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




R.K. ABERCROMBIE[1] **L.M. HIVELY**[1] **M.B. SCUDIERE**[2] **F.T. SHELDON**[1]

Oak Ridge National Laboratory (ORNL)
Computational Sciences and Engineering Division[1]
Engineering Science and Technology Division[2]
Oak Ridge, TN USA

Abstract

We present breakthrough findings via significant modifications to the Weigh-in-Motion (WIM) Gen II approach, so-called the *modified* Gen II. The revisions enable slow speed weight measurements at least as precise as in ground static scales, which are certified to 0.1% error. Concomitant software and hardware revisions reflect a philosophical and practical change that enables an *order of magnitude improvement* to sub-0.1% error in low-speed weighing precision. This error reduction breakthrough is presented within the context of the complete host of commercial and governmental application rationale including the flexibility to extend information and communication technology for future needs.

Keywords: Portable Weigh-in-Motion, Vehicle Oscillation Error Characterization, Time-serial Error Filtration, WIM Data Management Methodology.

Résumé

Dans cet article, nous présentons des résultats originaux au sujet de modifications importantes à l'approche WIM Gen II (WIM: Weigh-in-Motion, soit Poids en Mouvement). Les révisions à notre approche nous permettent de mesurer le poids des véhicules a basse vitesse, avec une précision comparable a celle des véhicules immobiles, soit à 0.1 % du poids effectif. Nous avons effectue des révisions simultanés au matériel et au logiciel pour refléter des changements philosophiques et pratiques qui nous permettent une amélioration considérable dans la précision du poids a basse vitesse. Cette avancée dans la réduction de l'erreur est présentée dans le contexte de la logique d'application commerciale et gouvernementale, qui inclut la flexibilité d'étendre la technologie de l'information et de la communication pour satisfaire de nouveaux besoins.

Mots-clés: Pesage en Mouvement, Caractérisation de l'erreur d'oscillation du véhicule, filtration de l'erreur de séries temporelles, méthodologie de gestion des données du pesage en mouvement.

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1. System Rationale

Vehicle characterization (e.g., weight, and volume) has obvious use for highway inspections, compliance checkpoints, safety, and security. Another use is accurate load planning. We describe a durable, accurate, portable, quickly assembled system for these purposes.

1.1 System Overview

The portable, low-speed Gen II system automatically acquires various data from a moving vehicle and its cargo: weight on each tire and axle; total weight; axle spacing; longitudinal and transverse center of balance. The system estimates vehicle volume (length, width, and height) from two digital camera images. The system identifies the vehicle via radio-frequency ID tags, barcodes, or manual entry. Data is managed via a Pocket PC/WiFi-enabled PDA or cell phone and/or XP-Windows ruggedized tablet with a secure infrastructure and data repository. The system works on smooth asphalt or concrete with no more than 2 degrees of longitudinal or transverse slope. The system's total weight is 2200 pounds (1000 kg) crated in a ruggedized box. The physical, electrical and software interfaces tolerate severe weather and human error.

1.2 Durability

The system durability was shown over a 2-year period. Transducer pads are warranted for 10 years (not including electronics). Load cells (embedded in the transducer pads) are warranted for 5 years (including electronics). Leveling, spacing and ramp pads are warranted for 10 years. Data/power cables are warranted for 5 years. The host computer with power supplies and access point has a 1-year warranty. We subsequently used a commercially-hardened computer with a 3-year warranty. Three pads (out of eighty-eight) exhibited problems on arrival at field sites, two of which were returned and retested as OK. One crated system at a site was flooded and stored outside for 3 months in standing water, causing one inoperable pad. The system requires the same number of interconnecting cables as transducer pads, plus the host computer connection. Only one out of 100 cables failed. No other failures occurred.

1.3 Time and Motion Efficiency

The Gen II system can weight low-speed (3-5 mph) vehicles at >4/minute. System assembly requires two workers; one person is needed for operation (two are recommended). Table 1 compares the performance of different weighing methods (Abercrombie, et. al, 2005).

