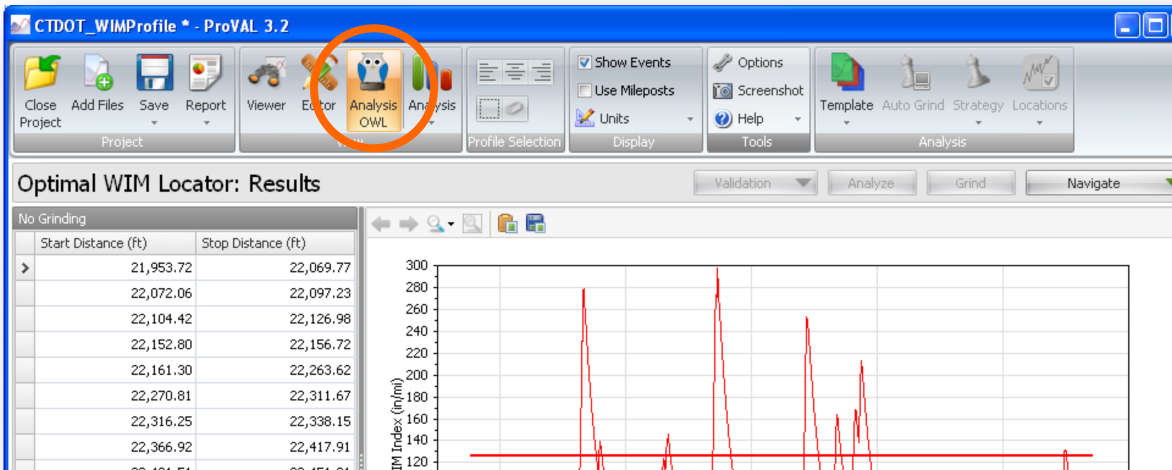
Implementation of ProVAL OWL

A Tech Brief

by the FHWA Surface Enhancement Team and ProVAL Support Team



Introduction

Profile Viewing and Analysis (ProVAL) software is an engineering software application used to view and analyze pavement profiles (www.RoadProfile.com). The development of ProVAL is sponsored by the US Department of Transportation, Federal Highway Administration (FHWA) ProVAL Support project (DTFH61-10-D-00013), Long Term Pavement Performance Program (LTPP), and Transportation Pooled Fund TPF-5(063) “Improving the Quality of Pavement Profiler Measurement”. It is easy to use, yet powerful to perform many types of profile analyses.

Under the “Task B: Provide for WIM System Enhancements” of the FHWA Surface Enhancement and Pavement Design Data project (DTFH61-08-D-00026), Optimal Weigh-in-motion (WIM) site Locator (OWL) was developed as a new module of the ProVAL software in order to implement the method in the upcoming revision of AASHTO MP 14 “Standard Specification for Smoothness of Pavement in Weigh-in-Motion (WIM) Systems”.

The purpose of this document is to describe the implementation of the OWL Module in ProVAL including the OWL algorithms and software features. It is meant to complement the ProVAL user’s manual and to assist beta testers on validating the final delivered system.

Major Changes in the Revised AASHTO MP 14

The major Changes in the Revised AASHTO MP 14 include three areas:

- WIM Index Calculation
  - Use one band-pass filter only.
  - Apply a sixth-order Butterworth filter.
  - Average over a short interval.
  - Place a shroud over the roughness profile.
- WIM Index Thresholds
  - Smoother pavement will be needed.
  - The index will penalize locations near hot spots.
- Requirements of Profile measurement
  - A larger footprint with bridging is preferred.
  - Inclusion of reference to M 328-10 Standard Specification for Inertial Profiler, and R 56-10 Standard Practice for Certification of Inertial Profiling Systems

Further details of the changes will be described in the revised MP 14 standard which is under review and balloting.

