Oak Ridge National Laboratory:
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"Performance Measure for Monitoring and Improving Weigh-in-Motion (WIM) Devices"

Presented at:

NATMEC 2010 - Improving Traffic Data Collection, Analysis, and Use

Session: Weigh-in-Motion: Equipment, Experiences, Applications

June 23, 2010
10:30 am – 12:00 pm
Room: Willow A

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Sheraton Seattle Hotel, Seattle, WA
June 21-24, 2010

Today's Agenda

- **Introduction to ORNL Weigh-In-Motion (WIM) with respect to error reduction:**
  - Video of representative use of portable WIM in US Military
- **Dynamic Weighing**
  - What affects practical use of dynamic weighing?
  - State of the Art
  - Deductions affecting practical use
  - Physically, where does environmental error come from and how is it currently reduced?
- **Mathematical Techniques Used for Error Reduction in Dynamic Weighing**
  - Model of oscillation over time
  - Where does environmental error come from and how is it modeled?
- **Experimental Setup and Examples**
  - Systematic Bias / Least Squares Best Fit
  - Successively remove residual error due to oscillation and algorithm applied
  - Multiple runs of variety of different axle weights of vehicles
  - Average % error during mode removal versus vehicle speed
  - Total vehicle, mode removal results from F-250
- **Future and Conclusion**
  - Art of the Possible

ORNL WIM … Weighing a Stryker

Ft. Lewis, WA

Click on picture to view video in mpg format.

What affects practical uses of dynamic weighing?

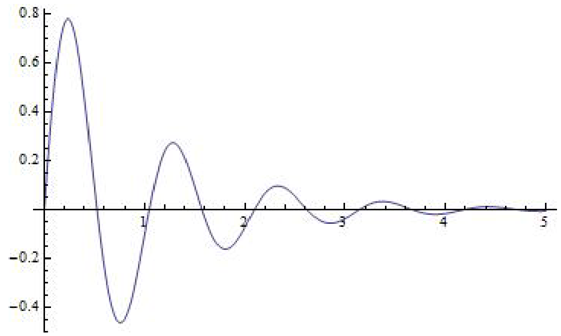
- **Characteristics of Device**
  - What are the true characteristics of the device under ideal conditions versus realistic conditions?
    - How precise is the device (answers repeatable from run to run)?
    - How accurate is the device compared to “ground truth”?
- **Operational Use of Device**
  - Is the device being used as it was intended?
    - Correct Setup?
    - Correct Speed of Vehicle?
- **Environmental Conditions where Dynamic Weighing Occurs**
  - How good is the road surface (approaches and exits)?
  - What is the condition of the vehicle being weighed?

State of the Art for Dynamic Weighing (from trade literature)

- **Accuracy figures for WIM systems (good or perfect approach and exit surface) are stated as follows:**
  - **approx. ± 25%: Simple piezo cable, max. 100 km/h (~62 mph), good surface.**
  - **approx. ± 15%: High-grade weight sensor in strip form, max. 100 km/h (~62 mph), good surface.**
  - **approx. ± 10%: Scales sensor in plate form, max. 100 km/h (~62 mph), very good surface.**
  - **approx. ± 5%: Scales sensor in plate form, max. 20 km/h (~12 mph), perfect surface.**
  - **approx. ± 1%: Axle weight scales with load cells, max. 5 km/h (~3 mph), perfect surface.**
- **Industry Comments:**
  - **On the one hand there are potential customers who require precision in the order of ± 1%, and that also at high speeds.**
  - **On the other hand there are frustrated users of WIM systems who consider the results achieved absolutely unusable.**

Physically, where does environmental error come from and how is it currently reduced?