Table 1 – Time and Motion Study Efficiencies of Military Weighing/Measuring Process

Weighing and Measuring Techniques	Min : Sec (w/ marking)	Min : Sec (no marking)	Personnel Required	% of Data w/ human error
Static Scale/ Tape Measure	7:38	4:48	3	9%
Wheel-Weight Scales/ Tape Meas.	7:46	4:52	7	14%
Gen II System	3:03	0:13	2	None found

Table 2 shows that the WIM Gen II efficiency advantages are offset by excessive error in weight measurements, in comparison to In-Ground Static (IGS) scales and portable wheel-weight scales (Abercrombie, et. al., 2007). The measure of 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. Dynamic-mode measurements in Table 2 were obtained from one, two, and three left-right pairs of weigh-pad combinations. The larger, stop-and-go weight errors arise from weight shifts among the axles from erratic slip-stick behavior in the suspension as the vehicle is driven onto the scale and stopped (Scheuter, 1998). These results show that: (1) the Gen II single-axle weight error was less than IGS error, (2) the WIM system cuts time-consuming manual procedures, human errors, and safety concerns, and (3) weight error for the Gen II system was <1%. The Gen II system determines center of balance with comparable precision to that of the traditional manual methods. Further tests (October 3-6, 2006) showed a percent error of ≥0.5% (Table 3), as a baseline for further error reduction.

Table 2 – Percent Error in Weight Measurements: Gen II versus IGS Scale

Measurement	IGS Scale	Gen II System Configurations and Modes			
		2-pad Dynamic	4-pad Dynamic	6-pad Dynamic	Stop-and-Go
Total Vehicle Weight	0.04%	0.51%	0.37%	0.37%	0.55%
Single-Axle Weight	0.86%	0.77%	0.50%	0.47%	0.62%
Center of Balance	NA	1.57% (3.99 cm)	2.31% (5.18 cm)	0.50% (1.12 cm)	0.40% (0.86 cm)

Note: 5 vehicles in 7 configurations (each configuration weighed 4 times) – weights between 2,540 and 23,360 kg. All the tests were performed on smooth, dry, level, concrete surfaces. Tests under non-ideal surface conditions are needed (e.g., rough but level) to show comparable performance assuming no subsurface deformation occurs (Scheuter, 1997). The stop-and-go mode under non-ideal surface conditions is recommended.

Table 3 – Representative Total Weight Measurement Percent Error Across 2-6 Pad Systems

Vehicle (Axle : Model)	Avg. Total Weight kg	2 Pads	4 Pads	6 Pads
2 Axle – Suburban	2,449	0.58	0.34	0.28
4 Axle – HEMTT Wrecker	23,294	0.46	0.35	0.31
4 Axle – Stryker	20,047	0.97	0.62	0.53
5 Axle –Tractor Trailer w/ load	28,184	0.45	0.41	0.49
6 Axle – Flatbed	21,023	0.96	0.83	0.83
WIM Average (all vehicle classes)		0.69	0.53	0.51

Note: Each cell averages over 20 runs. Vehicle weights range from 2,268 to 28,575 kg.

1.4 Volumetric Measurement from Digital Images

The Gen II system obtains vehicle volume from two orthogonal images (i.e., a side-view and a front/back view), called Cube, which receives the digital images; extracts, organizes, and displays the object features; obtains the three-dimensional measurements; and determines the vehicle volume. Cube measurements are as accurate as manual methods (tape measure and measuring sticks). Cube images are useful for very large and non-standard vehicles.

2. Characterization of Error in Weight Measurements

Weight-measurement error arises from complex vehicle oscillations of (i) a system of discrete masses (e.g., body, load, wheels) with (ii) spring interconnections (e.g., cab-load coupling, wheel suspensions) that are (iii) excited by aperiodic forces (e.g., uneven terrain, steering changes, acceleration, wind variability, load shifts, engine vibration) with (iv) 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) a smooth, flat, level approach/weighing/exit; (b) constant, slow speed in a straight line; (c) many measurements by several weigh pads; and (d) continuous motion to avoid slip-stick variability.