OWL Algorithm

The ProVAL OWL module is designed to determine qualified locations for Weight-In-Motion (WIM) sites based on smoothness criteria. It analyzes true pavement profiles collected from candidate or existing WIM sites based on the algorithm in the revision of AASHTO MP 14-08 "Standard Specification for Smoothness of Pavement in Weigh-in-Motion (WIM) Systems". The criteria are applied to screen WIM sites for excessive truck dynamic loading that exacerbates WIM scale error beyond levels recommended by the WIM-related ASTM and AASHTO standards.

The ProVAL OWL module also provides optional but very flexible user-defined grinding strategies. A comprehensive report can then be generated to include WIM index reports before and after grinding.

The OWL algorithm implemented in ProVAL includes the following steps in sequence:

1. Tire-Bridging Filtering
2. Band pass Filtering and Conversion to Slope
3. Rectification
4. Shrouding

Tire-Bridging Filtering

The purpose of tire-bridging filtering is to bridging pavement profiles over narrow concave features or negative surface texture to avoid adverse effects prior to roughness index computation. The bridging filter code implements the same algorithm described in the Critical Profiler Accuracy Requirements (CPAR) report (Karamihas, 2005) and Benchmark Testing Plan (Karamihas, 2007). This tire-bridging filter has been tested and validated extensively in the Bench Mark Testing and Golden Footprint projects.

The tire-bridging filter is an approximation of a set of parallel springs (Figure 1), where each spring is allowed to reach a maximum extension and lose contact with the road if it is over a low point. Since the filter is applied to profile, it acts as if a single spring acts on each profile point within the averaging length. If the needed tire force (or, in effect, the protrusion above a datum plane) is accounted for by the high points, then the low points are ignored.

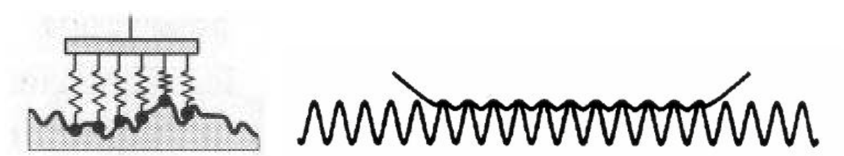


Figure 1. Fixed footprint tire model and illustration of tire-tread penetration into pavement textures. (Karamihas, 2005)

The effects of the tire-bridging filtering can be demonstrated in the following figure. In Figure 2, the narrow dips are attenuated after the bridging filter compared with the raw profile and the filtered profile with moving average.

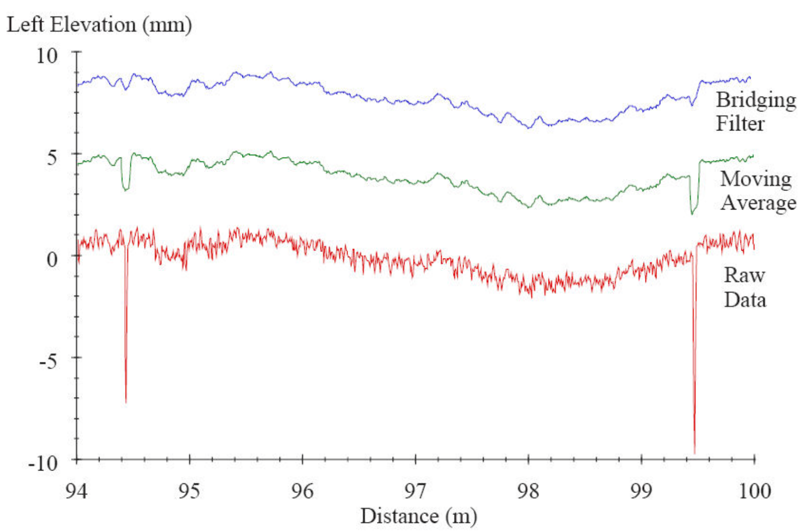


Figure 2. Comparison of raw profile, moving average filtered profile, and tire-bridging filtered profile. (Karamihas, 2005)

The algorithm of the tire-bridging filter implemented in OWL follows that in the revised MP 14 and is summarized as follows:

Apply a low-pass "bridging filter" to the profile, unless a low-pass filter with a base length or a similar influence on the frequency content was applied before recording the profile.

