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BREAKTHROUGH ERROR REDUCTION IN PORTABLE, LOW-SPEED WEIGH-IN-MOTION (SUB-0.1 PERCENT ERROR)

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INTRODUCTION / OBJECTIVES

The measure of Weigh-In-Motion (WIM) performance is percent error, which is defined as, $e = 100\,\sigma/\overline{w}$. Here, $\overline{w}$ is the average vehicle weight and σ is the sample standard deviation in the weight measurement.

- Federal and state agencies need certifiable vehicle weights for various applications, such as highway inspections, border security, check points, and port entries.
- ORNL WIM technology was previously unable to provide certifiable weights, due to natural oscillations, such as vehicle bouncing and rocking.
- Recent ORNL work demonstrated a novel filter to remove these oscillations.
- This work shows further filtering improvements to enable certifiable weight measurements (error < 0.1%) for a higher traffic volume with less effort (elimination of redundant weighing).
- **Further reduction of WIM error (Figure 1) requires analysis of the time-serial weight data for removal of these vehicle oscillations.**

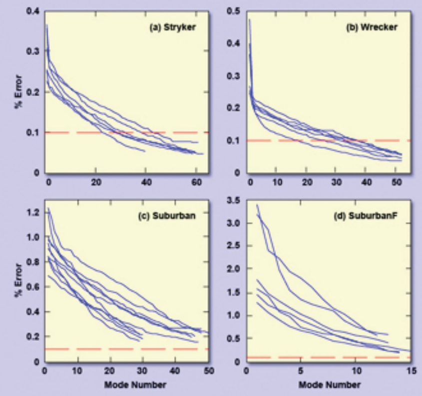

Figure 1. Decrease in residual (filtered) WIM error versus mode number for each of the four vehicle series in comparison to the 0.1% error limit for certifiable weights (dashed red line).

STATISTICAL/ANALYTICAL METHOD

Time-Serial Mode-Filtering Methodology for Error Reduction

The considerations of the introductory section lead to the conclusion that vehicle oscillations must be removed empirically to reduce measurement error. We have developed a novel error reduction methodology that removes the natural vehicle oscillations as follows:

- Characterize the time-serial WIM weigh measurement with respect to amplitude (*A*), frequency (ω_j), phase (φ_j) and exponential growth ($\alpha_j > 0$) and decay ($\alpha_j > 0$) of sinusoidal modes that contribute to oscillation error (Figure 2).
- Successively remove error due to oscillation (Figure 3).

Time-Serial WIM Weight Measurement

$$W(t) = w + \sum_j A_j \sin(\omega_j t + \varphi_j) e^{\alpha_j t} \quad \text{Eq 1}$$

$$w(t) = W(t) - \sum_j A_j \sin(\omega_j t + \varphi_j) e^{\alpha_j t} \quad \text{Eq 2}$$

$$w_i = W_i - \sum_j A_j \sin(i\omega_j + \varphi_j) e^{i\beta_j}, \text{ with } \beta_j = \alpha_j \Delta t \quad \text{Eq 3}$$

$$\overline{w} = (1/N) \sum_i w_i \quad \text{Eq 4}$$

$$\sigma = \sqrt{\sum_i (w_i - \overline{w})^2 / (N-1)} \quad \text{Eq 5}$$

$$e = 100\,\sigma/\overline{w} \quad \text{Eq 6}$$

Figure 2. Mode-filtering algorithm preparation.

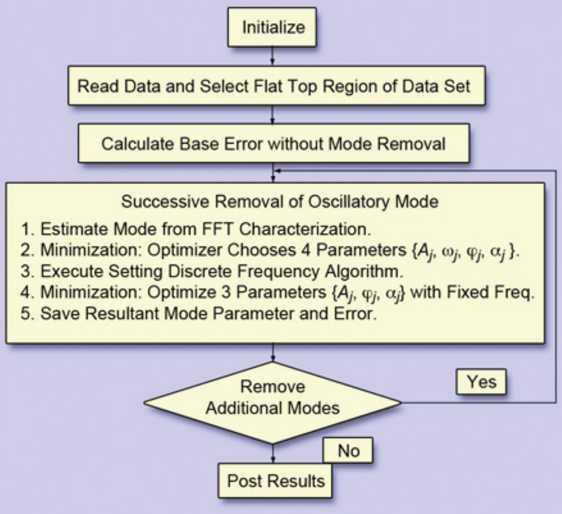

Figure 3. Mode-filtering algorithm.

