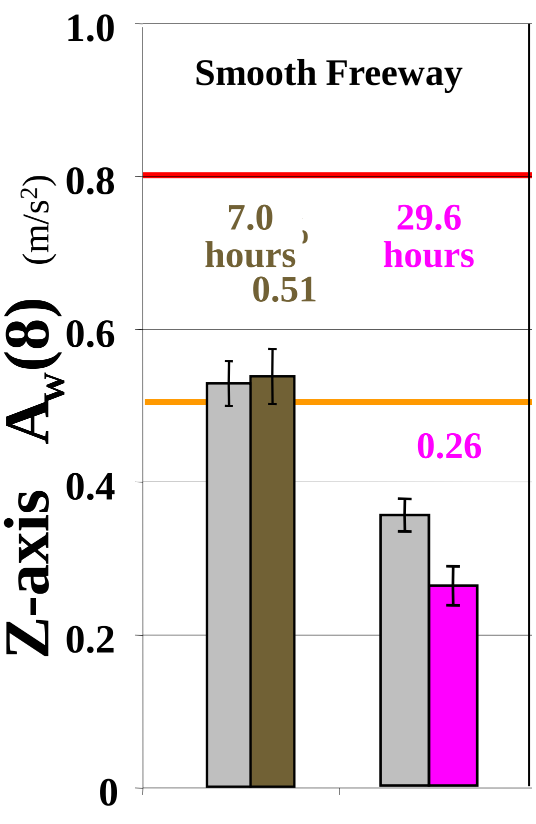
	8 hrs of Exposure		
	A_W (m/s²)	VDV (m/s$^{1.75}$)	
Exposure Limit	0.87	17.1	red line
Action Limit	0.43	8.5	orange line

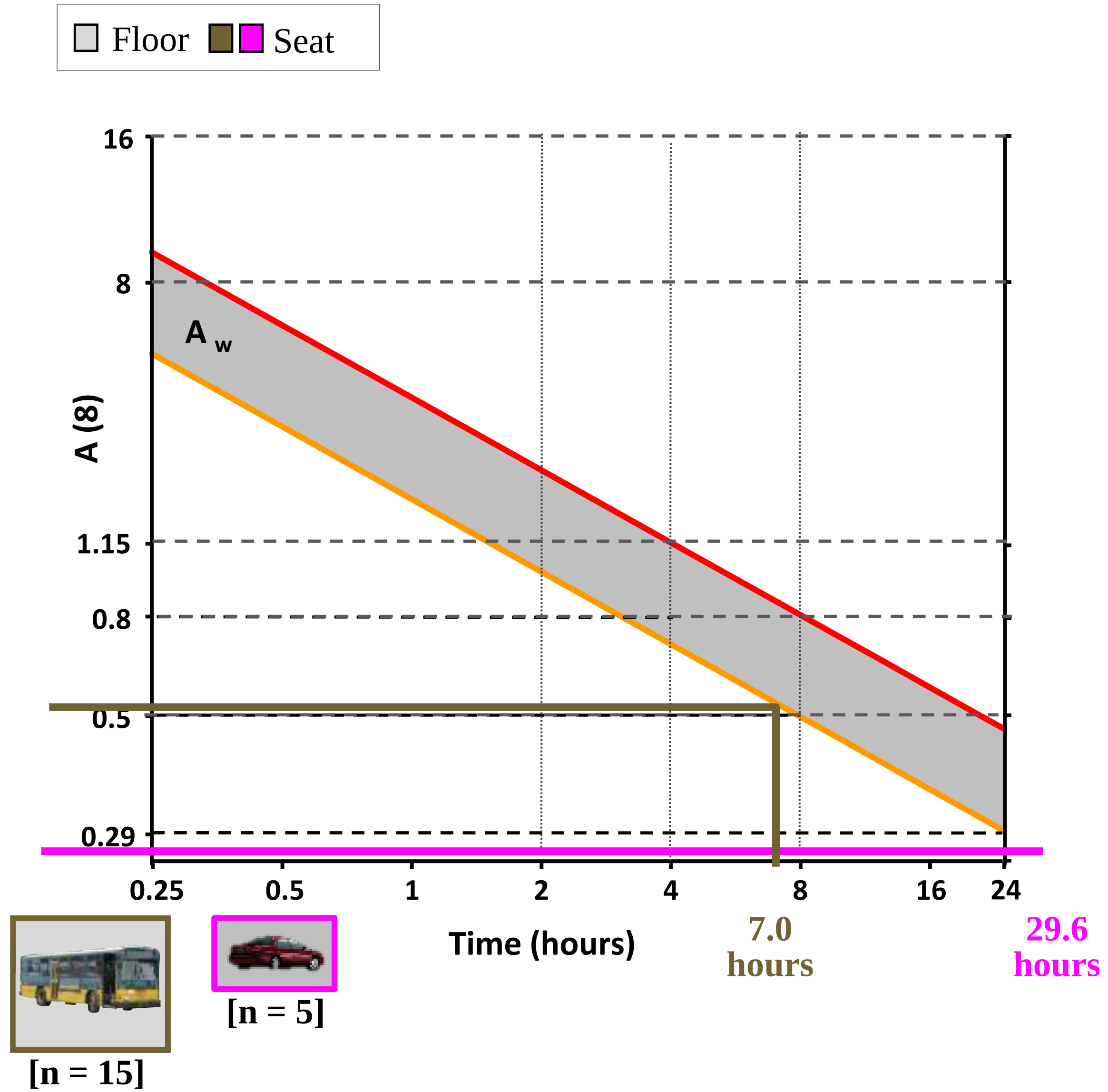
Driving Time to Action Limit



High Floor Coach Bus vs Car







EU Good Practice Guide to WBV

Guide to good practice on

Whole-Body Vibration

Non-binding guide to good practice with a view to implementation of Directive 2002/44/EC on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (vibrations).

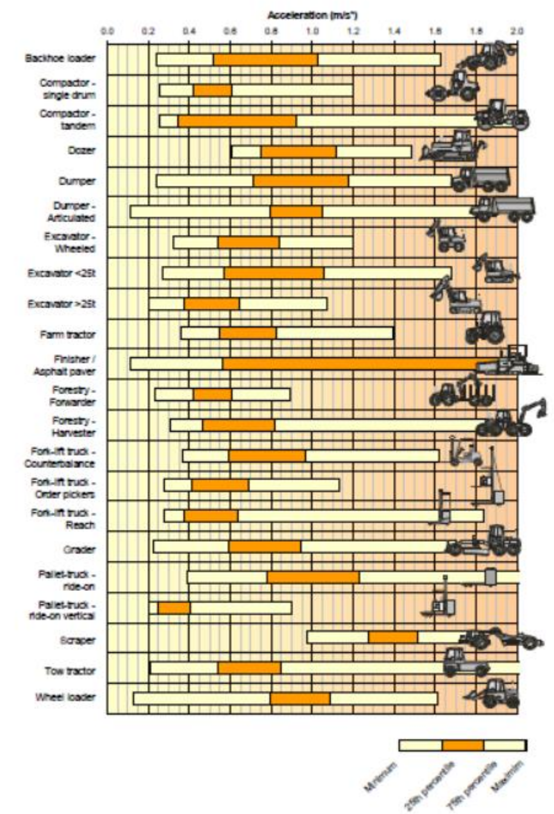
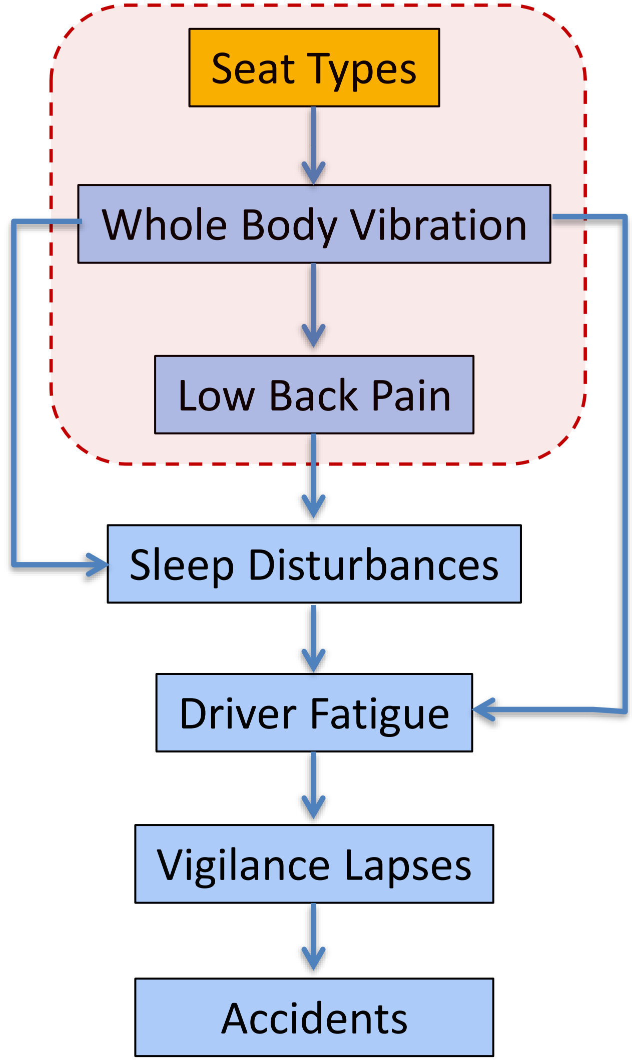


Figure 2 Examples of vibration magnitudes for common tools
Ranges of vibration values for common equipment on the EU market. These data are for illustration only. For more details see Annex B.