- **Weight-measurement error arises from:**
  - Complex vehicle oscillations of a system of discrete masses (e.g., body, load, wheels) with spring interconnections (e.g., cab-load coupling, wheel suspensions) that are
  - Excited by aperiodic forces (e.g., uneven terrain, steering changes, acceleration, wind variability, load shifts, engine vibration), with
  - Nonlinear damping by slip-stick friction and shock absorbers.
- **Low frequency oscillations (1-5 Hz) arise from:**
  - Rocking (side-to-side/front-to-back),
  - Vertical bouncing,
  - Load-bed flexure,
  - Twisting about coupling points, and
  - Collective modes.



- **Higher-frequency oscillations (9-14 Hz) depend on vehicle size (e.g., tire rotation).**
- **Present reduction of oscillations is by:**
  - A smooth, flat, level approach/weighing/exit;
  - Constant, slow speed in a straight line;
  - Many measurements by several weigh pads; and
  - Continuous motion to avoid slip-stick variability.

Model of Vehicle Oscillations Over Time

- **Further reduction of WIM error requires analysis of the time-serial weight data for removal of these vehicle oscillations.**

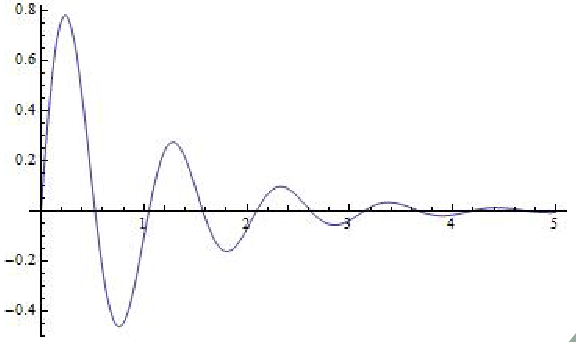
- **A model for the vehicle oscillations, $x(t)$, over time, t, uses a second-order, ordinary differential equation:**

$$m\frac{d^2x}{dt^2} + \gamma\frac{dx}{dt} + kx = F(t)$$

- **The variable m is the vehicle mass; γ is the damping coefficient; k is the spring constant for the vehicle suspension.**

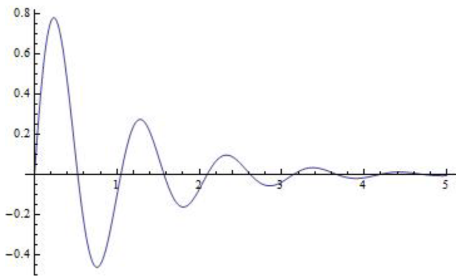
- **If $F(t)$ is a single impulse (e.g., bump in the road), then the solution to the differential equation is a decaying sine wave.**

- **More complex forcing functions will be decomposed as a superposition of decaying sine waves.**



Mathematically, where does environmental error come from and how is it modeled?

