Standard Specification for

Smoothness of Pavement in Weigh-in-Motion (WIM) Systems

AASHTO Designation: MP 14-05

American Association of State Highway and Transportation Officials
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1. SCOPE

1.1. Weigh-in-Motion (WIM) is the process of measuring the dynamic forces of moving vehicle tires on pavements and estimating the corresponding tire loads of the static vehicle. The dynamic forces of moving vehicles include the effects of road surface roughness and are modified by vehicle characteristics such as spring and un-spring mass, tire inflation pressures, out-of-round or dynamically unbalanced wheels and tires, suspension damping and the vehicles' aerodynamic characteristics. The smoothness of the pavement surface in WIM Systems directly affects the scale's ability to accurately estimate static loads from measured dynamic forces. Lack of smoothness creates difficulties in calibrating WIM equipment and may cause poor results from subsequent vehicle weight data collection efforts.

1.2. WIM system pavement smoothness is characterized by the output of a Class I profiler collecting data at 25 mm [1 in.] intervals. The data produced by such a profiler will approximate the actual perpendicular deviation of the pavement surface from an established horizontal reference parallel to the lane direction in the wheel tracks.

1.3. The specification requires field collection of pavement profile information of a WIM System or of a candidate WIM site. Computer software is then used to calculate indices of long- and short-range pavement surface roughness that have been correlated to distributions of tandem axle and gross vehicle weight error levels through extensive simulations of truck dynamic loading over measured profiles. Acceptable index levels are based on ensuring to a 95 percent level of confidence that the WIM System roughness will not produce errors that exceed the tolerance level limits recommended by ASTM.

1.4. The profiler test vehicle, as well as all attachments to it, shall comply with all applicable state and federal laws. Necessary precautions imposed by laws and regulations, as well as vehicle manufacturers, shall be taken to ensure the safety of operating personnel and other traffic.

2. REFERENCED DOCUMENTS

2.1. *AASHTO Standards*:

- MP 11, Inertial Profiler
- PP 50, Operating Inertial Profilers and Evaluating Pavement Profiles

2.2. *ASTM Standards*:

- E 867, Terminology Relating to Vehicle-Pavement Systems
- E 950, Standard Test Method for Measuring the Longitudinal Profile of Traveled Surfaces with an Accelerometer Established Inertial Profiling Reference
- E 1170, Standard Practices for Simulating Vehicular Response to Longitudinal Profiles of Traveled Surfaces
- E 1318, Standard Specification for Highway Weigh-in-Motion (WIM) Systems with User Requirements and Test Methods
- E 1364, Test Method for Measuring Road Roughness by Static Level Method

2.3. *Other Documents and References*:

- FHWA. *Traffic Monitoring Guide*, Fourth Edition. U.S. Department of Transportation, Federal Highway Administration, Office of Highway Information Management, Washington, DC, January 2001.
- FHWA. *Pavement Smoothness Specifications for LTPP WIM Locations*, Draft. Federal Highway Administration, Office of Infrastructure Research, Development, and Technology, McLean, Virginia, January 2002.
- FHWA. *A Program Guide to WIM Smoothness Index Software*. Federal Highway Administration, Office of Infrastructure Research, Development, and Technology, McLean, Virginia, 2005.
- Karamihas, Steven M. and Thomas D. Gillespie. *Smoothness Criteria for WIM Scale Approaches*. University of Michigan Transportation Research Institute, Ann Arbor, Michigan, September 2002.
- Karamihas, Steven M. and Thomas D. Gillespie. *Advancing Smoothness Criteria for WIM Scale Approaches—Final Report*. University of Michigan Transportation Research Institute, Ann Arbor, Michigan, April 2004.

3. TERMINOLOGY

3.1. *Definitions*:

3.1.1. *dynamic axle load (kg or lb), n*—the component of the time-varying forces applied perpendicularly to the road surface by the tires of any one axle of a moving vehicle.

3.1.2. *index, n*—a number or formula expressing some property, form, ratio, etc. of the relation or proportion of one amount or dimension to another.

3.1.3. *roughness, n*—vertical deviation of a pavement surface from a horizontal reference along a wheel track with characteristics that effect vehicle dynamics, including dynamic axle loads.

3.1.4. *profile record, n*—a data record of the surface elevation or slope along one or both wheel tracks of the road surface.

3.1.5. *weigh-in-motion (WIM), n*—the process of estimating a moving vehicle's gross weight and the portion of that weight that is carried by each wheel, axle, or axle group, or combination thereof, by measurement and analysis of dynamic vehicle tire forces. (See Terminology, ASTM E 867.)