Section 3.1 discusses training experiments toward achieving our goal of <0.1% error via mode- filtering of the time-serial data to remove vehicle oscillations. Section 3.2 describes the test experiments that confirmed achievement of the 0.1% goal.

2.1 Time Serial Mode-Filtering Methodology for Error Reduction

The considerations of the previous 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 from W_i to obtain filtered weight values w_i, which takes the form $w_i = W_i - \varepsilon_i$. Where, ε_i is the term that describes the oscillations as the summation term in right hand side of Equation 1. Consequently, the error reduction filtering decomposes the time-serial weight measurement, $W(t)$, into the form:

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

Here, w is the filtered vehicle weight. The j^{th} sinusoidal mode has an amplitude (A_j), frequency (ω_j), and phase (φ_j). The summation, Σ_j, is over all oscillatory modes. The data have both exponential growth ($\alpha_j > 0$) and decay ($\alpha_j < 0$), which is modeled by the term, $e^{\alpha_j t}$. Re-arrangement of Equation (1) extracts the filtered weight:

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

The left-hand side of Equation (2), $w(t)$, explicitly depends on time. Indeed, the results of Section 3 show that the filtered weight is a function of time, even after removal of many oscillatory modes. Time-serial measurements, $W(t)$, were obtained at a sampling rate of 1 KHz as vehicles traversed the two-foot-long weigh pads. Minimal transients in the weight data occur in the central (one foot) section of the weigh pad, corresponding to a "flat-top" interval that was used for the weight-determination analysis. The flat-top region was traversed in less than 200 milliseconds, allowing acquisition of many cycles of the fast dynamics and less than one cycle of the slow oscillations. The values of $W(t)$ are available only at discrete time values, $W(t) = W(i\Delta t) \equiv W_i$. The corresponding discrete form for the filtered weight values $w(t) = w(i\Delta t) \equiv w_i$. The discretized form of Equation (2) then becomes:

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

Equations (1) − (3) are a finite-Fourier decomposition of the vehicle oscillations for discrete frequencies, $\omega_j = j\pi/2N$. Here, N denotes the number of data points in the flat-top region. Very short flat-top intervals ($N < 10$) are ignored in this analysis. The average vehicle weight is:

$$\overline{w} = (1/N) \sum_i w_i \ . \tag{4}$$

The corresponding sample standard deviation, σ, in the weight is given by:

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

The summations in these equations are from i=1 to N (the number of points in the flat top region). The resultant percent error, e, in the vehicle weight is:

$$e = 100\,\sigma/\overline{w} . \tag{6}$$

Equations (4) – (6) apply with or without the removal of oscillation modes in Equation (3).

3. Discussion of Experiments and Activities

The experimental test protocol involved: 1) Weigh the vehicle on a certified IGS scale; 2) Weigh the vehicle dynamically via the *modified* Gen II system; 3) Repeat step 2 three to seven times for each vehicle; 4) Weigh the vehicle on a certified IGS scale; and 5) Repeat steps 1-4 for each of several vehicles. Steps 1 and 4 provide two identical and independent weight measurements from the IGS scale for each vehicle. Steps 2 and 3 provide several identical and independent weigh-in-motion measurements for the same vehicle. This protocol allows a statistical comparison of the mode-filtered Gen II system weights to the IGS scale, which is accurate to 0.1% for total weight only. This protocol allows calibration of the mode-filtered WIM weight to for example, certified IGS scale measurements in the future according to the International Recommendation OIML R 134-1 Edition 2003 (E).