Causality Map

Industry Standard Seat

Enhanced Seats



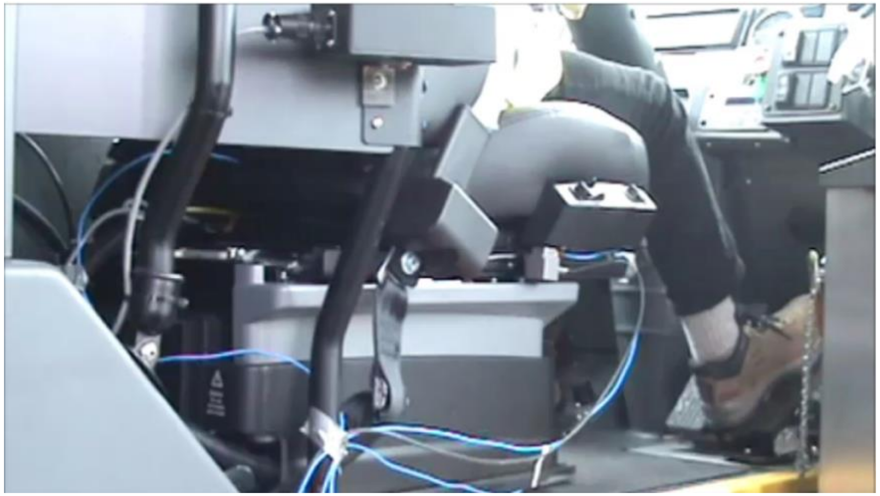
Comparison of Seat Suspension Technologies

1950’s

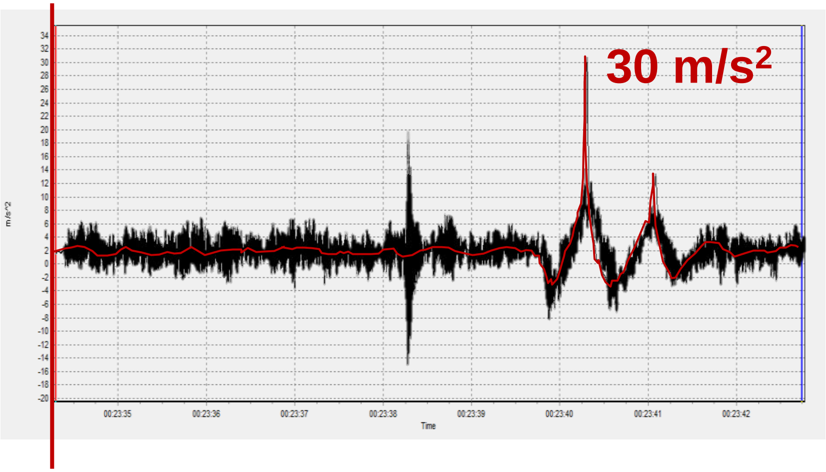
1960’s

1980’s

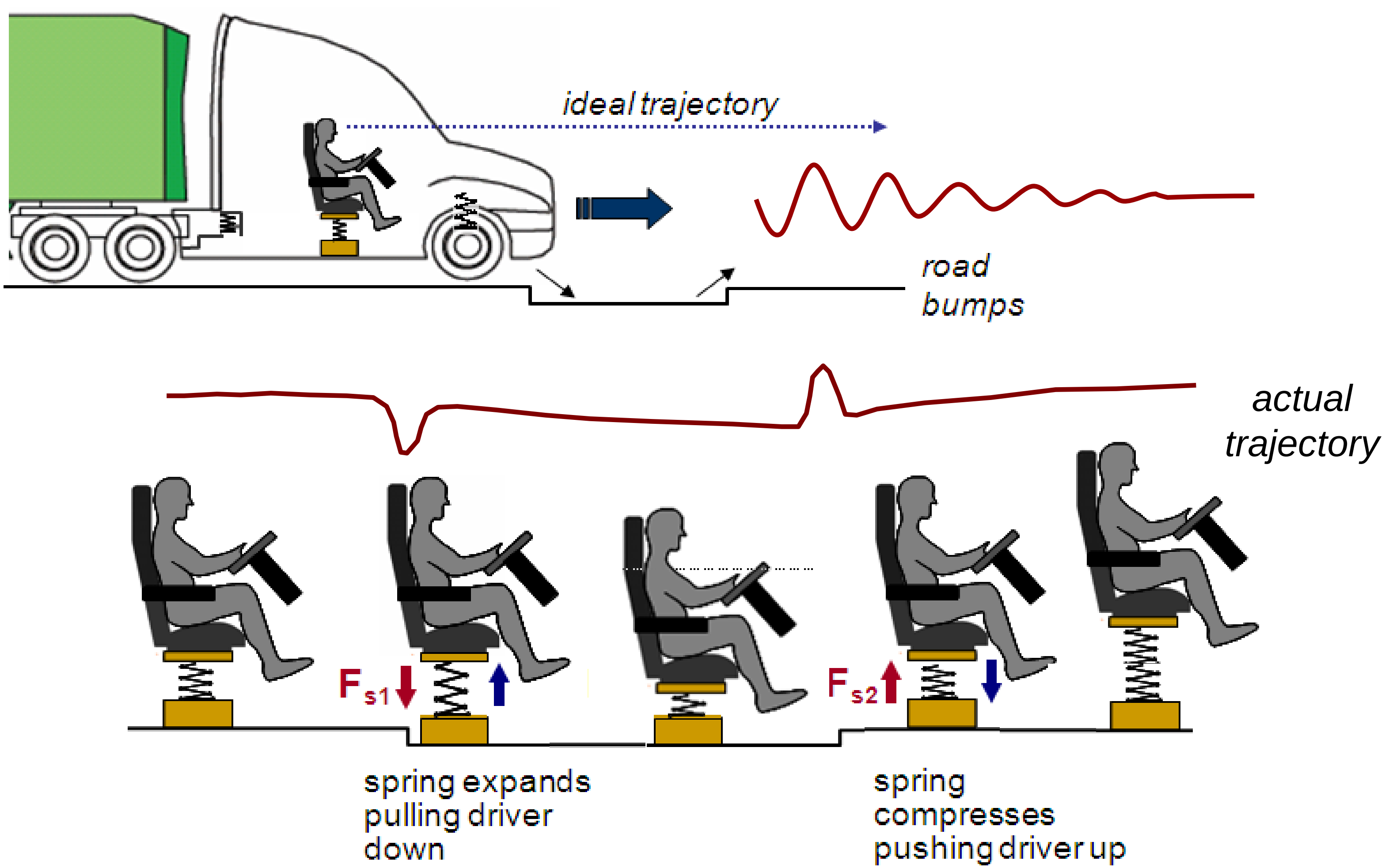
	Static	Mechanical Suspension	Air-Ride
Uses	On-Road	On/Off Road	Many
Cost	Low	+ Moderate	++ Moderate
Pros	?	?	?
Cons	?	?	?



Air Suspension Seat



Challenges with Passive Suspension Seats



Amplify vibration when going over small perturbations at moderate to high speed

Seat Suspension Design Matters

Occupational Medicine 2012;**62**:519–524
Advance Access publication on 9 July 2012 doi:10.1093/occmed/kqs096

Whole-body vibration exposure in metropolitan bus drivers

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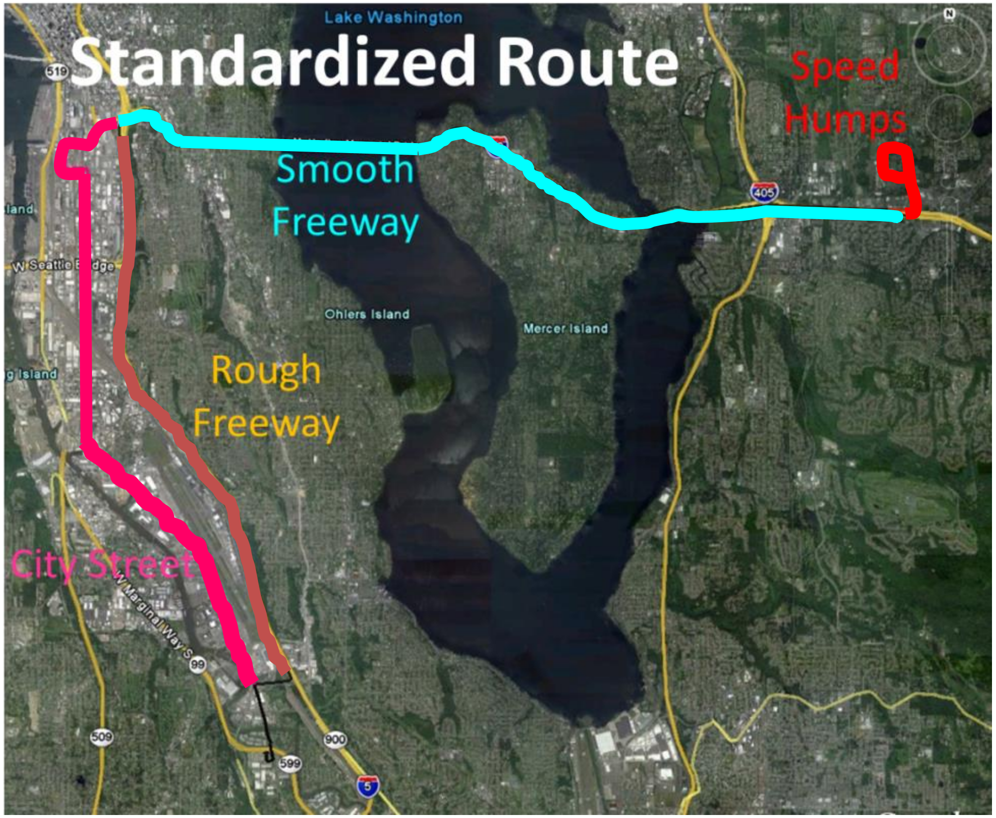
Study Design