The bridging filter emulates tire behavior by assuming that the positive (upward) content in the profile over the tire contact patch will penetrate into the tread by a consistent depth DB, but that negative (downward) content has no influence.

For each data point in the raw profile PR(i), seek a value for the bridged profile P(i) as follows.

Step 1: Set the desired depth.

$$D = D_B \tag{1}$$

Step 2: Assume a value for the bridged profile.

$$P(i) = P_R(i) - D \tag{2}$$

Step 3: Calculate the average depth of penetration of the raw profile above the bridged profile.

$$D_A = \frac{1}{2I_B + 1} \sum_{i-I_B}^{i+I_B} \max(0, P_R(i) - P(i)) \tag{3}$$

$$I_B = \text{NINT}(B/2) \tag{4}$$

B is the base length. The function "NINT" produces the nearest integer of its argument.

Step 4: Test the depth.

$$D_A / D > 0.001 \tag{5}$$

Set D=D-DA and return to Step 1.

Step 5: Shift the profile upward.

$$P(i) = P_R(i) + D_B \tag{6}$$

Apply Equation [3] at every point along the profile for a base length (B) of 250 mm [9.84 in.] and a depth (DB) of 1 mm [0.04 in.]. For cases where the sum used in equation A1.3 would require data that are outside of the limits of the raw profile, pad the signal by assuming a constant elevation equal to the appropriate endpoint.

Bandpass Filtering and Conversion to Slope

The Butterworth filter set provided for ProVAL is used for bandpass filtering and conversion to slope. The ProVAL Butterworth filter set includes a high-pass filter and a low-pass filter. The band-pass filtering option simply applies the high-pass filter with the requested long-wavelength cut-off then the low-pass filter with the requested short wavelength cut-off. Both filters are applied in a cascaded form of a third order Butterworth filter in the forward and reverse directions. This raises the order of each filter to six. Both filters will use double precision 8-byte floating point. (Karamihas, 2007)

A third order Butterworth low-pass filter has the transfer function:

$$H(s) = \frac{1}{s^3 + 2s^2 + 2s + 1} \tag{7}$$

The filter may be cascaded by applying a first order Butterworth filter:

$$H_1(s) = \frac{1}{s + 1} \tag{8}$$

and a complementary second order filter:

$$H_2(s) = \frac{1}{s^2 + s + 1} \tag{9}$$

The implementation of the ProVAL Butterworth low-pass filtering includes the following steps:

- Step 1: First Order, Forward Direction
- Step 2: Second Order, Reverse Direction
- Step 3: First Order, Reverse Direction
- Step 4: Second Order, Forward Direction

A third order Butterworth high-pass filter has the transfer function:

$$H(s) = \frac{s^3}{s^3 + 2s^2 + 2s + 1} \tag{10}$$

The filter may be cascaded by applying a first order Butterworth filter:

$$H_1(s) = \frac{s}{s + 1} \tag{11}$$

and a complementary second order filter:

$$H_2(s) = \frac{s^2}{s^2 + s + 1} \tag{12}$$

The implementation of the ProVAL Butterworth high-pass filtering includes the following steps:

- Step 1: First Order, Forward Direction
- Step 2: Second Order, Reverse Direction

- Step 3: First Order, Reverse Direction
- Step 4: Second Order, Forward Direction

For the implementation in OWL, a band-pass filter is tuned to emphasize profile features that affect truck dynamic using 1.07 m and 16.46 m as the cut-off wavelengths. The output is in profile slope.

Rectification

The output band-pass filtered profiles are rectified or taken absolute values (Figure 3).