3.1 Training Data Experiments

An initial error-reduction approach was developed and tested on twenty-eight (28) time-serial "training" data sets that included measurements of two heavy and two light vehicles. The mode-filtering algorithm (Section 2.1) was subsequently applied to many more "test" data sets for a realistic demonstration of error reduction using the above experimental protocol. These training datasets were obtained during field tests at Fort Lewis October 3-6, 2006. Two military vehicles were each weighed six times: a Stryker armored vehicle (total weight 20,047 kg) and a military wrecker (total weight 23,294 kg). A civilian station-wagon-class vehicle (Chevrolet Suburban) was also weighed ten times without a load and again six times with a 90.7 kg load. All four data sets were analyzed as part of the methodological "training" set to provide a robust filtering algorithm to reduce measurement error. Filtering results in the removal of multiple (M) error modes using amplitude (A_j), frequency (ω_j/ω_f), phase (φ_j), growth/decay rate (α_j), and residual error (e) thresholds (as defined in Section 2.1) for each mode. For example, the Stryker series had average errors of 1.355%, 0.227%, 0.214%, 0.201%, and 0.047% for removal of zero, one, two, three, and M (=52) modes, respectively. These results clearly showed that high-order mode-filtering reduces the error below the 0.1% level for slow-speed vehicle-weight measurements (with an average residual error of 0.045%).

Test data were obtained at ORNL's National Transportation Research Center on May 8-10, 2007. Four vehicles were weighed: Ford F-250, Freight Liner truck, General Motors H3 Hummer, and Chevrolet Silverado. Weights were obtained from two pads (one pair) that simultaneously measured the left- and right-side tires as the vehicle was driven slowly over the *modified* Gen II system. The single-pad weight varied from 400 kg (Silverado) to 2,500 kg (Freightliner). Table 4 summarizes the results. The "IGS Total" shows variability (range/average) up to 4.54 kg /2107 kg (0.215%) for the Silverado total weight, which is more than twice the certified IGS error of 0.1% for total weight only. The "WIM Total" row shows the filtered Gen II results: mean weight and standard deviation (in parentheses). The last row shows the number of filtered-WIM values that have an error below 0.1%; the total rate of sub-0.1%-errors is 266/308 or 86%. Clearly, the error (*e*) quantifies the precision of the WIM weight (from the Gen II *modified* system), while accuracy corresponds to the difference between the IGS and filtered-WIM values.

Table 4 – Data Characterization (ranges given for IGS row) and Error-Reduction Results

Axle & Total Value		**F-250**	**Freight Liner**	**Hummer H3**	**Silverado**
IGS	**Axle-1** kg	2050 2037	5008 4971	1143 1139	1261 1256
	Axle-2 kg	1311 1320	1950 1973	1107 1157	848 848
	Axle-3 kg	N/A	1769 1783	N/A	N/A
	Total kg	3361 3357	8727 8727	2250 2250	2109 2105
WIM	**Axle-1** kg	1985 (29)	4894 (49)	1110 (9)	1308 (5)
	Axle-2 kg	1301 (5)	1842 (14)	1081 (7)	827 (4)
	Axle-3 kg	N/A	1784 (20)		
	Total kg	3304 (62)	8534 (62)	2195 (16)	2042 (5)
***e* < 0.1%**		61/64 = 95%	86/102 = 84%	54/70 = 77%	65/72 = 90%

Note: IGS rows give weight ranges and WIM rows give weight and standard deviation.