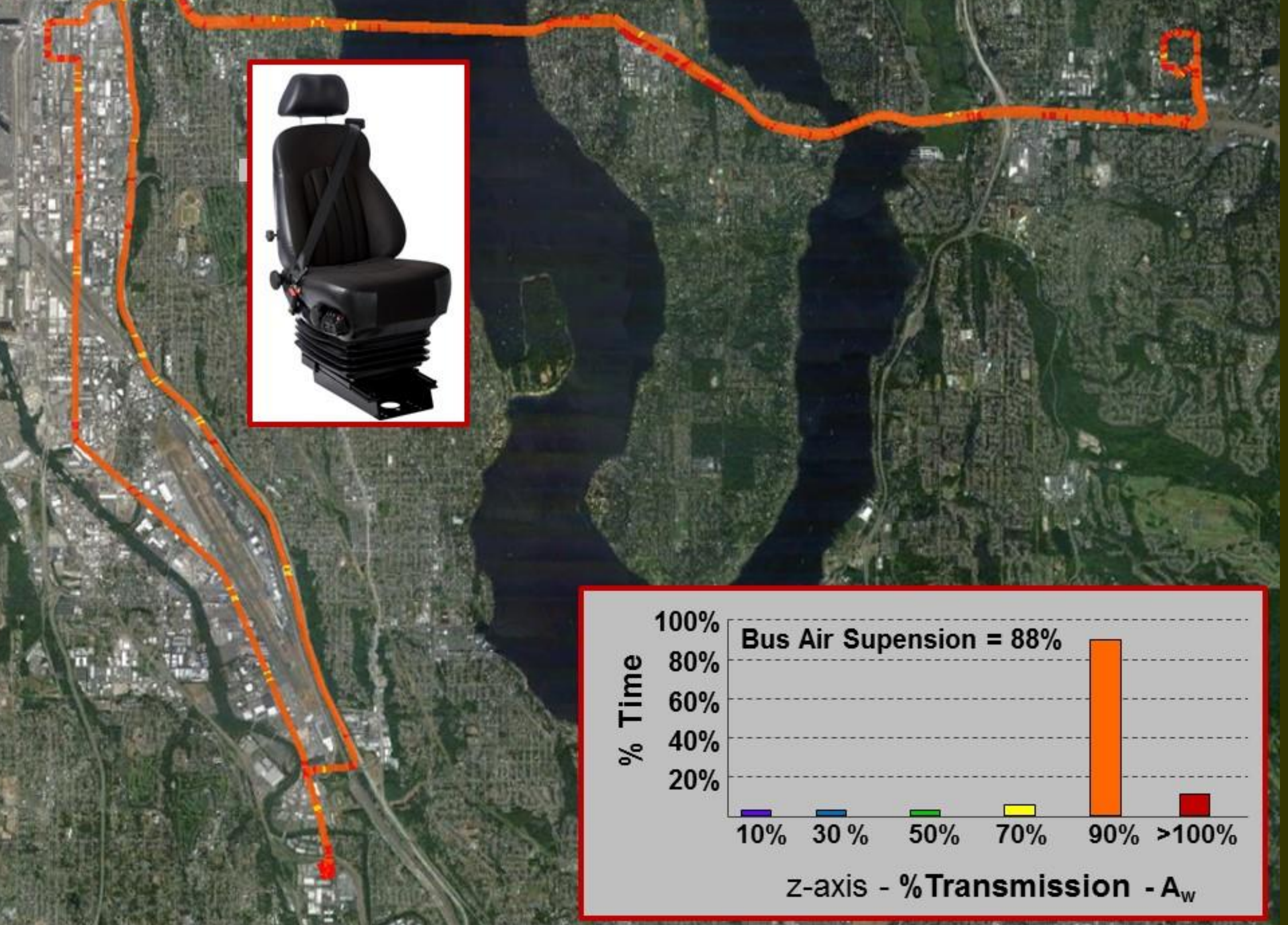
Air-Ride

6 yr old 13.3m low-floor coach bus

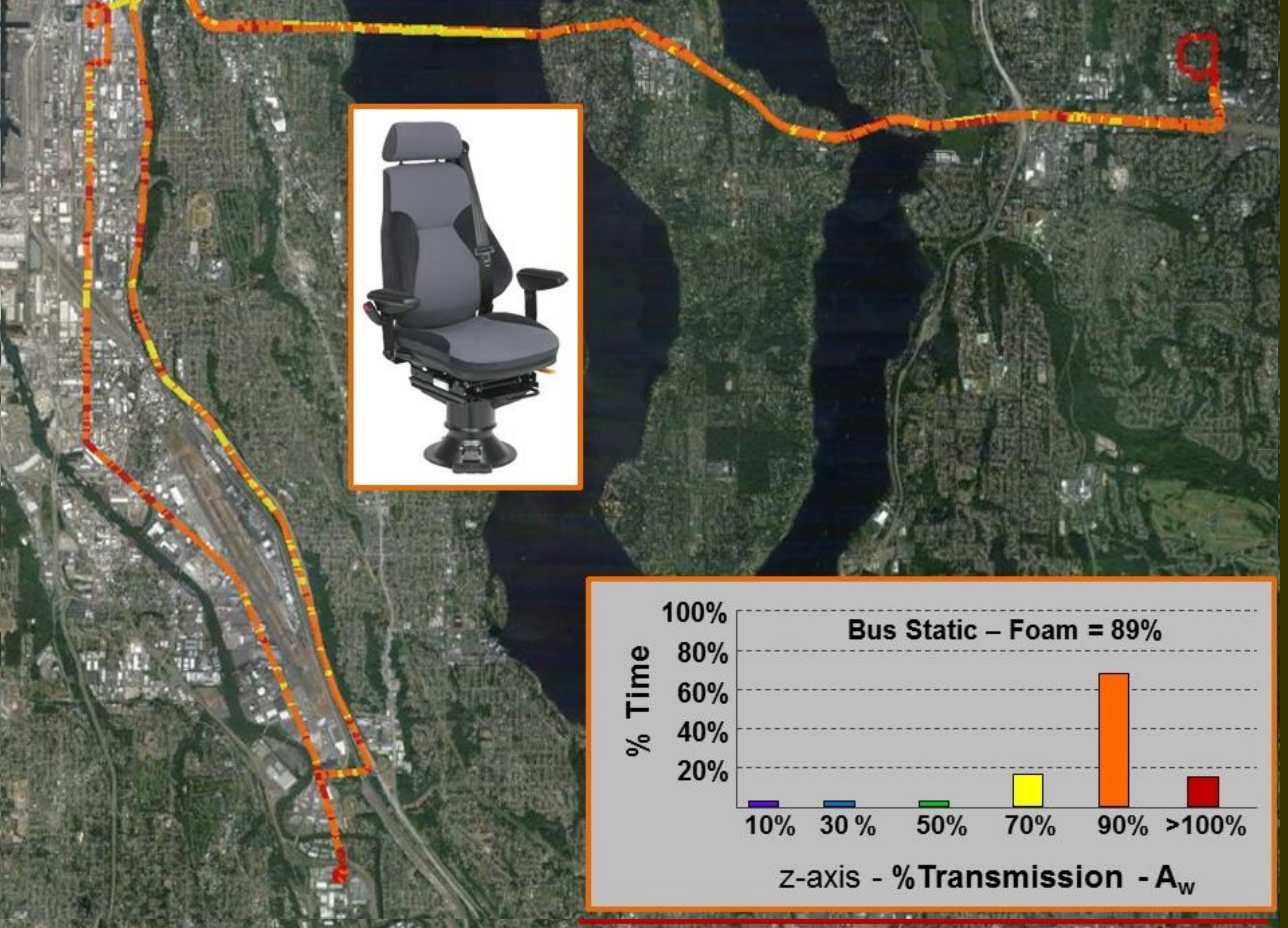
15 Subjects



Vibration Transmitted from Bus Floor to Seat of the operator



Vibration Transmitted from Bus Floor to Seat of the operator



Take Home Messages

- The current air-suspension seat may not ne optimized for on-road vehicles
- The current long travel suspension seat may not necessary for on-road vehicles

Comparison of Seat Suspension Technologies

1950's **1960's** **1980's** **2010**

	Static	Mechanical Suspension	Air-Ride	ElectroMech Active
Uses	On-Road	On/Off Road	Many	Trucking
Cost	Low	+ Moderate	++ Moderate	+High
Pros	+++ WBV Not Weight Dependent	++ WBV	+++ WBV Less Weight Dependent	WBV?
Cons	Bumps	Weight Dependent Amplify WBV	Amplify WBV	Currently On-Road

New Truck Seats are Available

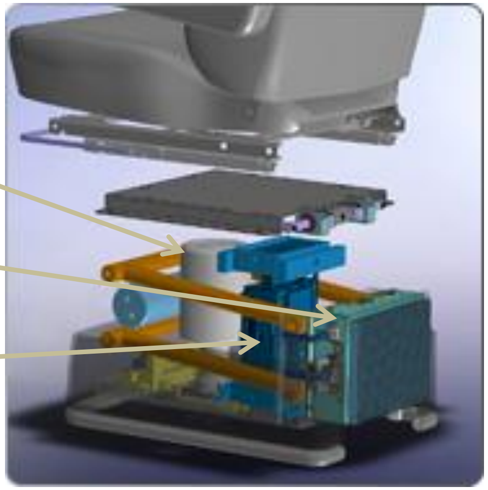
- **To combat challenges with air-ride seats, new “active suspension” truck driver seats have recently been developed and introduced**

New Technology Seats:

① **Air suspension system like a conventional truck seat**

② **Sensor in seat base, microprocessor processes seat sensor data in order to cancel forces in real time**