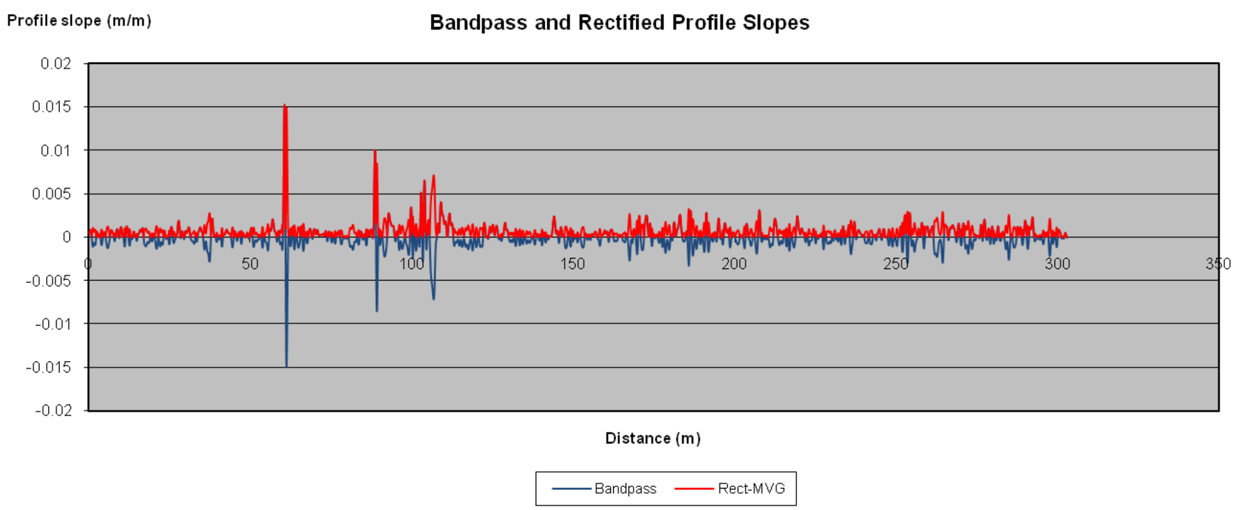


Figure 3. Bandpass filtered profile slope and rectified profile slope.

Shrouding

Shrouding algorithm was developed specifically for the WIM index in MP 14-11. To help avoid underestimating WIM scale error near areas of localized roughness, a “shroud” is placed over the rectified, filtered profile slope to increase the WIM scale roughness index near hot spots.

The “aft” shroud is based on exponential decay from localized peaks with a preset distance constant of 15.24 m [50 ft] for hot spots upstream of a point of interest. To apply the shroud, step through the signal from the start ($i+I_B$) to the end (N_S-I_B).

For each point in the signal, search the points upstream (i.e., step through possible values of j from 1 to i-1) until the following condition is satisfied:

$$F(i) < F(i-j) \bullet e^{-\Delta xj/\tau_a} \qquad (13)$$

Where Δx is the longitudinal distance interval and τ_a is the distance constant. For the first value of j in which equation [13] is satisfied, replace F(i) as described in equation [14], and move on to the next point in the signal. (Once a "hit" is found, it is not necessary to continue through any more possible values of j.)

$$F(i) = F(i - j) \bullet e^{-\Delta xj / \tau_a} \quad (14)$$

The "forward" shroud is based on exponential decay from localized peaks with a preset distance constant of 1.524 m [5 ft] for hot spots downstream of a point of interest. To apply the shroud, step through the signal from the end (N_S-I_B) to the start (i+I_B).

For each point in the signal, search the points downstream (i.e., step through possible values of j from 1 to N_S-I_B -i) until the following condition is satisfied:

$$F(i) < F(i + j) \bullet e^{-\Delta xj / \tau_f} \quad (15)$$

Where Δx is the longitudinal distance interval and τ_f is the distance constant. For the first value of j in which equation [15] is satisfied, replace F(i) as described in equation [16], and move on to the previous point in the signal. (Once a "hit" is found, it is not necessary to continue through any more possible values of j.)

$$F(i) = F(i + j) \bullet e^{-\Delta xj / \tau_f} \quad (16)$$

The implementation of the shrouding in the ProVAL OWL includes: a shroud distance constant, 15.24 m, for road following a feature and Shroud distance constant, 1.524 m, for road preceding a feature.