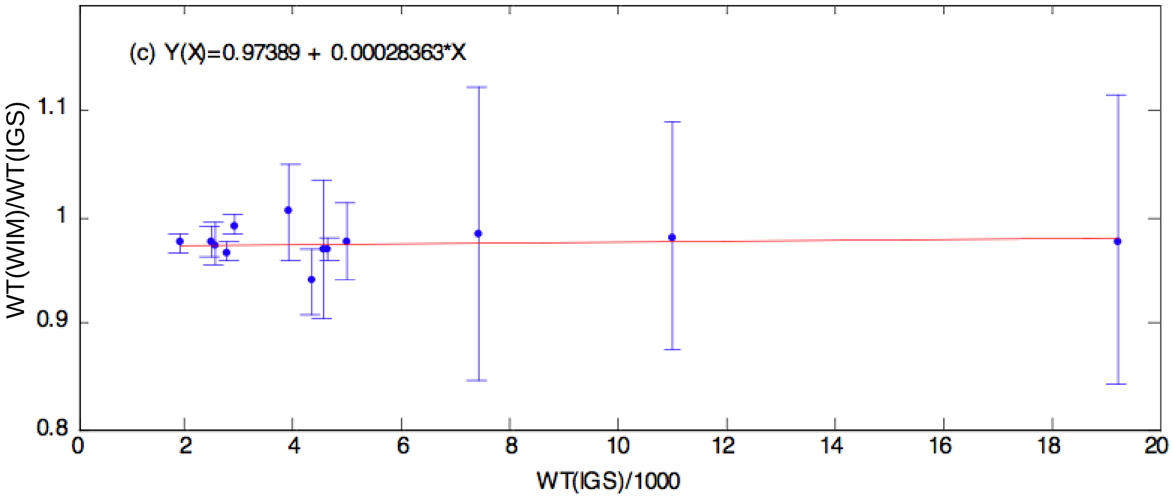

Figure 1 - Least squares best fit Y = (WIM weight)/(IGS weight) showing WIM accuracy

Figure 1 provides a least squares fit of the weight for all four vehicles and yields an excellent straight line. The combined total and single axle weights line is Y(X) = 0.97389 + 0.00028X which shows WIM values are low by 2.1% (~0.02 below Y(X) = 1 line). This form of filtered-WIM weight calibration against the IGS measurement is simple and computationally fast.

3.2 IGS Scale Conversion to WIM

An IGS scale at Fort Lewis, WA, was converted to enable the weighing of vehicles as they are driven across the weighing platform. This conversion provides weigh-in-motion functionality without interfering with the scale's ability to weigh vehicles in static mode (i.e., parked on the scale). The IGS scale weighing accuracy and precision is specified as ±0.1% and 9kg, respectively. The weigh-in-motion (WIM) measurements from testing conducted during October 2006 showed accuracy and resolution similar to the static scale measurements, ±0.5% and 9kg, respectively. The weigh-in-motion functionality provides a significant amount of measurement automation thereby reducing the time required to measure axle weights from several minutes to less than one minute as well as making it possible to record the weights directly to an electronic load-planning database.

3.3 Experimental Protocol and Mode Filtering Results

A new set of time-serial measurements were acquired on September 17, 2007 at ORNL's National Transportation Research Center to validate the mode-filtering technique. This experiment involved the same test protocol as the previous "test" sets with in-ground scale measurements after every 3 to 7 WIM crossings (totaling eight IGS measurements), which explain the non-sequential set numbering in Table 5 which is illustrated in Figure 2. The experiment used two 16-channel data acquisition systems (DASs) to acquire time-serial weights simultaneously from both the front and back axles of three vehicles (Ford F-250, Hummer H3, and Caravan) at a sampling rate of 4 kHz. Pad spacing was adjusted to equal vehicle axle spacing, thus providing complete *and* simultaneous acquisition of total vehicle weight. The front and back axle weight data can be summed to obtain total-vehicle weight versus time, thus implicitly removing side-to-side rocking, front-to-back rocking and vertical bouncing prior to the application of the mode-filtering algorithm. Use of a 16-channel DAS/axle did not allow sufficiently accurate synchronization between both axles to obtain total weight directly. Consequently, the time lag between the front and rear weight data was varied to find the minimum sample standard deviation in the total weight and effectively synchronize the data. The sampling procedure is not needed when the electronics guarantee all weigh pad pairs that suspend each axle are synchronized.