③ **Linear electromagnetic actuator counteracts forces**

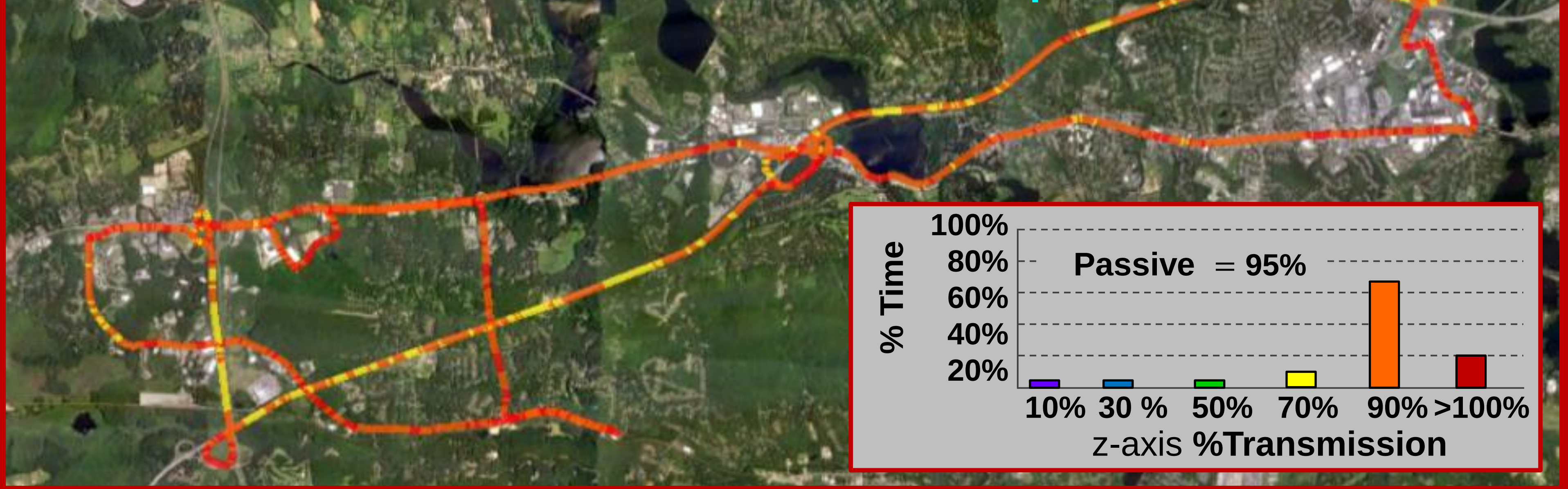


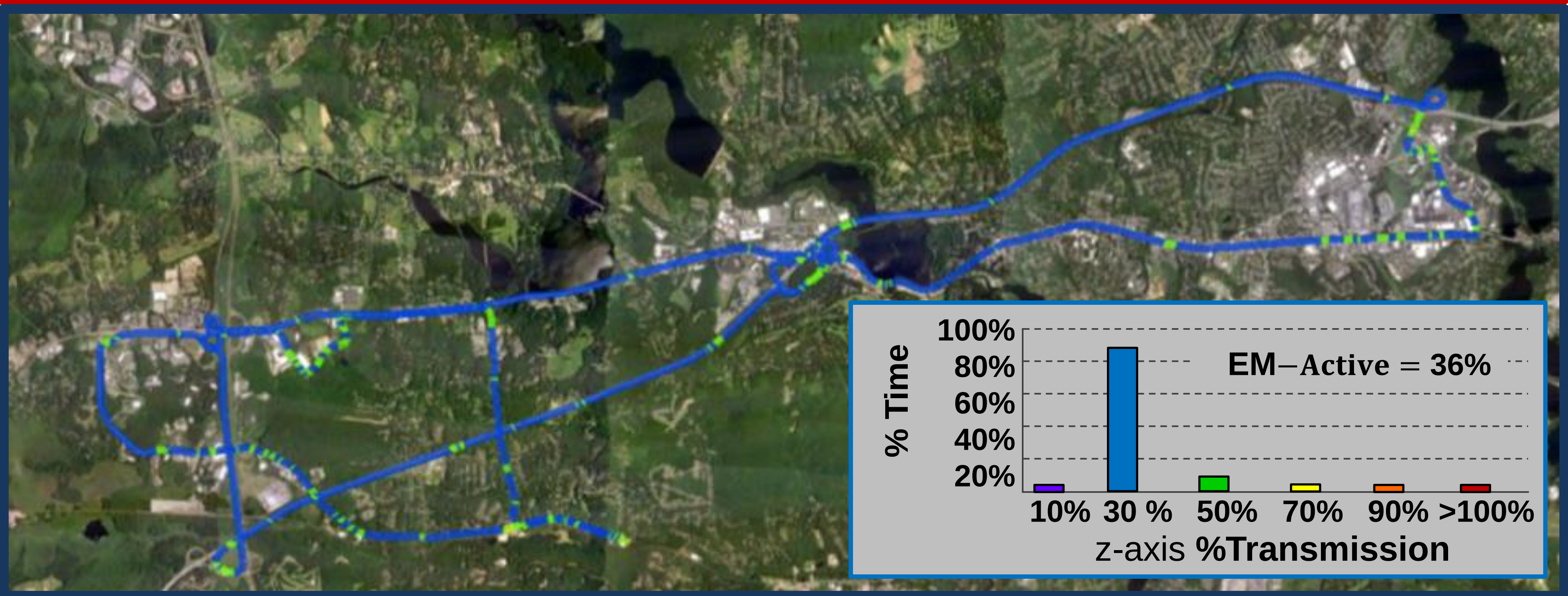
- **The UW has tested the new technology seats in a group of 16 truck drivers**

Passive

EM Active

Vehicle Vibration Transmitted to Operator





Annals of Work Exposures and Health, 2018, Vol. 62, No. 8, 1000–1011
doi: 10.1093/annweh/wxy063
Advance Access publication 17 July 2018
Original Article

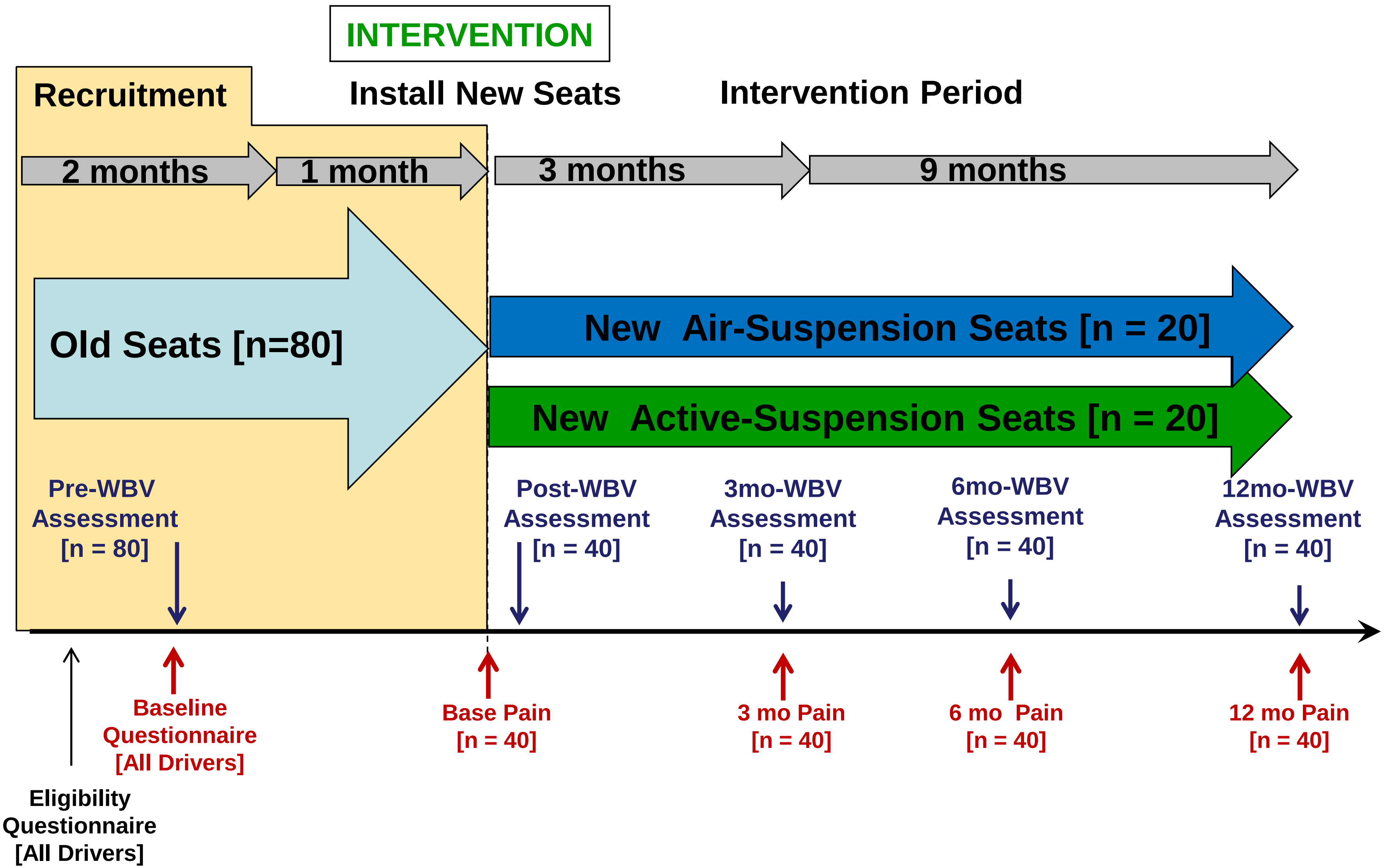
BOHS
The Chartered Society for Worker Health Protection

OXFORD

Original Article

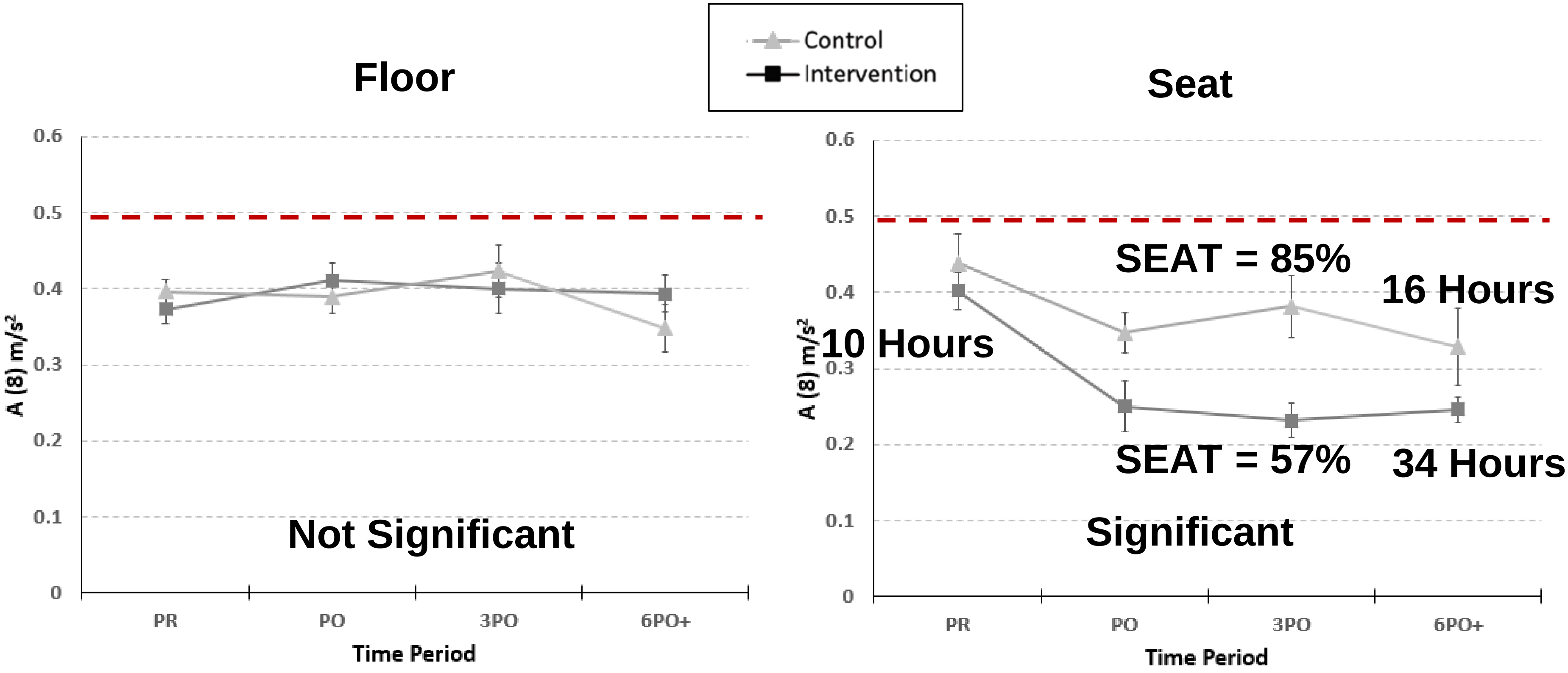
A Randomized Controlled Trial of a Truck Seat Intervention: Part 2—Associations Between Whole-Body Vibration Exposures and Health Outcomes

Jeong Ho Kim[1,*], Monica Zigman[2], Jack T. Dennerlein[3,4] and Peter W. Johnson[2]


INTERVENTION
Recruitment
Install New Seats
Intervention Period
2 months
1 month
3 months
9 months
Old Seats [n=80]
New Air-Suspension Seats [n = 20]
New Active-Suspension Seats [n = 20]
Pre-WBV Assessment [n = 80]
Post-WBV Assessment [n = 40]
3mo-WBV Assessment [n = 40]
6mo-WBV Assessment [n = 40]
12mo-WBV Assessment [n = 40]
Baseline Questionnaire [All Drivers]
Base Pain [n = 40]
3 mo Pain [n = 40]
6 mo Pain [n = 40]
12 mo Pain [n = 40]
Eligibility Questionnaire [All Drivers]