An example of shrouding is shown in Figure 4.

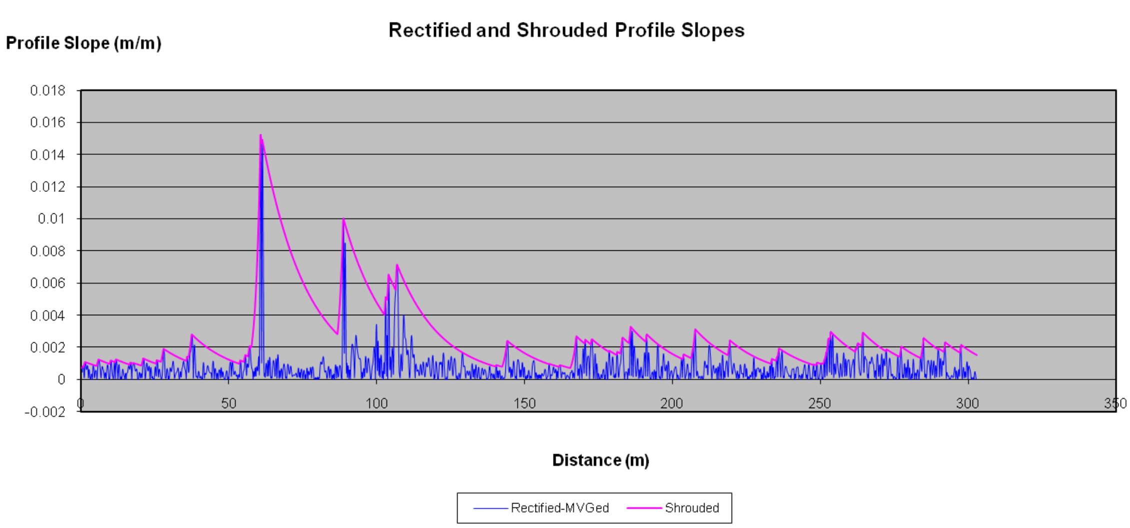


Figure 4. Comparison of rectified profile slope and shrouded profile slope.

Grinding Simulation

The grinding simulation in OWL is similar to that in the ProVAL Smoothness Assurance Module. Please refer to the ProVAL user's manual for further details.

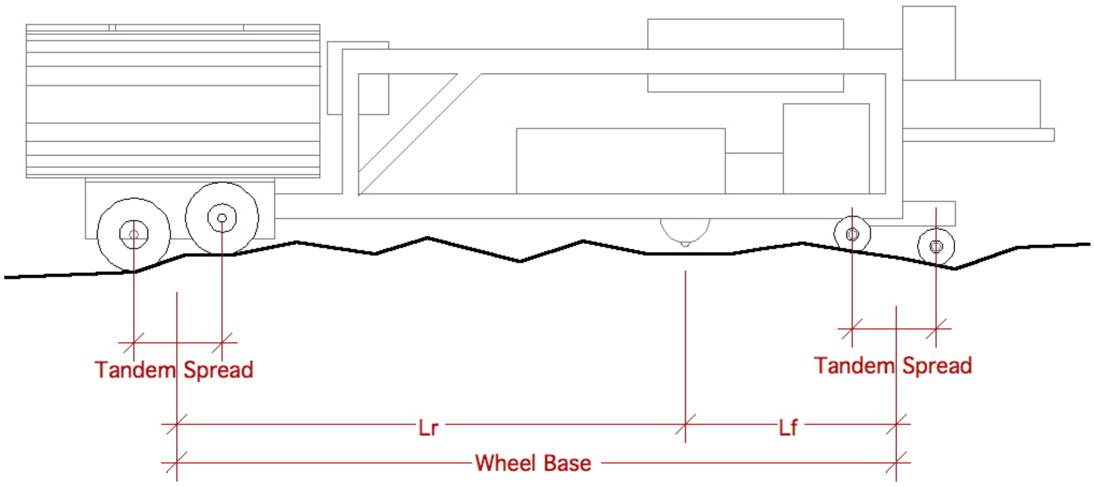


Figure 5. Simulated grinder in ProVAL.