3.2. *Definitions of Terms Specific to This Standard*:

3.2.1. *short-range roughness, n*—vertical deviations of the pavement surface from a horizontal reference within a range of pavement from 2.8 m [9.2 ft] preceding a WIM scale to 0.5 m [1.6 ft] beyond it.

3.2.2. *long-range roughness, n*—vertical deviations of the pavement surface from a horizontal reference within a range of pavement from 25.8 m [84.6 ft] preceding a WIM scale to 3.2 m [10.5 ft] beyond it.

4. TEST METHOD TO EVALUATE THE SMOOTHNESS OF PAVEMENT IN A WIM SYSTEM

4.1. *Performance Requirements*:

4.1.1. Functional performance requirements for Types I and II WIM systems were established and tabulated within ASTM E 1318. Table 1 summarizes the tolerance limits for 95 percent probability of conformity to WIM accuracy standards for axle loads, axle-group loads, and gross vehicle weights. Karamihas and Gillespie have developed short- and long-range profile-based indices that can predict the potential WIM error level due to roughness of the pavement. The development and use of these are documented within Annex A1.

4.1.2. Each Type I WIM scale location shall be chosen so that the short- and long-range roughness indices calculated from the pavement profile record of the WIM System do not exceed 0.5 m/km [31.7 in./mile] for either of the wheel tracks. Each Type II WIM scale location shall be chosen so that the short- and long-range roughness indices calculated from the pavement profile record of the WIM System do not exceed 1.25 m/km [79.2 in./mile] and 0.9 m/km [57.0 in./mile], respectively for either of the wheel tracks. The achievement of these values is needed to ensure that a WIM site is likely to produce load estimates that meet the requirements of ASTM E 1318. When location requirements dictate scale placement in rough pavement, the existing pavement can be modified (overlayed, ground, etc.) or replaced to meet these smoothness requirements.

4.1.3. The very presence of a WIM scale will often create localized roughness within the pavement in its vicinity. If this localized roughness is just outside the range of the Short-Range Index (SRI) (2.8 m [9.2 ft] preceding a WIM scale to 0.5 m [1.6 ft] beyond it) then it will elevate the WIM error levels without any effect on the SRI value. To correct this, a Peak SRI value shall be calculated. This value is defined as the maximum value of SRI for all locations from 2.45 m [8.0 ft] ahead of the scale to 1.5 m [4.9 ft] beyond the scale. For Peak SRI, 0.75 m/km [47.5 in./mile] should be used as the acceptable threshold for Type I WIM and 1.6 m/km [101.4 in./mile] should be used for Type II WIM. Values below these figures are needed for both wheel tracks to ensure that a WIM site is likely to produce load estimates that meet the requirements of ASTM E 1318.

Table 1—Functional Performance Requirements for Type I and II WIM Systems

Function	Tolerance for 95% Probability of Conformance	
	Type I	Type II
Wheel Load	±25 %	—
Axle Load	±20 %	±30 %
Axle-Group Load	±15 %	±20 %
Gross Vehicle Weight	±10 %	±15 %

4.1.4. In addition to the initial calculations of short- and long-range roughness indices for WIM scale location acceptance, the pavement smoothness of each existing WIM scale shall be verified annually. Profile records shall be collected and indices recalculated each year to ensure that the scale remains likely to produce load estimates that meet the functional performance requirements of ASTM E 1318.

4.1.5. In specifying a location for a WIM scale with more than one sensor on a single wheel track (typical with piezoelectric WIM equipment), the position of the scale shall be defined as the point midway between the sensors. Short- and long-range indices are to be referenced to this midway point.

4.1.6. Under certain conditions, jointed concrete pavement surface may exhibit significant changes in roughness due to variations in the temperatures of the pavement. Profile records of these pavements shall be taken at least twice, at times that correspond to approximate extremes of temperatures that are likely to be experienced at the candidate location. The location for a WIM scale shall be chosen so that the short- and long-range roughness indices calculated from either of these profile records do not exceed the limits.

4.2. *Summary of Practice*—Test methods for evaluating the smoothness of pavement in an existing WIM System are presented here. These procedures are applicable for determining whether either short-range or long-range roughness levels are at levels that would indicate a WIM scale is likely to produce acceptable levels of weighing error as defined in Table 1. The smoothness tests require the collection of longitudinal profile data with a sampling rate of 25 mm [1 in.] (Class I) according to the procedures in ASTM E 950. Computer analysis of these profiles serves to create indices of short- and long-range roughness that will be compared to acceptable threshold values.