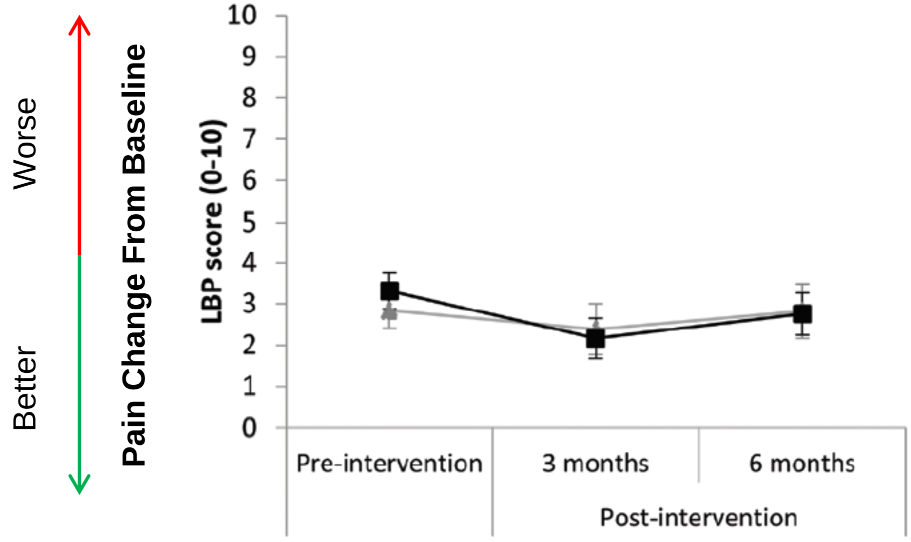
Results

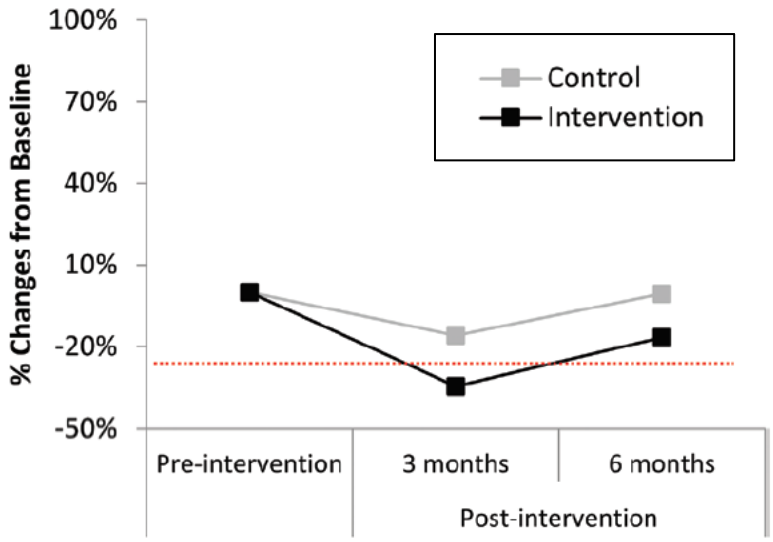
Average Weighted Vibration – A(8)



Results

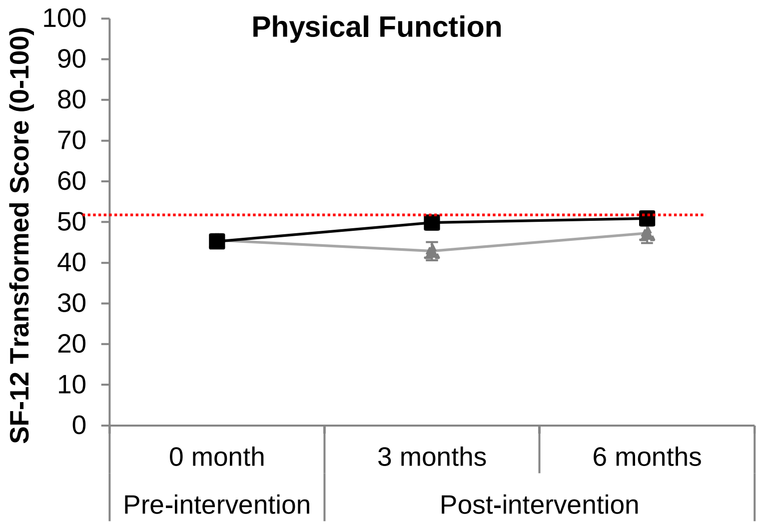
Low Back Pain Results

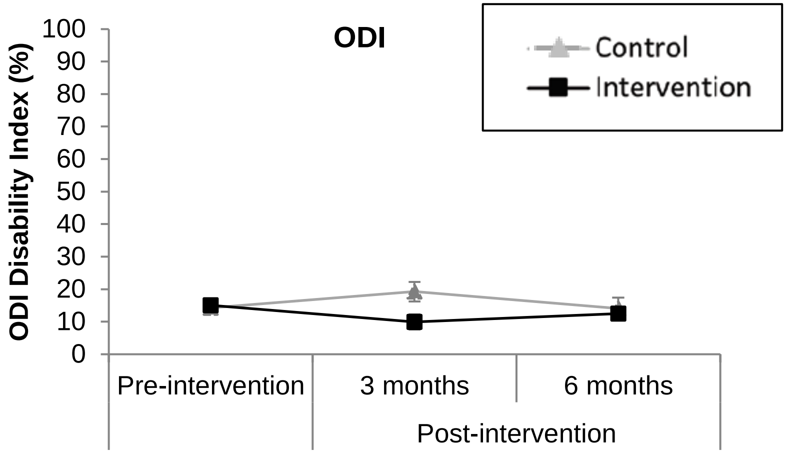


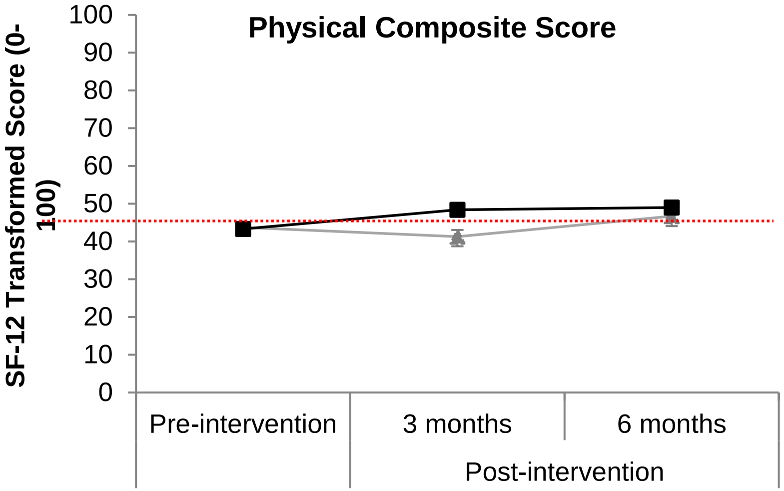


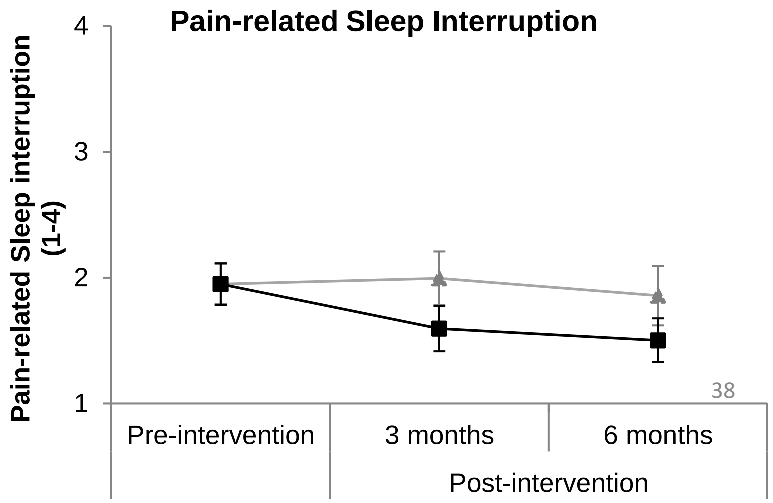
Not Significant

Red line - Clinical Significance.


Physical Function
SF-12 Transformed Score (0-100)
100
90
80
70
60
50
40
30
20
10
0
0 month
3 months
6 months
Pre-intervention
Post-intervention

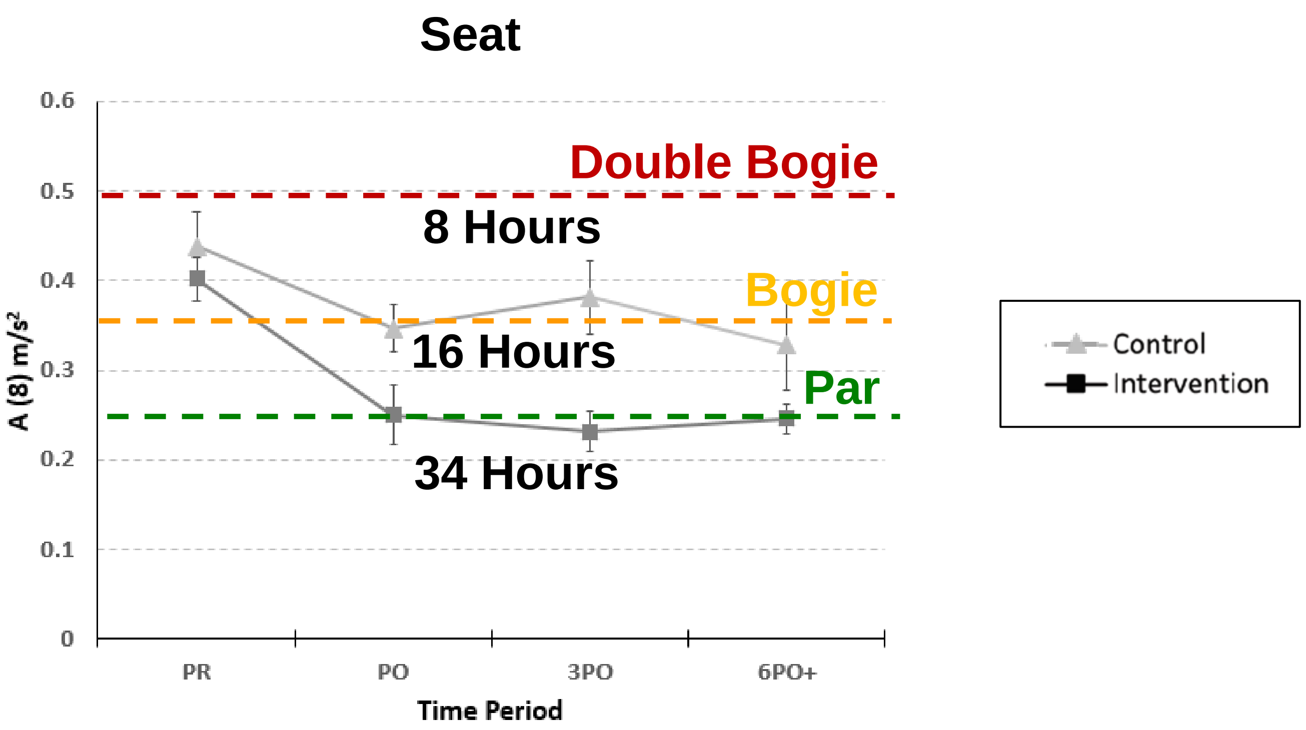

ODI
Control
Intervention
ODI Disability Index (%)
100
90
80
70
60
50
40
30
20
10
0
Pre-intervention
3 months
6 months
Post-intervention