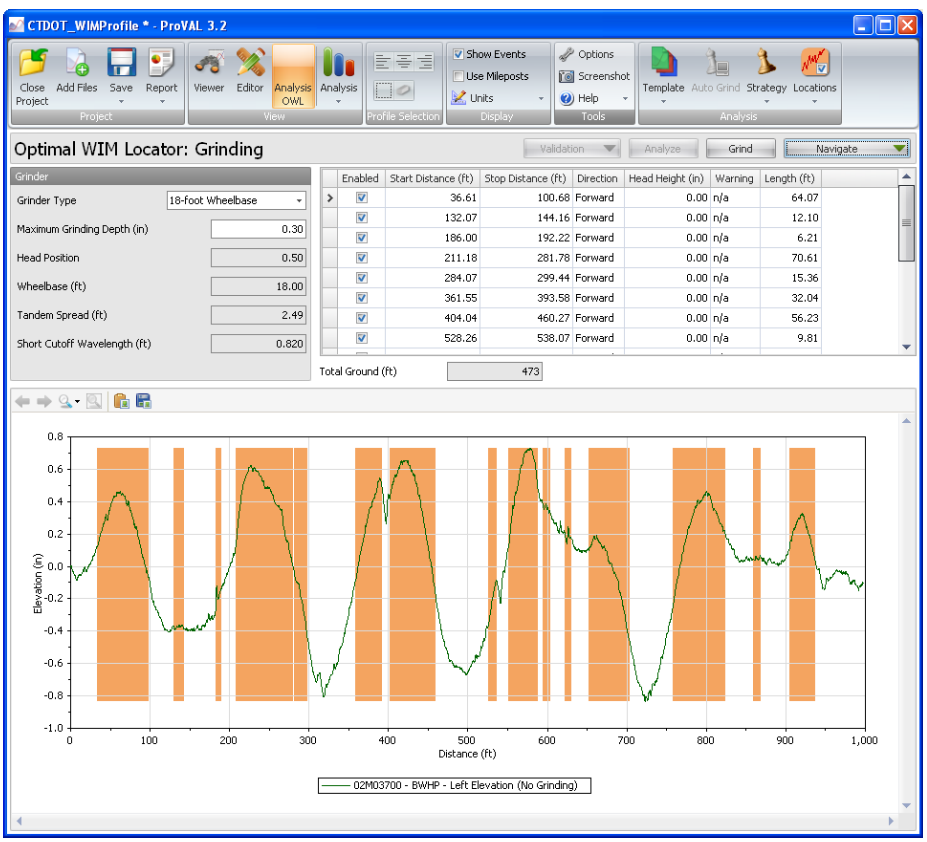


Figure 6. An example inputs of grinding simulation.

OWL Reports

The report contains one set of results for Type I or Type II (depending on the user's selection) WIM index analyses. Type I and Type II settings will be set per the revised AASHTO MP 14 specification including: lower threshold, and upper threshold. The revised AASHTO MP 14-11 will make use of only one WIM indexes as opposed to two in MP 14-8.

The development of the WIM index thresholds is based on extensive vehicle simulation and the ASTM WIM error tolerance. The WIM index mirrors the WIM error as shown in Figure 7.