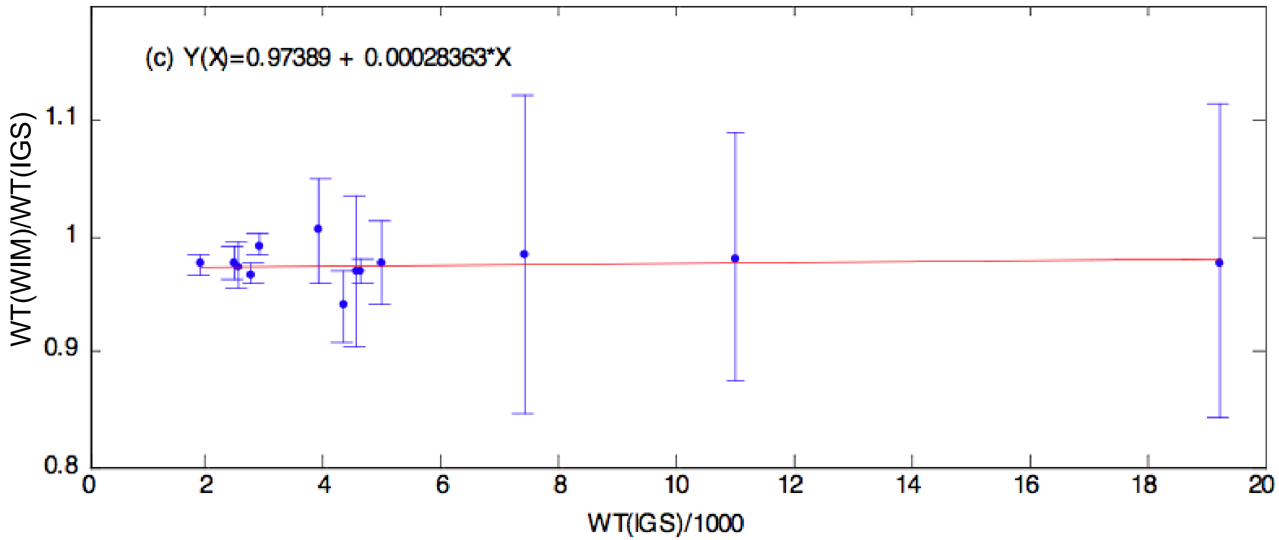
$$W(t) = w + \sum_j A_j \sin(\omega_j t + \varphi_j)\, e^{\alpha_j t}$$



- **Here, w is the filtered vehicle weight that WIM seeks to measure.**
- **Sinusoidal mode j is characterized by an**
  - **amplitude (A_j),**
  - **frequency (ω_j),**
  - **phase (φ_j), *and***
  - **exponential growth ($\alpha_j > 0$) *or decay* ($\alpha_j < 0$).**
- **The summation, Σ_j, is over all of the oscillatory modes.**

Systematic Bias / Least Squares Best Fit:
WIM Accuracy: WIM weights versus IGS weights

- **Systematic bias (~2.6% weighing light with a rise of 0.3%/1,000 lbs) of WIM generated weights when compared to same vehicle weighed via In-ground static scale.**
- **Calibration of the filtered-WIM values to the certified-IGS weights yielded excellent straight-line fits for total weights, single-axle weights (308 measured), and both (shown below).**
- **Weight range: ~2,000 – ~20,000 lbs with vehicles used (measurements): Chevrolet Silverado (72), GM H3 Hummer (70), Ford F-250 (64), and Freightliner Tractor (102).**