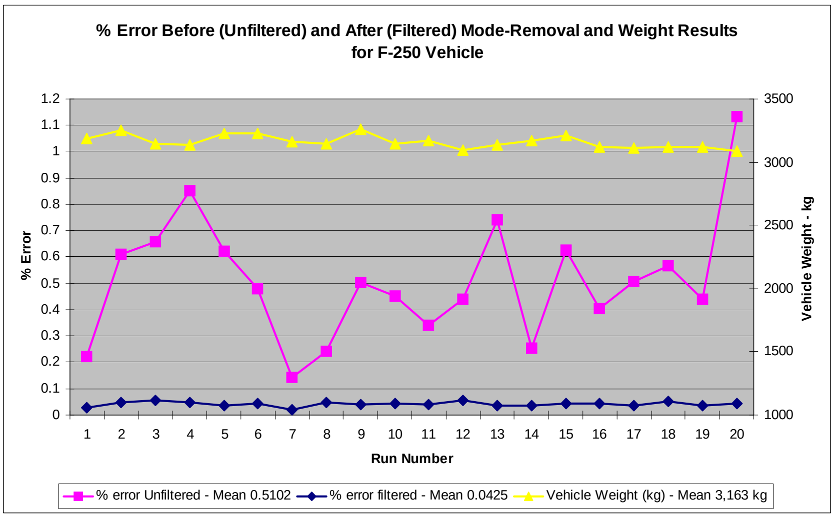

Figure 2 - F-250 Weighings: Percent Error Unfiltered and Filtered

Table 5 – F-250 Vehicle Weight and Error Data (see Figure 2)

Set #	**% error *e*(unfltrd)**	**% error *e*(fltrd)**	$\overline{w}$ **kg**
01	0.2199	0.0297	3190
04	0.6109	0.0492	3254
05	0.6580	0.0537	3145
06	0.8496	0.0458	3137
07	0.6226	0.0354	3224
08	0.4773	0.0453	3228
11	0.1439	0.0214	3163
15	0.2426	0.0479	3146
17	0.5013	0.0411	3264
18	0.4503	0.0438	3142
19	0.3411	0.0382	3169
20	0.4404	0.0573	3094
21	0.7406	0.0371	3134
23	0.2528	0.0346	3171
28	0.6265	0.0445	3209
31	0.4022	0.0427	3121
32	0.5088	0.0376	3114
33	0.5655	0.0517	3121
34	0.4377	0.0374	3120
35	1.1327	0.0447	3089
Mean	0.5102	0.0425	3163
$\sigma/\overline{w}$			0.017

Table 5 summarizes the results for the F-250 vehicle after mode-filtering algorithm of these total-weight data, including the unfiltered percent error, the filtered percent error, and total weight. These results are a substantial improvement over the previous results, namely: (1) all filtered-errors, are <0.1% after mode removal, (2) all filtered-weights are within two standard deviations of the average (no outliers), and (3) total weight is consistent with the certification requirement, in contrast to single-wheel or single-axle weights as analyzed above. Thus, the use of mode-filtering on total-weight data provides both lower error (more precision), as well as more accuracy (no outliers). Therefore, our <0.1% error goal was obtained using the *modified* Gen II system via a novel mode-filtering algorithm with weigh-pad spacing adjustments to obtain the total vehicle weight (i.e., weigh all axles simultaneously).

4. Conclusions

The error-reduction methodology is independent of the weigh-pad-measurement physics (e.g., piezoelectric, strain-gage, quartz, load-cell, and bending-plate). The filtering method can be applied to WIM strip sensors via an appropriate data acquisition system that dynamically samples at a sufficiently high rate, with sufficient bit precision and sufficiently accurate sensor calibration. The layout density and length of runway need to support the total weight of all vehicles over some (yet to be determined) finite duration. The scalability of these algorithms to high-speed WIM measurements with similar precision is doubtful.

The novel mode-filtering algorithm decreased error to <0.1% in the *modified* Gen II System (Table 5). A systematic calibration error in the Gen II weigh pads was exposed by statistically comparing the filtered-WIM measures to those of the *certified* IGS scale. Gen II values are typically low by approximately 2.1% and can be corrected by improving the weigh pad calibration procedure at manufacture time (i.e., the present stain-gauge-based weigh-pad system has a calibration tolerance as follows: ±23 kg for a load of ≤2,268 kg (1%) and ±46 kg for a load of 2,268 - 7,711 kg (≤2%)). Calibration of the filtered-WIM values to the certified-IGS weights yielded excellent straight-line fits. The *modified* Gen II system supports the <0.1% error, as well as the obvious safety and efficiency advantages.

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