Physical Composite Score
SF-12 Transformed Score (0-100)
100
90
80
70
60
50
40
30
20
10
0
Pre-intervention
3 months
6 months
Post-intervention


Pain-related Sleep Interruption
Pain-related Sleep interruption (1-4)
4
3
2
1
Pre-intervention
3 months
6 months
Post-intervention

Results

Average Weighted Vibration – A(8)



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Whole Body Vibration Exposures: Assessing the Cost and Health Effects of Different Seats

Kat Gregersen[1,2], June Spector[2], Shan Liu[3]
David Veenstra[4], Peter W. Johnson [,2,3]

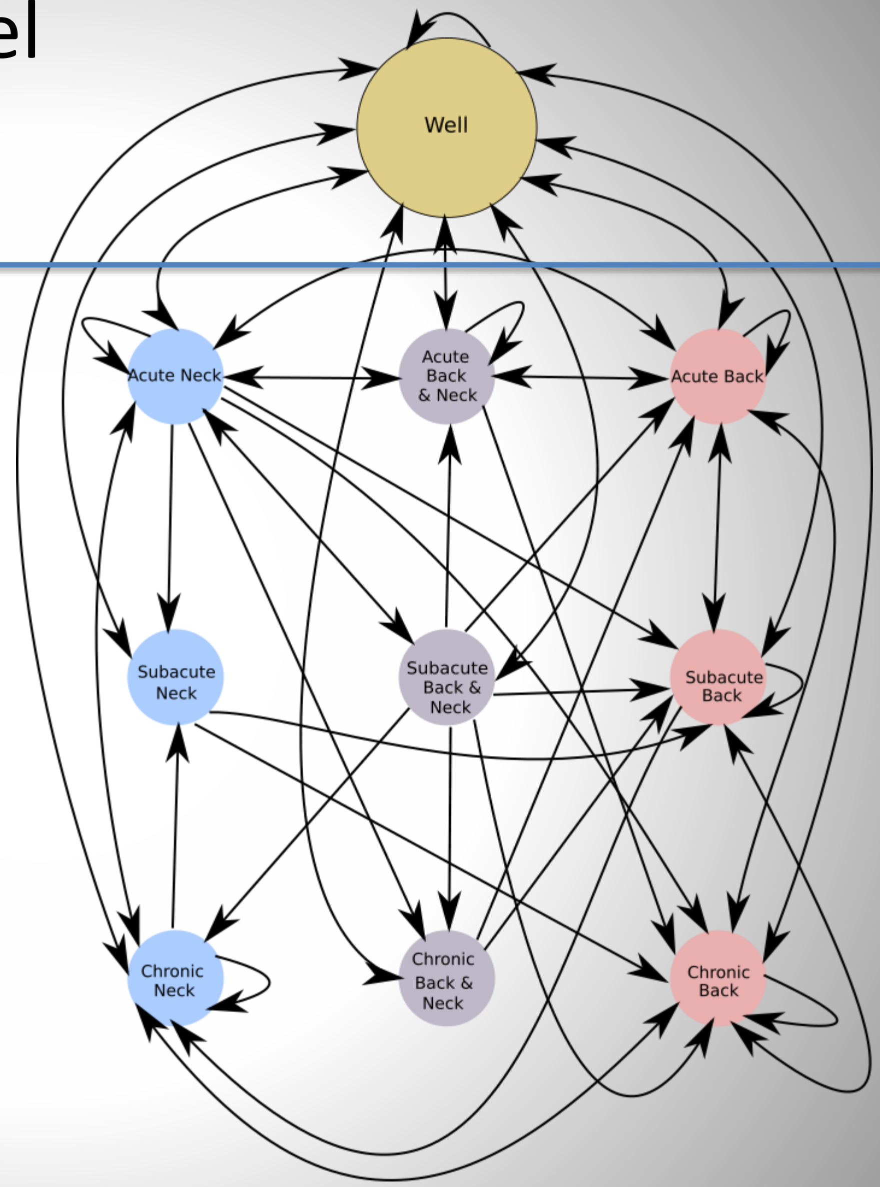
[1] Washington State Department of Labor and Industries
[2] University of Washington Department of Environmental and Occupational Health Sciences
[3] University of Washington Department of Industrial and Systems Engineering
[4] University of Washington Department of Pharmacy

What would be a cost-effective seating strategy to reduce LBP and costs among Metro bus drivers?

1. **Existing – keeping and maintaining seats over the 15 year life of a bus**
2. **Periodic Replacement of Passive-Suspension Seats**
   - Current passive-suspension seats wear out easily
   - High level of maintenance
3. **Static Seat**
   - Less expensive and reduced maintenance
   - Comparable vibration exposures to passive-suspension seat
4. **Active-suspension driver seat**
   - More expensive than existing passive-suspension seats
   - Reduces vibration exposures approx. 50%
   - Shown to reduce LBP by up to 30%

Methods: Markov Model

- **15-year worker comp claim database for King County Metro (1999-2013)**
- **15 cycles = 15 year typical life of a Metro bus**
- **1 year cycles**
- Models the **likelihood of filing a worker comp claim** each year
- **Circles represent health states**
- **Arrows represent allowed transitions**



Methods: Markov Model

Acute: < 3 wks

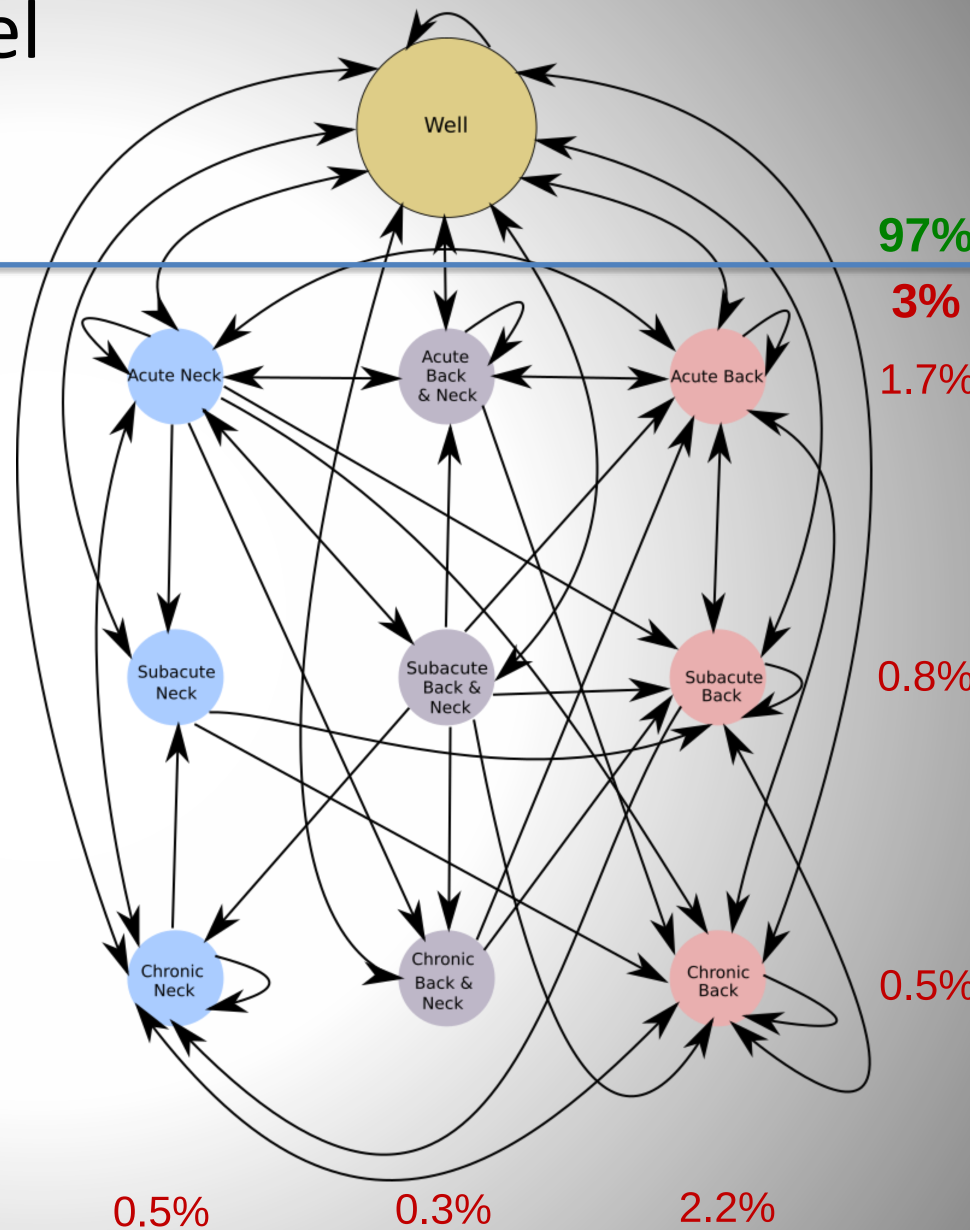
$3,892

Sub-acute: 3 wks – 3mo

$15,722

Chronic: >3 mo

$107,431



Cost and Utility Inputs

Cost Inputs - 1,500 Bus Fleet where buses are maintained for 15 years

- Existing: **$2,805 + $950 maintenance years 5 and 10**
- Static Seat: **$2,500 + $300 maintenance years 5 and 10**
- Active-Suspension Seat: **$3,995 + $950 maintenance years 5 and 10**
- Seat Replacement every 5 years: **$6,415 + no maintenance costs**

- Mean Claim Costs
  - Adjusted for claim maturity
  - Adjusted for inflation to 2015 dollars (CPI)
  - Indirect Costs Modifier: **1.22** (claims administration and taxes)