4.3. *Significance and Use*—Karamihas and Gillespie conducted a correlation of calculated short-range and long-range index values to WIM scale error for a large-scale study of pitch-plane simulations of 3S2 vehicles. Karamihas and Gillespie further verified this study of simulations of WIM scale errors associated with 3-axle single-unit trucks. These correlations allow the indices to be used to determine whether the WIM Systems pavement smoothness is sufficient to achieve weight measurements of 3S2 trucks (5-axle tractor-semi-trailers) and 3-axle single-unit trucks that fall within ASTM error tolerance levels. The calculation of short- and long-range roughness indices that fall within those that correlate to the scale measurement tolerances specified in Table 1 means that the scale is very likely to produce an acceptable level of weighing error.

4.4. *Procedure*:

4.4.1. *Profile Records*—Obtain profile records of both left and right wheel paths according to the procedures outlined in ASTM E 950 for Class I profilers using a 25-mm [1-in.] longitudinal sampling interval. These records should begin at least 122 m [400 ft] prior to the WIM scale sensor and extend to 30 m [100 ft] after the scale sensor or beyond. For WIM scales that are comprised of two or more sensors, the location of the scale will be defined as the longitudinal midpoint of the locations of the two outermost sensors. Record the WIM scale location as an Intermediate Feature Location Marker within the profile record as per Section 6.3.4 of ASTM E 950. Obtain a total of three records, compare the outputs for each and evaluate each for equipment-related spikes. Continue collecting profile records until the operator is satisfied that at least one error-free record has been obtained.

4.4.2. *Calculation of Indices*—A complete description of the procedure to calculate short- and long-range smoothness indices is described in Annex A1—Computation of Profile Based Short- and Long-Range Indices. The procedure has been coded within the WIM Smoothness Index software available from FHWA's Long-Term Pavement Performance Program (LTPP) Product Delivery Team. This non-proprietary software performs the computations from Annex A1 with either AASHTO PP 50 or ERD text file versions of the profile records from any longitudinal profiler as inputs. Source code is available from FHWA's LTPP Product Delivery Team. Perform 'Site

Evaluation' analysis of the WIM System with the WIM Smoothness Index software. Short-and Long-Range Index as well as peak short-range index values will be calculated for both left and right wheel paths of the WIM System.

4.4.3. Although including pavement features located more than 26 m [85 ft] ahead of a WIM scale does not improve its predictive ability, the Long-Range Index (LRI) criterion might fail to screen out WIM sites with a major disturbance just beyond this range if the rest of the pavement is smooth. Although this is unlikely to occur in practice, a useful way to protect against very rough pavement features that are not captured by the LRI value at the scale location is to inspect the value of LRI for 30 m [100 ft] upstream of the scale to ensure that it does not exceed the lower threshold over this range.

4.5. *Interpretation of Results*—Lower threshold values of long-range, short-range and peak short-range indices are those below which a WIM System is very likely to produce an acceptable level of weighing error. Upper threshold values of these indices are those above which a site is very likely to produce an unacceptable level of weighing error. Threshold values for each of these three values for Type I and II WIM scales are tabulated below. A location shall be chosen that will result in acceptable index values. An acceptable LRI Value is required for a minimum of 30 m (100 ft) prior to the chosen location.

Table 2—Roughness Index Thresholds for Type I WIM

Index	Lower Threshold (m/km)	Upper Threshold (m/km)
Long Range	0.5 [31.7 in./mile]	2.1 [133.1 in./mile]
Short Range	0.5 [31.7 in./mile]	2.1 [133.1 in./mile]
Peak Short Range	0.75 [47.5 in./mile]	2.9 [183.7 in./mile]

Table 3—Roughness Index Thresholds for Type II WIM

Index	Lower Threshold (m/km)	Upper Threshold (m/km)
Long Range	0.9 [57.0 in./mile]	3.8 [240.8 in./mile]
Short Range	1.25 [79.2 in./mile]	5.7 [361.2 in./mile]
Peak Short Range	1.6 [101.4 in./mile]	6.6 [418.2 in./mile]

4.6. *Precision and Bias*—This is a test method that produces pass-or-fail results. The precision of the test is related to the degree of correlation between calculated index values and errors in measured values of tandem axle and cross vehicle weights. Since these relationships exhibited some scatter in a simulation study, conservative values for index cut-off values were chosen such that there was 95 percent confidence that a scale that met the index criteria would produce levels of weighing error that meet the ASTM E 1318 standards in the study.