RESULTS

1. The novel mode-filtering algorithm decreased error, attributable to natural oscillation, to < 0.1% in the *modified* Low-Error WIM System (Figure 4).
2. This was accomplished by successfully applying the time-serial mode-filtering algorithm to the time-serial WIM weight data set as illustrated in Figure 5.
3. A systematic calibration error in the current WIM weigh pads was exposed by statistically comparing the filtered-WIM measures to those of the certified In-Ground Scale (IGS) weighed statically.
4. Calibration of the filtered WIM values to the certified IGS weights yielded excellent straight-line fitting (Figure 6). The *modified* Low-Error WIM system supports the < 0.1% error, as well as the obvious safety and efficiency advantages.

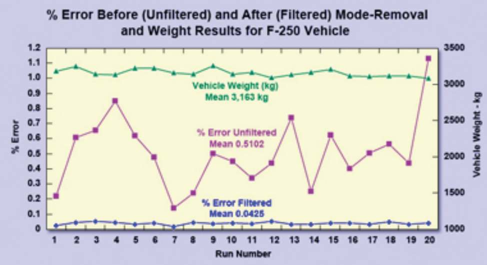

Figure 4. F-250 Weighings: percent error unfiltered and filtered.

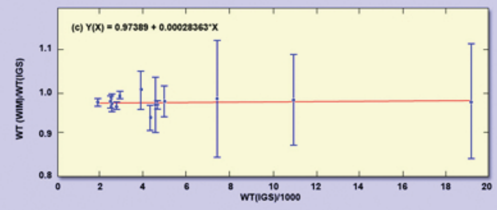

Figure 6. Least squares best fit Y = (WIM weight)/(IGS weight) showing WIM accuracy.

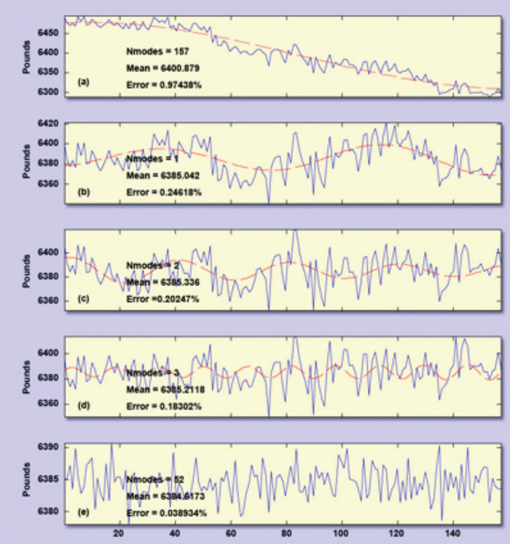

Figure 5. Time-serial weight measurement versus time: (a) raw data (blue line) with red best fit, (b, c, d, e) best fit after 1, 2, 3, and 52 modes.

CONCLUSIONS/ PERSPECTIVES/ ACKNOWLEDGEMENTS

1. Breakthrough findings were presented via significant modifications to the WIM system, so-called the *modified* Low-Error WIM. The revisions enable slow speed weight measurements at least as precise as in ground static scales, which are certified to 0.1% error.
2. Concomitant software and hardware revisions reflect a philosophical and practical change that enables an order of magnitude improvement from previous results to sub-0.1% error in low-speed weighing precsion. These revisions have been licensed and the next version will be commercially available for further testing within a year.
3. The *modified* Low-Error WIM also retains the efficiency and safety advantages inherent in all WIM systems.

This manuscript has been authored by UT-Battelle, LLC under contract DE-AC05-00OR22725 with the U.S. Department of Energy.