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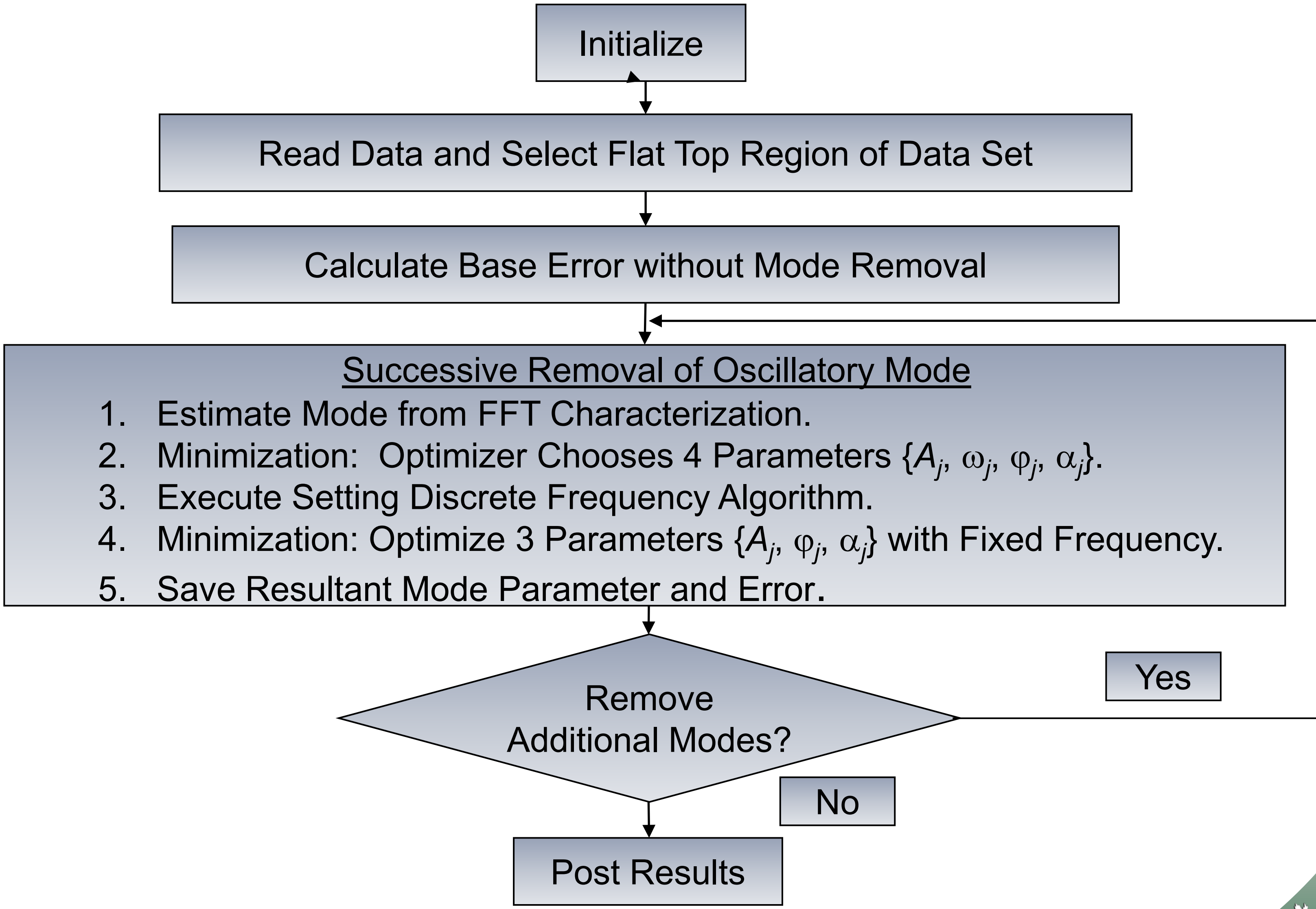
Successively Remove Residual Error Due to Oscillation



Example of Algorithm Applied:

Time-Serial weight measurement versus time: (a) raw data (blue line) with red best fit, (b, c, d, e) best fit after 1, 2, 3, and 52 modes.