5. TEST METHOD TO EVALUATE THE SMOOTHNESS OF PAVEMENT IN A WIM SYSTEM

5.1. *Summary of Test Method*—A test method for determining an optimal position for WIM scale within a limited site is presented here. The procedures are applicable for determining a precise placement of a WIM scale within the linear distance covered by a profiler record that will result in minimum short-range and long-range roughness levels. The smoothness tests require the collection of longitudinal profile data with a sampling rate of 25 mm [1 in.] (Class I) according to the procedures in ASTM E 950. Computer analysis of these profiles at varying longitudinal scale placements serves to locate the WIM placement that will minimize short- and long-range roughness. Comparison of these values with acceptable threshold values will indicate if the site is suitable. To protect against very rough pavement features that are not captured by the LRI value at the scale location, inspect the value of LRI for 30 m (100 ft) upstream of the scale to ensure that it does not exceed the lower threshold over this range.

5.2. *Significance and Use*—A correlation of calculated short-range and long-range index values to WIM scale error was conducted for a large-scale study of pitch-plane simulations of 3S2 vehicles. This correlation allows the indices to be used to determine whether the WIM system pavement smoothness is sufficient to achieve weight measurements of 3S2 (5-axle tractor-semi-trailers) and 3-axle single unit trucks that fall within ASTM error tolerance levels. The calculation of short- and long-range roughness indices for each candidate scale location within a profile record may be used to determine the correct positioning of a scale to maximize its likelihood of producing acceptable levels of weighing error as outlined in Table 1.

5.3. *Test Methods*:

5.3.1. *Profile Records*—Obtain profile records of both left and right wheel paths according to the procedures outlined in ASTM E 950 Class I profilers using a 25-mm [1-in.] longitudinal sampling interval. These records shall meet the minimum requirements for vertical measurement resolution outlined in ASTM E 950 for Class I profilers; and should cover the entire longitudinal extent of roadway to be considered for the WIM scale placement. Obtain a total of three records, compare the outputs for each and evaluate each for equipment-related spikes. Continue collecting profile records until the operator is satisfied that at least one error-free record has been obtained.

5.3.2. *Calculation of Indices*—A complete description of the procedure to calculate short- and long-range smoothness indices is described in Annex A1—Computation of Profile-Based Short- and Long-Range Indices. The procedure has been coded within the "WIM Smoothness Index" software available from FHWA's LTPP Product Delivery Team. This non-proprietary software performs the computations from Annex A1 with ERD text file versions of the profile records from any longitudinal profiler as inputs. Perform 'Location Selection' analysis of the WIM System pavement with the WIM Smoothness Index software. Short- and long-range as well as peak short-range index values for both left and right wheel paths will be calculated and graphed for each potential WIM scale location within the record.

5.4. *Interpretation of Results*—Lower threshold values of long-range and short-range indices are those below which a WIM site is very likely to produce an acceptable level of weighing error. Upper threshold values of these indices are those above which a site is very likely to produce an unacceptable level of weighing error. Threshold values are tabulated within Table 2. A location shall be chosen that will result in acceptable index values. An acceptable Long-Range Index value is required for a minimum of 30 m [100 ft] prior to the chosen location.

5.5. *Precision and Bias*—See Section 4.6.

ANNEXES

(Mandatory Information)

A1. COMPUTATION OF PROFILE-BASED LONG- AND SHORT-RANGE INDICES

A1.1. *Four-Pole Butterworth filter*:

A1.1.1. A pre-filter shall be applied. An elevation profile for each wheel track is replaced with a slope profile, obtained point-by-point by subtracting adjacent elevation values and dividing by the sample interval.

A1.1.2. An ideal band-pass filter passes some range of frequencies without distortion and suppresses all other frequencies. A Butterworth filter fulfills these needs. The exclusion of very short and very long wavelengths minimizes the effects of high amplitude, short wavelength change in the profile at the edges of the spatial weighting function. It also prevents absolute elevation or grade from influencing index values by filtering very long wavelength signals. The transfer function for the frequency response for this filter can be written as:

$$P(s^2\Omega_h^2) = F((s^2 + 2\xi\Omega_l s + \Omega_l^2)(s^2 + 2\xi\Omega_h s + \Omega_h^2)) \quad \textit{(A1.1)}$$

where:

$P(x)$ = input function and $F(x)$ is the filtered profile,

Ω_h = high spatial cutoff expressed as a wavelength,

Ω_l = low spatial cutoff expressed as a wavelength,

ξ = dimensionless damping ratio, set at 0.707 for a Butterworth filter.