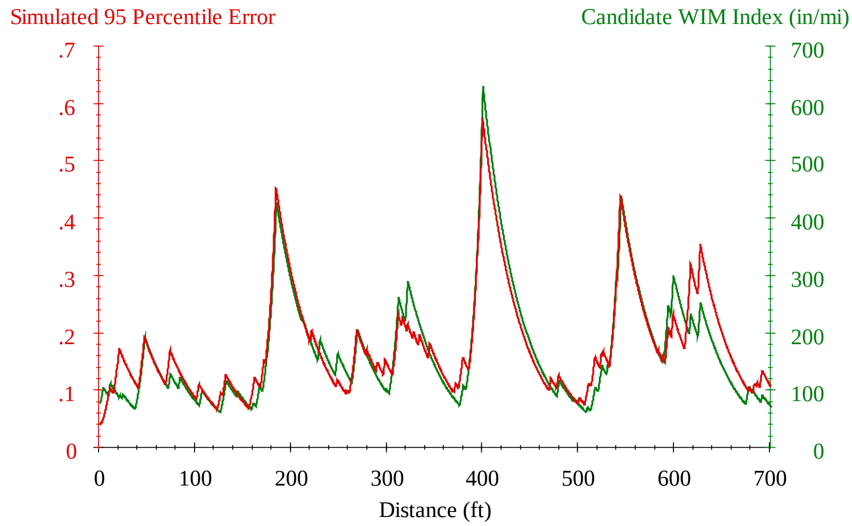


Figure 7. Consistency between WIM errors and WIM index.

The threshold values for the WIM index can be determined from the 95 percentile tandem axle weighting errors. The threshold values for the WIM index includes a lower and upper threshold values for each type of WIM sites (see Table 1). Note that the threshold values are tentative and will be updated once the AASHTO MP 14 standard is finalized. The WIM indexes for qualified WIM sites shall be between the lower and upper limits.

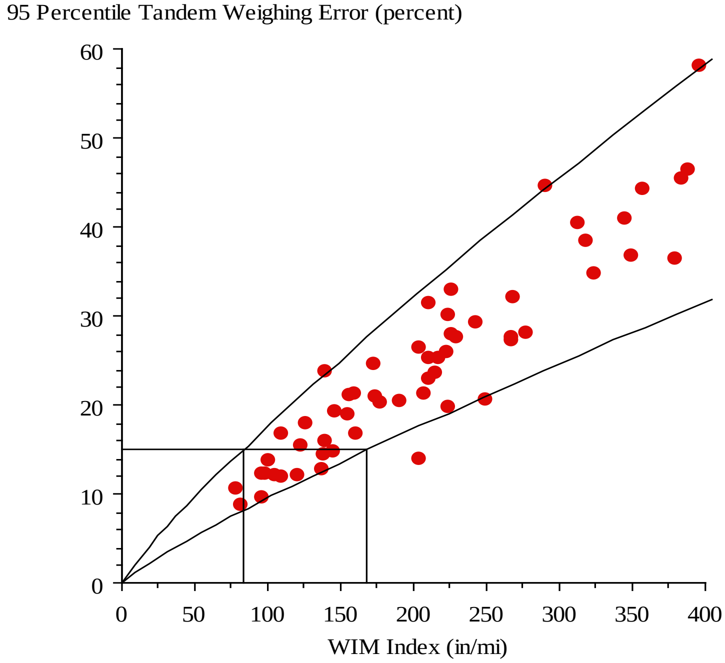


Figure 8. Tandem Axle Weighing Error versus WIM Index, WIM Pilot Profiles.

Table 1 – WIM Index Thresholds

Index Type	Lower Threshold, m/km (inches/mile)	Upper Threshold, m/km (inches/mile)
Type I	1.339 (84.84)	2.700 (171.09)
Type II	1.861 (117.89)	3.752 (237.73)

The ProVAL OWL report includes:

- A WIM index plot with a horizontal line at the lower threshold and another at the upper threshold.
- If the user selects a comparison profile, the screen will include a companion plot below the WIM index plot.
- A table to list acceptable WIM locations (start and stop locations).