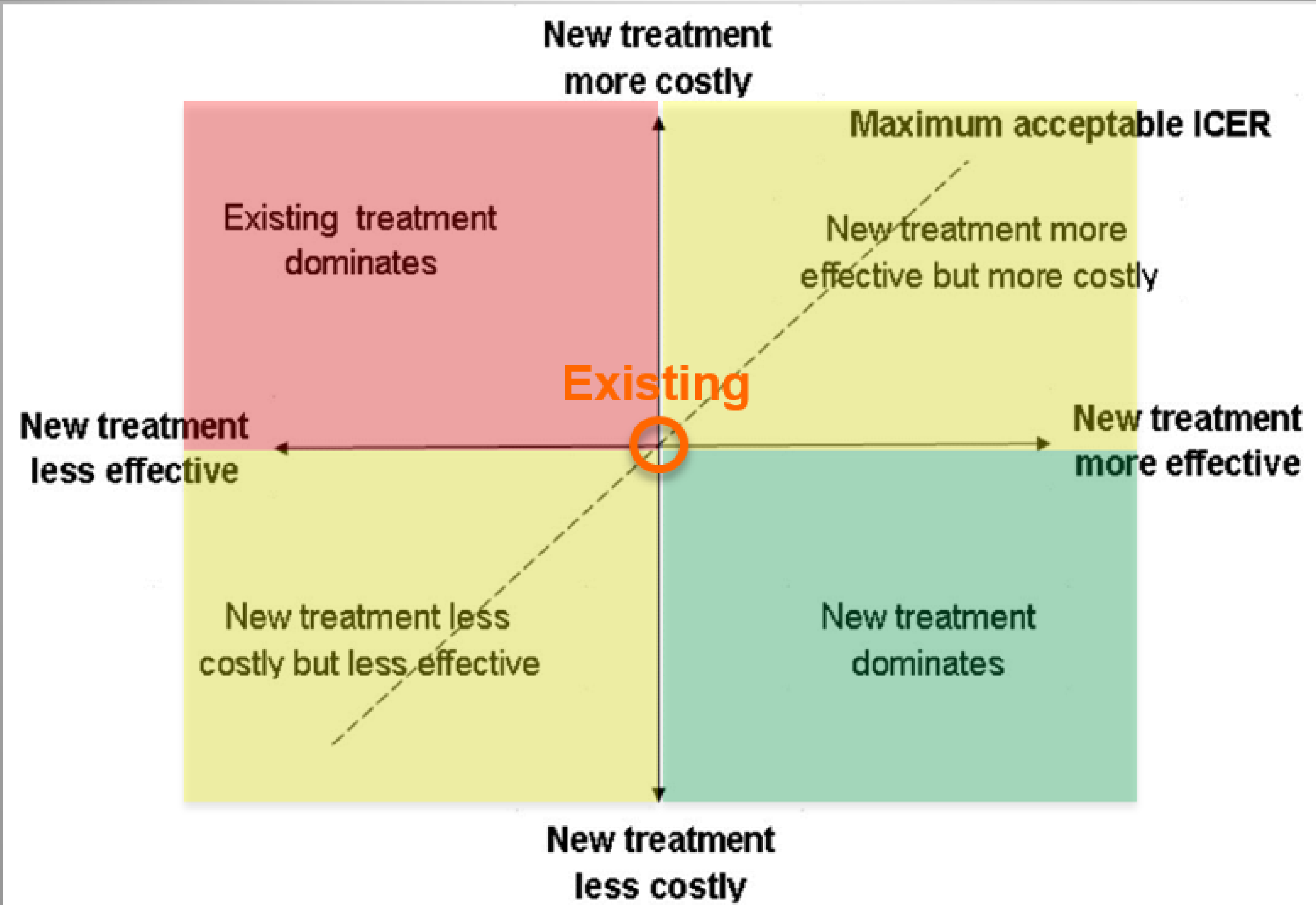
Utility Inputs

- Back Pain: **0.67,** Neck Pain: **0.62,** Back & Neck Pain: **0.62,** No Claim: **0.82**
- Utilities weighted for the expected time in each health state
- Willingness to pay $50,000 per Quality Adjusted Life Year (QALY)

Savings

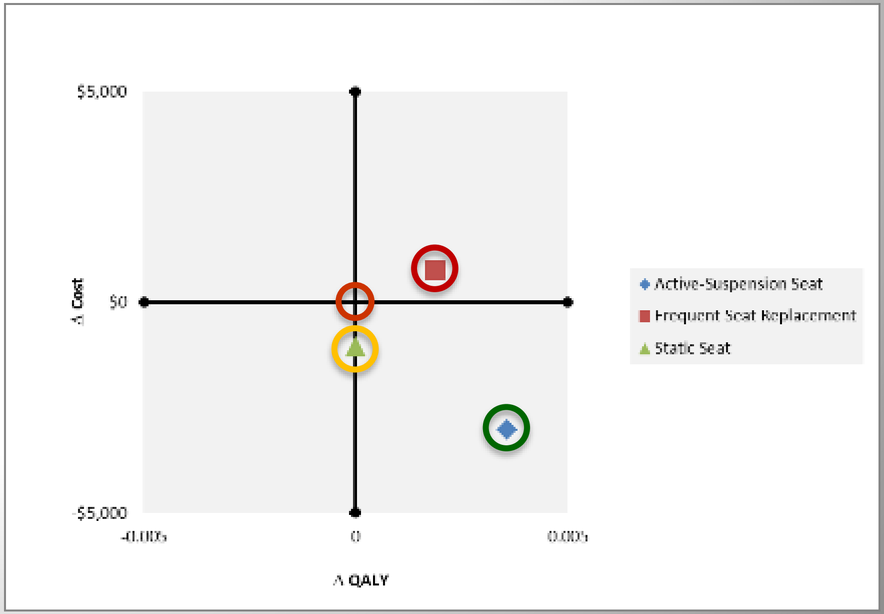
- Existing: **no savings**
- Static Seat: -**$650 maintenance years 5 and 10, no effect on "well" to "claim" states**
- Active-Suspension Seat: -**15% in transition probabilities from "well" to "claim" states**
- Seat Replacement every 5 years: -**5% in transition probabilities "well" to "claim" states**

Model Results



Model Results

	Amount per Bus over 15 Years			Cost for	
	Seat + Maint	Claims Costs	Total Costs	1500 Bus Fleet	(Cost) / Savings
Existing	$4,331	$28,168	$32,500	$48.7 M	
Static Seat	$2,982	$28,168	$31,150	$46.7 M	- $2.0 M
Active Seat	$5,221	$23,799	$29,300	$43.9 M	-$4.5 M
Seat Replacement	$7,312	$26,801	$34,113	$51.2 M	(+$2.5 M)



Results Summary

- Active-Suspension Seat **cost-effective**
  - Health benefits outweigh seat costs potential cost-savings of $4.5 million
  - Would be cost-effective down to a %5 reduction in WBV-related claims
- Static Seat **cost-effective**
  - Reduced maintenance costs save $2 million
  - Is unlikely to reduce claim rates
- Frequent Seat Replacement **not cost-effective**
  - Increased seat costs
  - Seat costs outweigh heath benefit cost $2.5 million