Replacing s in the theoretical transfer function with the derivative operation $sy = \frac{\partial y}{\partial x}$, the frequency response can be expressed as an equation:

$$b_2 \frac{\partial^2 P}{\partial x^2} = \frac{\partial^4 F}{\partial x^4} + a_1 \frac{\partial^3 F}{\partial x^3} + a_2 \frac{\partial^2 F}{\partial x^2} + a_3 \frac{\partial F}{\partial x} + a_4 F \quad \textit{(A1.2)}$$

where:

$b_2 = \Omega_h$

$a_1 = 2\xi(\Omega_l + \Omega_h)$

$a_2 = \Omega_l^2 + 4\xi\Omega_l\Omega_h + \Omega_h^2$

$a_3 = 2\xi\Omega_l\Omega_h(\Omega_l + \Omega_h)$

$a_4 = \Omega_l^2\Omega_h^2$

or in matrix form:

$$\frac{\partial F(x)}{\partial x} = AF(x) + BP(x) \quad \textit{(A1.3)}$$

where:

$$F(x) = \begin{bmatrix} F(x) \\ \frac{\partial F(x)}{\partial x} \\ \frac{\partial^2 F(x)}{\partial x^2} \\ \frac{\partial^3 F(x)}{\partial x^3} \end{bmatrix}, \; A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -a_4 & -a_3 & -a_2 & -a_1 \end{bmatrix}, \text{ and } B = \begin{bmatrix} 0 \\ b_2 \\ -a_1 b_2 \\ (a_1^2 - a_2)b_2 \end{bmatrix}$$

The $F(x)$ matrix is analogous to the array of state variables of the Quarter Car filter which completely describe the state of the simulated system. A state transition matrix, describing the response of the system over the interval between points i–1 and I, can be used to solve the differential equations for the Butterworth filter. The response is:

$$F_i = SF_{i-1} + PP_i \quad \textit{(A1.4)}$$

S and P can be calculated:

$$S = e^{At} \qquad (A1.5)$$

and $P = A^{-1}(S - I)B \qquad (A1.6)$

where:

t = time interval between profile samples,

I = 4 × 4 identity matrix.

The calculation of S requires taking e to a matrix power. This may be done through a Taylor series expansion:

$$e^{At} = I + \sum_{i=1}^{N} \frac{A^i t^i}{i!} \qquad (A1.7)$$

where:

N = number large enough to obtain the required accuracy.

To solve differential equations such as Equation A1.3, it is necessary to estimate the values of the state variables at a starting time. To initialize the Butterworth filter, the elements of the F array for i = 1 shall be set as:

$$F_i = \left[0 \;\; 0 - \Omega_h^2 (p_{L_0/\Delta} - p_1)/L_0 \;\; 2\xi\Omega_h^2(\Omega_h + \Omega_l)(p_{L_0/\Delta} - p_1)/L_0\right] \qquad (A1.8)$$

where:

L_0 = the initialization length,

Δ = the interval between profile samples,

P_i = profile elevation at point i.

A2. SPATIAL WEIGHTING OF THE FILTERED SIGNALS

A2.1. A ‘box’ spatial weighting function is applied to the band-pass filter output. Such a function has a value of unity within its boundaries and zero outside of them. The boundaries of this function will be set at the values tabulated in Table 3. This weighting function shall be applied after the filter, meaning that the filter response rather than the profile is weighted. The result is that profile features outside the weighting function window can influence the index.

Table A2.1—Weighting Function Boundaries

	Preceding Scale Location	Beyond Scale Location
Short Range Index	3.0 m [10 ft]	0.3 m [1 ft]
Long Range Index	25.0 m [82.0 ft]	3.0 m [10 ft]

A3. AVERAGE-RECTIFIED INDEX ACCUMULATION

A3.1. Following the application of a weighting function, individual short-range and long-range index values are to be calculated by accumulating over the range of weighting function boundaries.

$$\text{Index} = \left[\frac{1}{N_2 - N_1 + 1} \sum_{i=N_1}^{N_2} abs(F_i \bullet W_i)^P\right]^{1/P} \qquad (A3.1)$$

where:

F = filtered profile,

N_1 = sample number of the first spatial weighting function boundary,

N_2 = sample number of the second spatial weighting function boundary,

W = weighting function, and

P = accumulator exponent (set to 1 for average-rectified accumulation).