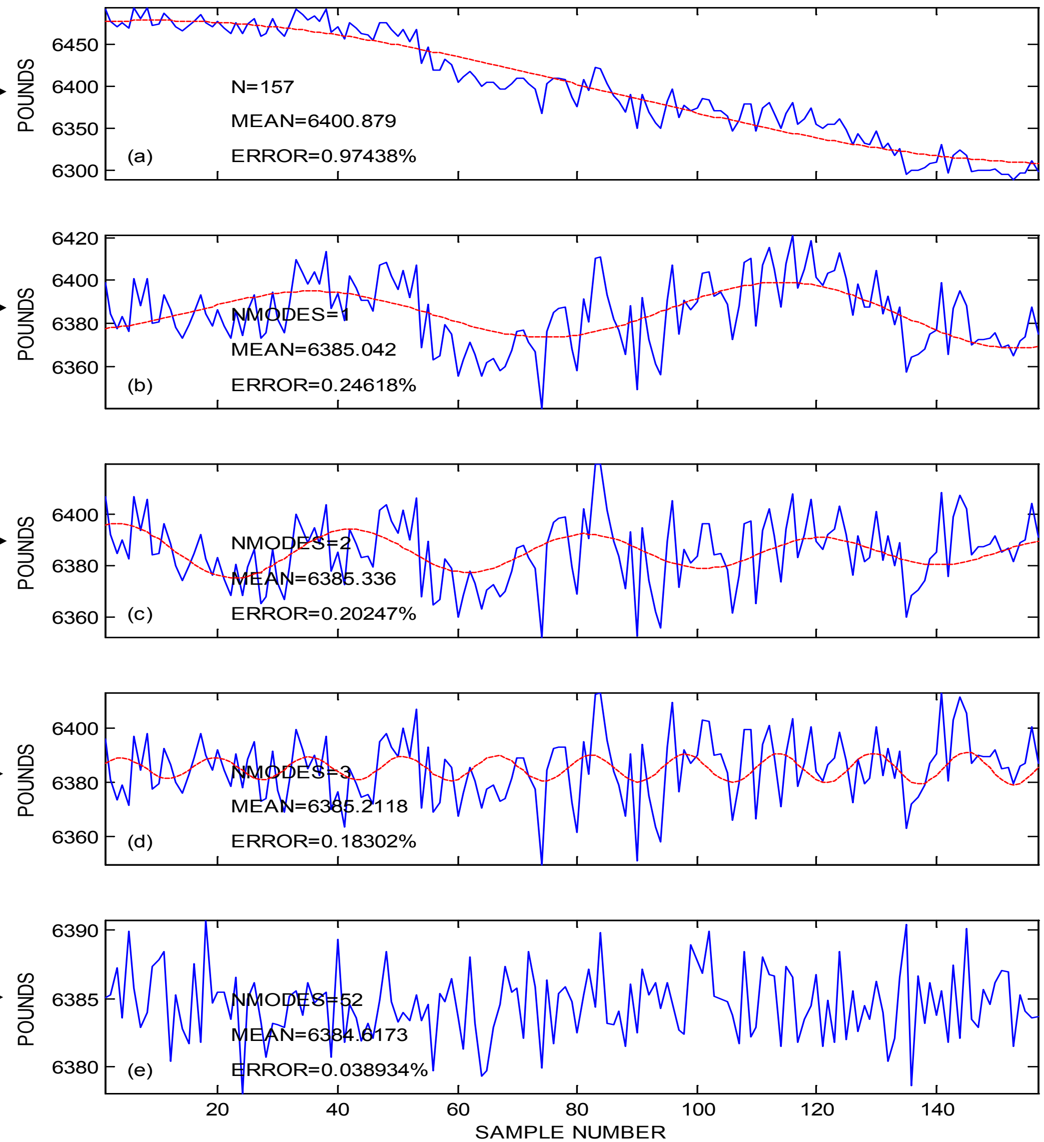
Sample: N = 157, σ = 62 lbs
Range: 6300-6500, 200 lbs
Mean 6,400 lbs., error = ±0.975%

(b) Mode = 1, σ = 16 lbs
Range: 6380-6400, 20 lbs
Mean 6,385 lbs., error = ±0.246%

(c) Mode = 2, σ = 13 lbs
Range: 6380-6400, 20 lbs
Mean 6,385 lbs., error = ±0.202%