An example of OWL report is presented in Figure 9:

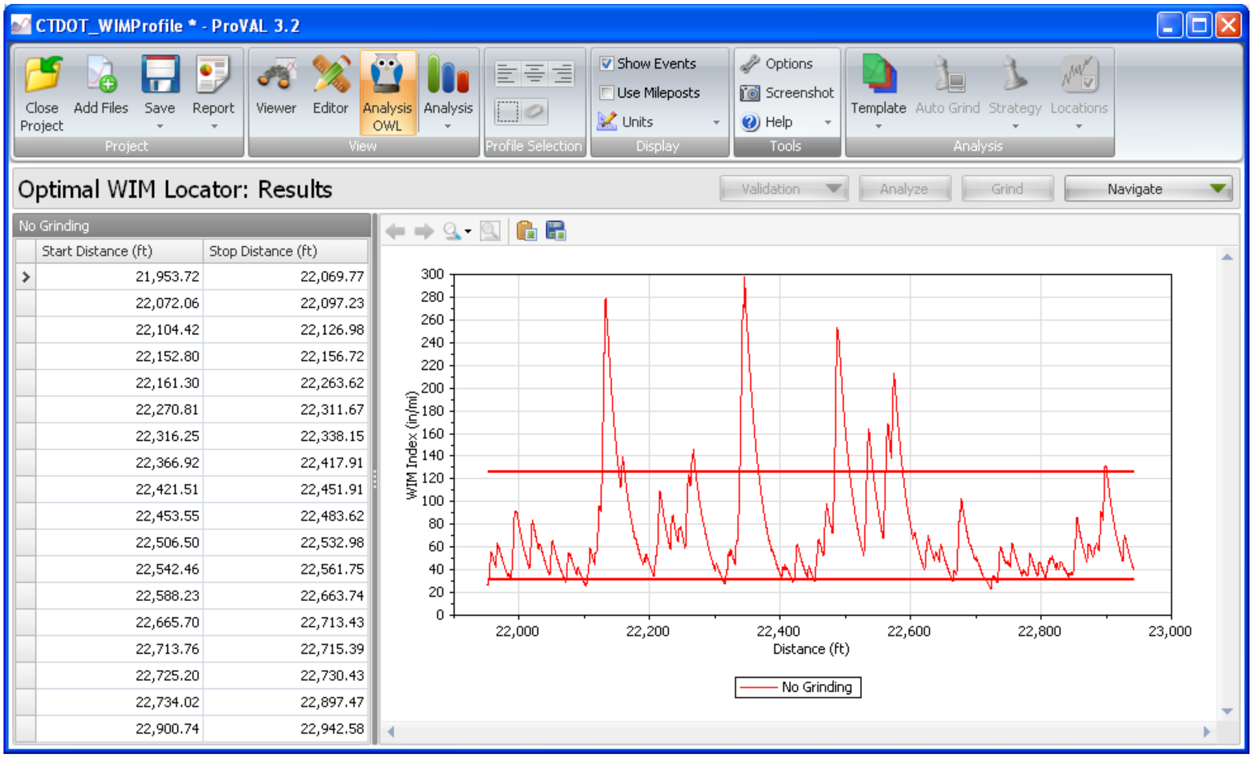


Figure 9. An example of OWL reports.

References

AASHTO, MP 14-08 “Standard Specification for Smoothness of Pavement in Weigh-in-Motion (WIM) Systems”, American Association of State Highway and Transportation Officials, (2010).

AASHTO, MP 14-11 “DRAFT - Standard Specification for Smoothness of Pavement in Weigh-in-Motion (WIM) Systems”, American Association of State Highway and Transportation Officials, (2011). Revised by Steve Karamihas and currently under review and balloting.

Karamihas, S. M., Critical Profiler Accuracy Requirements, University of Michigan Transportation Research Institute Report UMTRI-2005-24, 117 p, (2005).

Karamihas, S. M., Benchmark Testing Plan, unpublished, p.47, (2007).