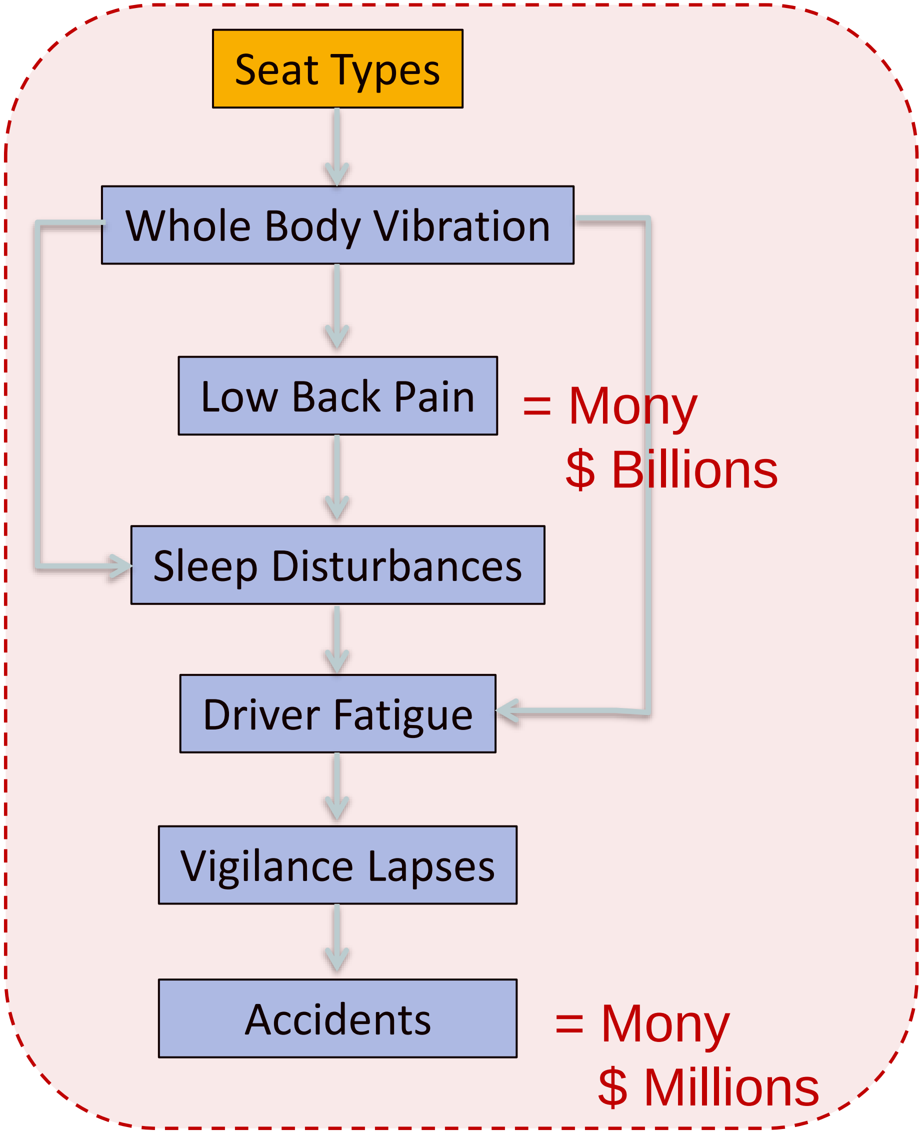
Safety & Trucking

Causality Map

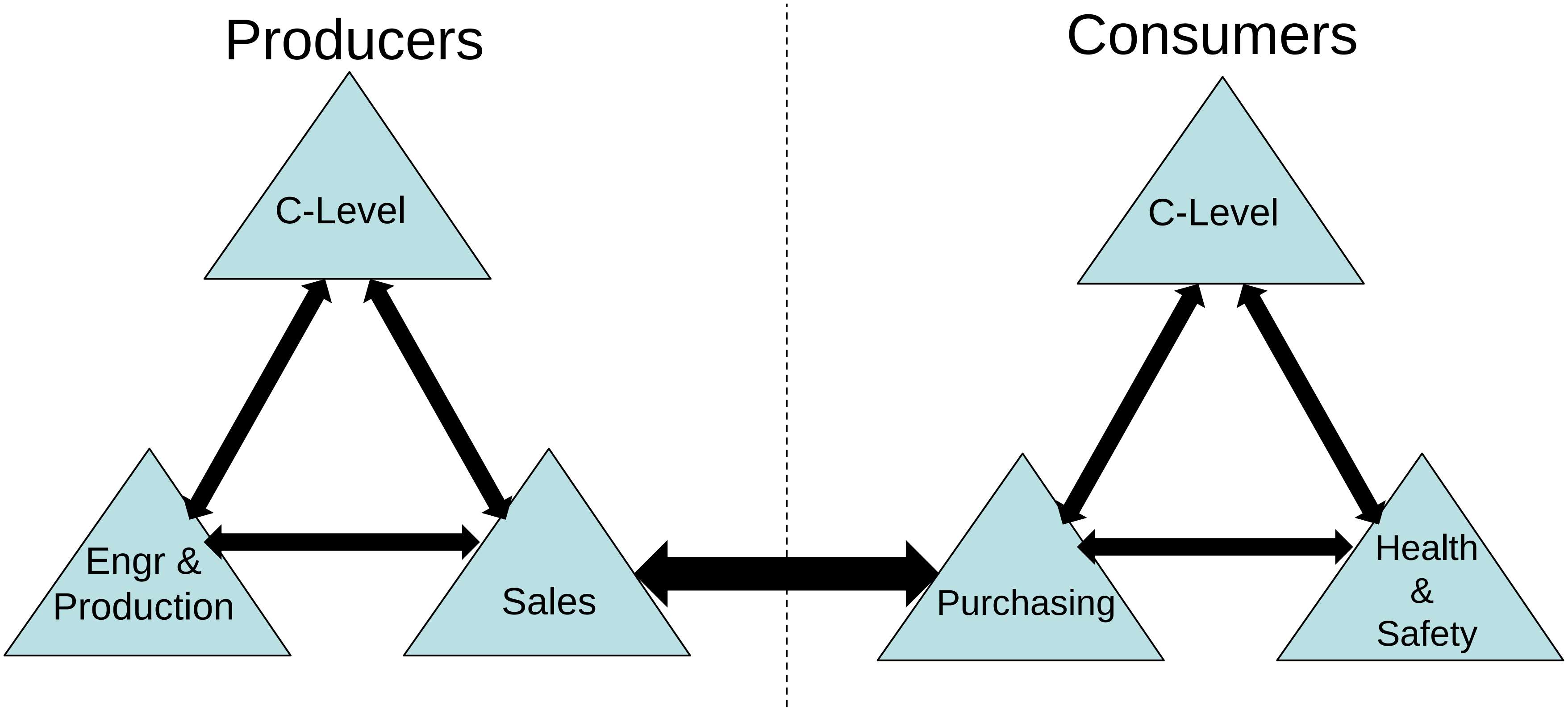
Ergo = Mony

Industry Standard Seat

Enhanced Seats

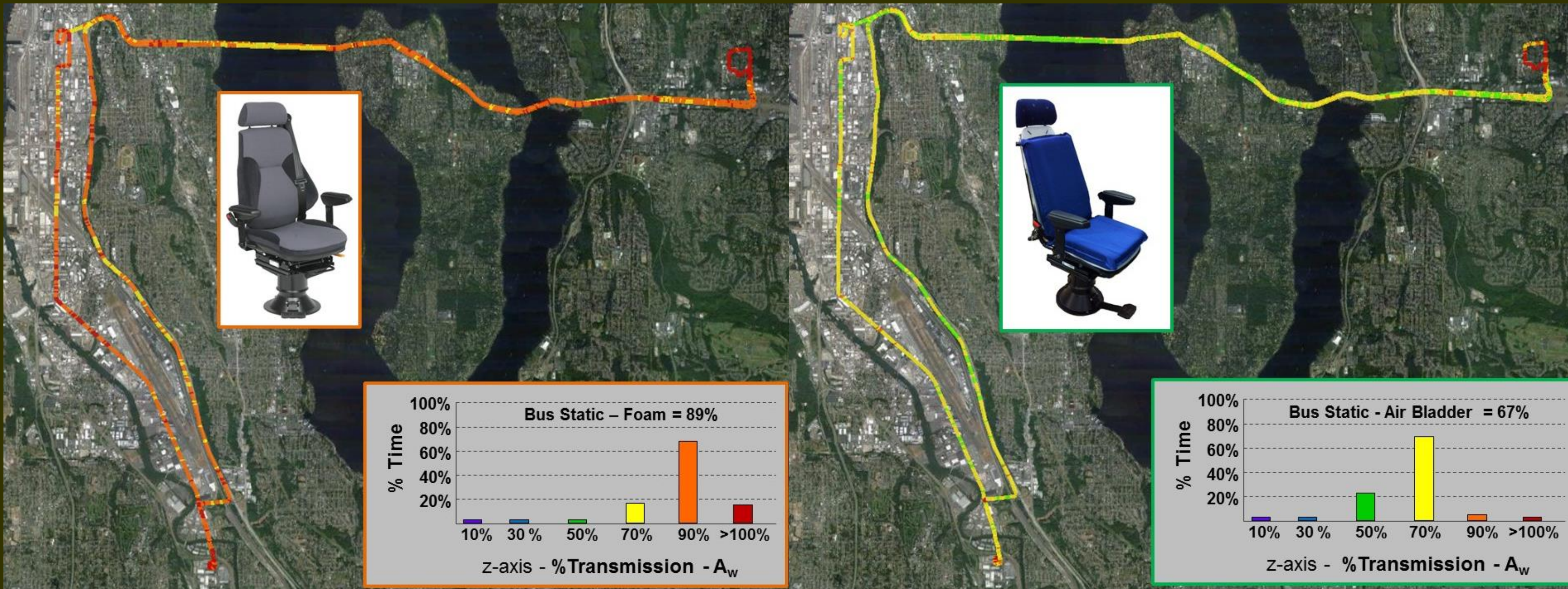


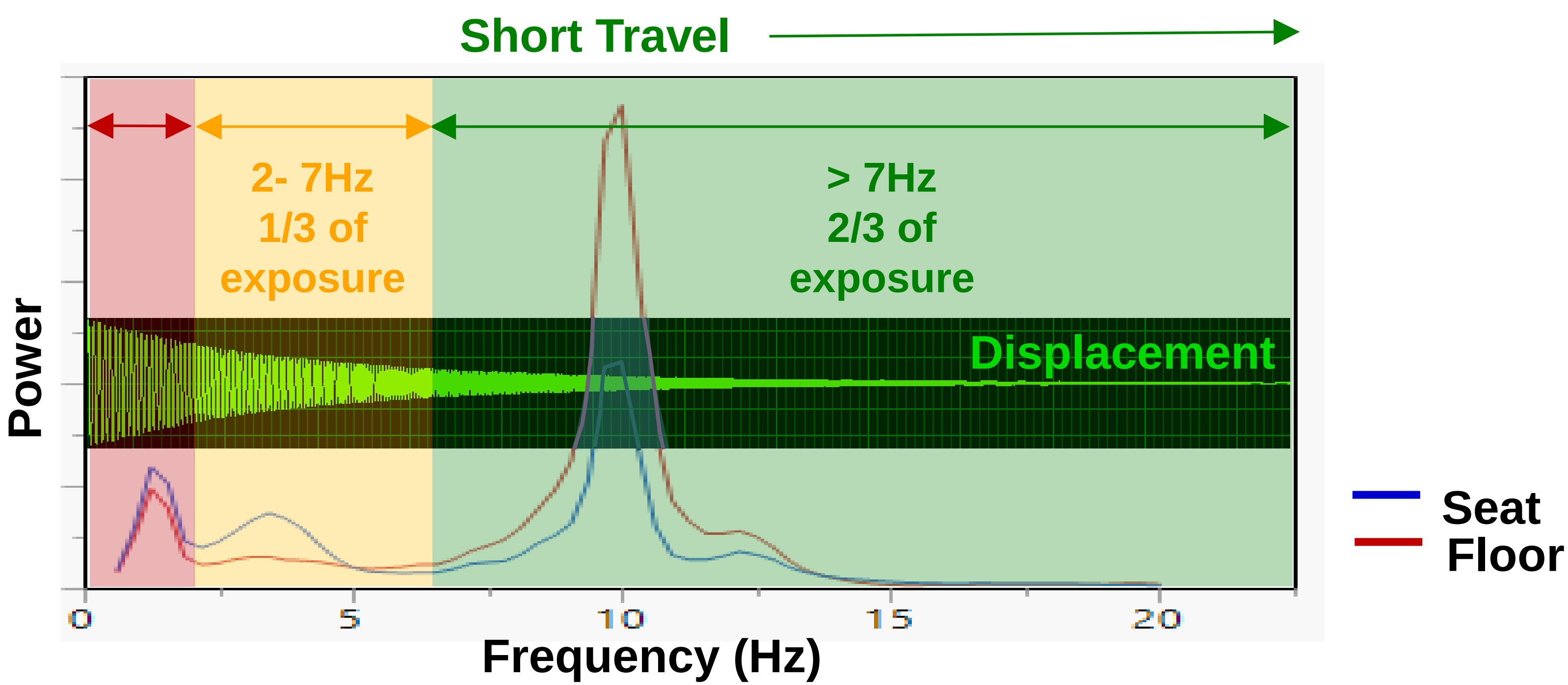
Social Procurement



Train Manufacturers to Produce and Consumers to Buy Quality Seats

Vibration Transmitted from Bus Floor to Seat of the operator



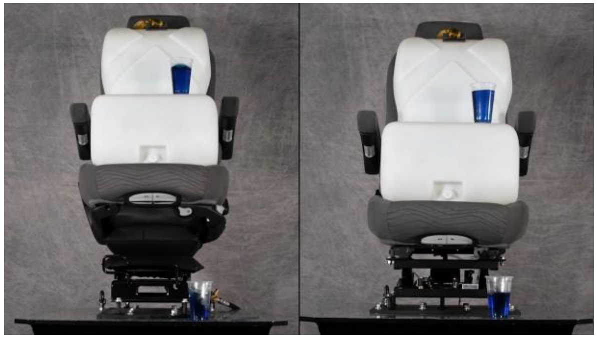


Suspension Systems Technologies

https://suspension-systems.com

Sine Sweep 16 to 6 Hz

Random On-Road Vibration



Rough Road Seat Comparison

Ergonomic and Research Consulting, Inc.

peterwj11@gmail.com

Take Home Messages

- The current, longer travel air-suspension seat may not be optimal and may not needed for on-road vehicles
- Higher performing active suspension seats are available to better protect vehicle operators
- New, higher performing passive suspension seats may be available in the future to better protect vehicle operators

UNIVERSITY of WASHINGTON