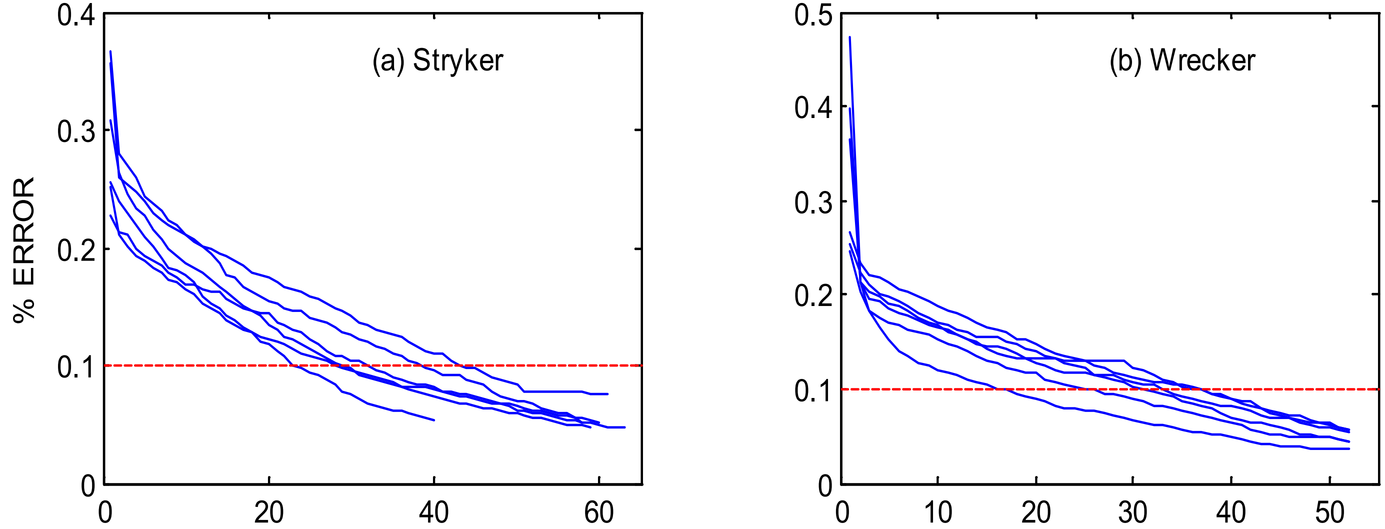
(d) Mode = 3, σ = 12 lbs
Range: 6380-6400, 20 lbs
Mean 6,385 lbs., error = ±0.183%

(e) Mode = 52 , σ = 2.5 lbs
Range: 6380-6400, 20 lbs
Mean 6,385 lbs., error = ±0.039%

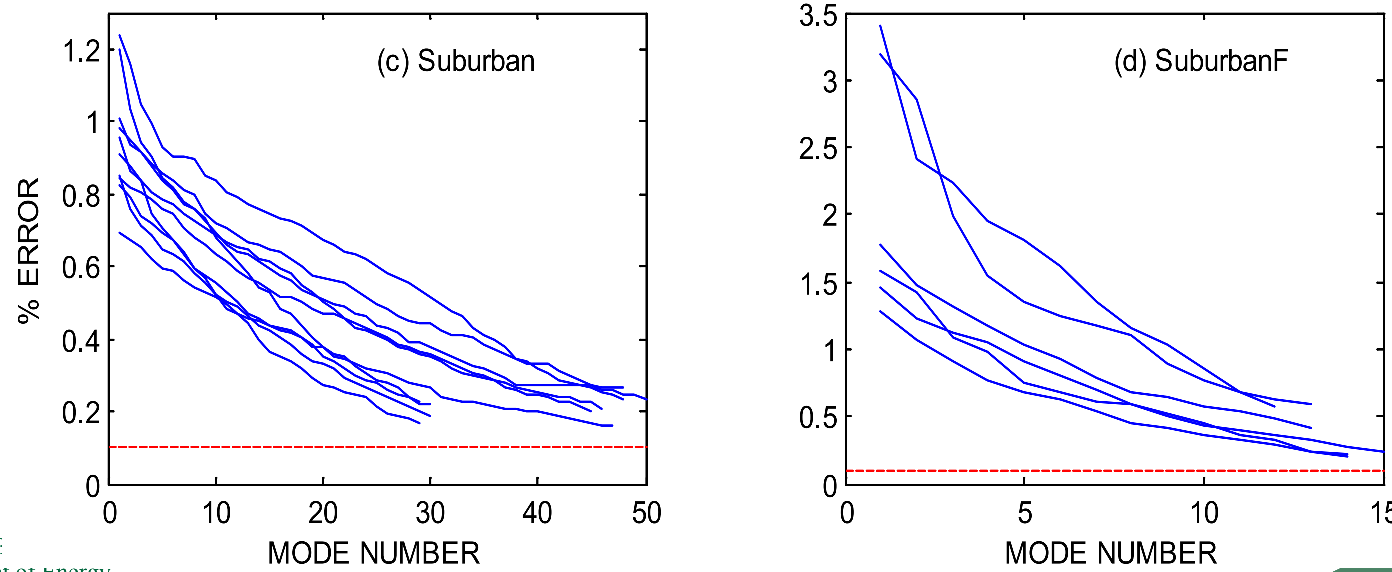


Multiple Runs from Variety of Vehicles

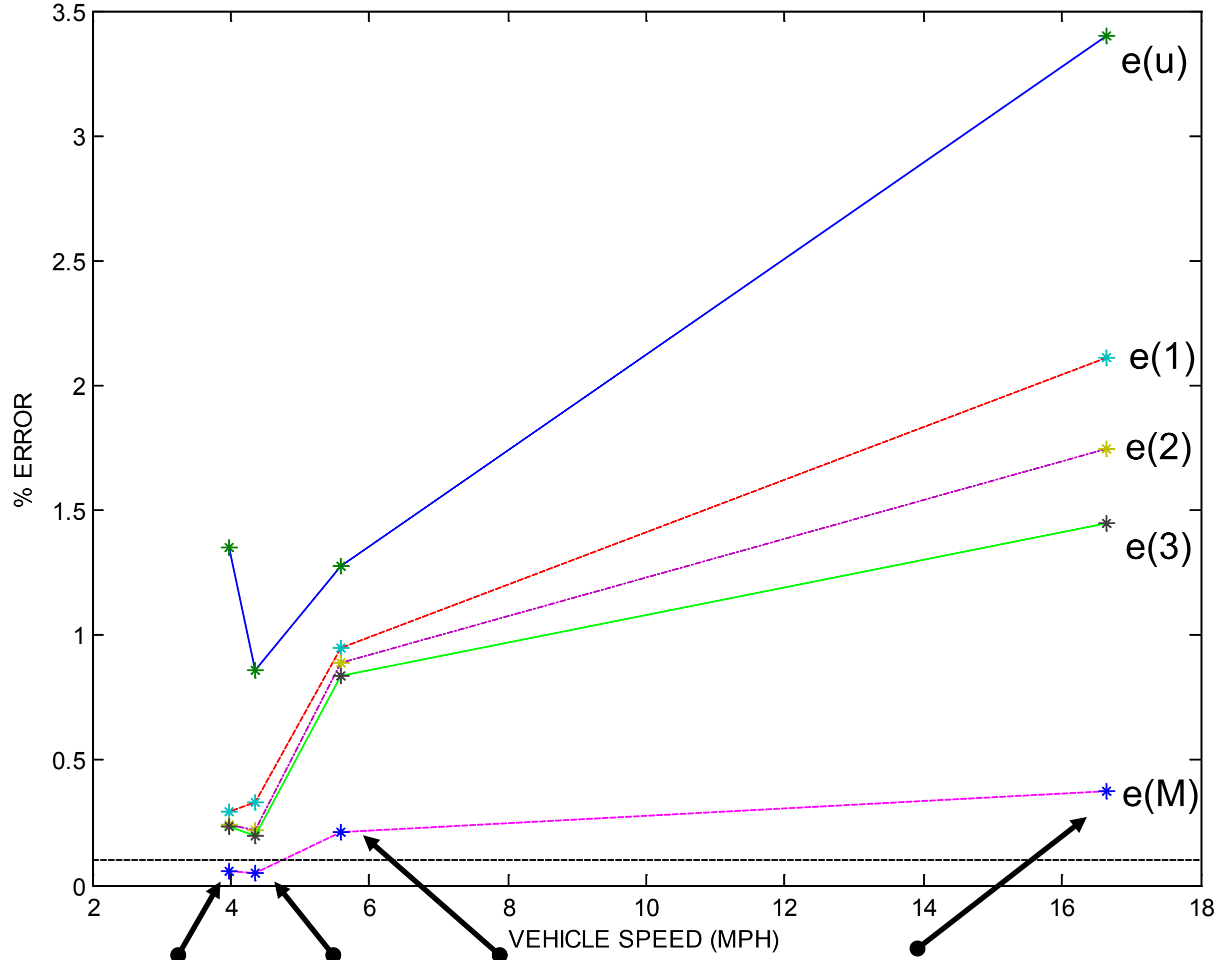
(Decrease in residual filtered WIM error)



Decrease in **residual (filtered) WIM error** versus mode number for each of the four vehicle series in comparison to the 0.1% error limit for certifiable weights (dashed red line): (a) Stryker armored vehicle, (b) military wrecker vehicle, (c) unloaded Suburban, and (d) Suburban with 200 pounds of load.



Average % Error During Mode Removal Versus Vehicle Speed



Vehicle	Stryker	Wrecker	Suburban	Suburban (F)
Average Speed (mph)	4	4.3	5.6	16.6
# of Total Mode removed (M) for each of 6 runs	40,58,59, 60,61,63	All 52	29,30,45,46,47,48	12,13,13,13,14,15

F-250 – Total Vehicle, Mode Removal Results

- **Table summarizes the results after application of the mode-filtering algorithm to these total-weight data, including the**
  - **unfiltered error, $e(u)$, and**
  - **filtered error, $e(min)$.**
- **These results are a substantial improvement over the previous results, namely:**
  - **all error values, $e(min)$, are well below 0.1% after mode removal;**
- **Consequently, the use of mode-filtering on the total weight data provides lower error (more precise).**

Run #	*Original % error* $e(u)$ %	*Mode % error* $e(\min)$ %
1	0.2199	0.0297
2	0.6109	0.0492
3	0.6580	0.0537
4	0.8496	0.0458
5	0.6226	0.0354
6	0.4773	0.0453
7	0.1439	0.0214
8	0.2426	0.0479
9	0.5013	0.0411
10	0.4303	0.0438
11	0.3411	0.0382
12	0.4404	0.0573
13	0.7406	0.0371
14	0.2528	0.0346
15	0.6265	0.0445
16	0.4022	0.0427
17	0.5088	0.0376
18	0.5655	0.0517
19	0.4377	0.0374
20	1.1327	0.0447
mean	0.5102	0.0420

Futures – What does the future hold?

- What if we could similarly reduce error in other types of:
  - Weighing devices (other types of scales), or
    - In-ground scales
    - Bridge Weigh-in-Motion (BWIM)
  - Conveyances
    - Planes
    - Light rail trains
    - Heavy rail trains

ORNL WIM … Weighing a Stryker
Static Scale Conversion to WIM

Click on picture to view video in mpg format.

ORNL WIM … Weighing Helicopters

Blackhawk Movie (Quick Time Movie) click on text

Conclusions

- **Mathematically, we have demonstrated that we can reduce error caused by environmental conditions:**
  - **Weight-measurement error arises from:**
    - **complex vehicle oscillations of a system of discrete masses (e.g., body, load, wheels) with spring interconnections (e.g., cab-load coupling, wheel suspensions) that are**
    - **excited by aperiodic forces (e.g., uneven terrain, steering changes, acceleration, wind variability, load shifts, engine vibration), with**
    - **nonlinear damping by slip-stick friction and shock absorbers.**
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    - **twisting about coupling points, and**
    - **collective modes.**
  - **Higher-frequency oscillations (9-14 Hz) depend on vehicle size (e.g., tire rotation).**

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Meeting the challenges of the 21st century

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