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Airport Pavement Multiple-Event Roughness Detection and Evaluation

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16. Abstract

Airport pavements are critical to American commerce. Like all structures, these pavements are susceptible to wear and damage through use and external forces, these factors can cause costly repairs and maintenance to keep the pavement functional and safe to use. The Federal Aviation Administration (FAA) has a number of Advisory Circulars that act as guidance for the construction and maintenance of airport pavements and provide evaluation guidelines and tools to assess their condition. However, when it comes to evaluating pavement roughness, current guidance addresses single-event roughness issues for runaways only. FAA roughness evaluation software, ProFAA, provides airports with a tool to comply with Advisory Circular 150/5380-9. This runway roughness specification provides guidance to the airfield pavement community to address runway roughness issues. However, the technology described in this specification only addresses single-event roughness and is for runways only. The research effort described in this report is comprised of two phases. In Phase 1 of this project, a method was developed to locate and quantify multiple-event roughness (MER) for runways and taxiways using measured profile data only. In Phase 2, the objective was to incorporate that method into the existing ProFAA software. Additionally, this research examines the impact on related guidance and recommends changes to existing Advisory Circulars to incorporate the MER method.

This report describes the MER process, the incorporation of the method into ProFAA, and the impact on related FAA Advisory Circulars.

17. Key Words
ProFAA, Airport pavement roughness, Airport pavement management, Runway/taxiway roughness evaluation, Aircraft dynamic response, Multiple-bump detection

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LIST OF ACRONYMS

ABS	Absolute value
AC	Advisory Circular
APR	APR Consultants, Inc.
APRas	Airport Pavement Roughness Assessment Software
AR&L–ER	Autor Rod & Level–External Reference
BB	Blanking band
BBI	Boeing Bump Index
CG	Center of Gravity
CL	Centerline
CP	Cockpit
CS	Case study
CSV	Comma-separated value
FAA	Federal Aviation Administration
G or (g)	Forces of gravity
MER	Multiple-event roughness
MLG	Main landing gear
NLG	Nose landing gear
PCC	Portland concrete cement
PI-100	Profile Index for a 100-Foot Simulated Profilograph
PI-25	Profile Index for a Standard 25-Foot Profilograph
PMP	Pavement management program
PST	Pilot simulator test
RQF	Ride quality factor
RSE	Rolling straightedge (Feet)
RTS	Robotic total station
TN	Technical Note

EXECUTIVE SUMMARY

The Federal Aviation Administration's (FAA) most current guidance to address airfield pavement roughness is provided in Advisory Circular (AC) 150/5380-9, *Guidelines and Procedures for Measuring Airfield Pavement Roughness*. and AC 150/5380-7B, *Airport Pavement Management Program(PMP)*; however, this guidance is limited to addressing single-event pavement roughness and is limited in scope to runways only. Additionally, the FAA roughness evaluation software, ProFAA currently is not equipped to evaluate multiple-event roughness. The aim of the research described in this report is to describe the development of a method to locate and quantify multiple-event roughness (MER) on runways and taxiways using measured profile data only. This report also discusses the changes made to the FAA's roughness evaluation software, ProFAA and suggested revisions to Advisory Circular (AC) 150/5380-9, *Guidelines and Procedures for Measuring Airfield Pavement Roughness*. and AC 150/5380-7B, *Airport Pavement Management Program(PMP)*. Finally, this report examines the benefits of establishing a baseline profile to track roughness development over the life of a pavement.

This research project was comprised of two phases. The completed Phase 1, the multiple-event roughness (MER) analysis, included the development of a method to locate and quantify MER on runways and taxiways using measured profile data only. Phase 2 of this research project incorporated the MER process developed in Phase 1 into the FAA's profile evaluation software, ProFAA.

AC 150/5380-9 provides guidelines for assessing airport runway roughness levels using ProFAA. The Boeing Bump Index (BBI) has been the primary evaluation tool for determining if a runway is acceptable, excessive, or unacceptable. The MER analysis in ProFAA provides a new assessment capability for inclusion in AC 150/5380-9. It should be noted that MER does not replace BBI but works in conjunction with it. This report discusses the recommended changes to the AC to address the MER function and its applications.

The limits of acceptability for the MER process were developed empirically in Phase 1 using measured profile data collected over the past 30 years and with the FAA's Pilot Simulator Testing (PST) profiles. More profiles have been measured since the completion of Phase 1. These additional profiles were analyzed using the MER analysis process to further test the limits of acceptability developed in Phase 1, the results of which are discussed in this report.

As part of Phase 2 of this research project, this report also includes a review of the following FAA ACs to determine if the MER analysis process impacts their intended function.

- FAA AC 150/5380-6, *Guidelines and Procedures for Maintenance of Airport Pavements*
- FAA AC 150/5380-7B, *Airport Pavement Management Program (PMP)*
- FAA AC 150/5300-13A, *Airport Design*

It is anticipated that FAA AC 150/5380-7B, *Airport Pavement Management Program (PMP),* could be impacted significantly. This report contains a suggested approach to include the MER

analysis process into a proactive PMP regarding pavement roughness detection, quantification, and corrective action. The impact of the MER analysis process on FAA AC 150/5380-7B is summarized in Section 4.3.2.

In Phase 2 of this research effort, a task was included to estimate the benefits of a baseline profile for the purpose of tracking differential settlement and roughness growth over the life of the pavement. This report shows the results and potential benefits of tracking changes in profile shape and includes the results of long-term tracking of several case histories.

1. INTRODUCTION

The Federal Aviation Administration (FAA) Advisory Circular (AC) 150/5380-9, *Guidelines and Procedures for Measuring Airfield Pavement Roughness*, provides guidance for determining when a runway has become too rough. The assessment method in this AC uses the Boeing Bump Index (BBI) to identify roughness as acceptable, excessive, or unacceptable. The FAA's runway evaluation software program, ProFAA, is used to compute BBI and provides other tools for assessing runway roughness.

The current version of FAA AC 150/5380-9 considers only single-event roughness and is only for runway pavements. It does not address multiple-event roughness (MER). The research reflected in this report was conducted in two phases. Phase 1 (Gerardi & Gerardi, 2023) included developing a method capable of assessing MER for runways and taxiways using measured profile data only. The method was developed using the publicly available software ProVAL. The MER analysis developed in Phase 1 needed to be incorporated into ProFAA. In addition, FAA AC 150/5380-9, *Guidelines and Procedures for Measuring Airfield Pavement Roughness*, needed to be updated to reflect the MER process. This led to Phase 2 of this research.

Phase 1 defined three types of pavement roughness based on aircraft response to each one.

- **Type 1—Shock.** The result of encountering a sharp change in elevation, such as a single-step-type bump, a faulted slab, spall, or very short wavelength bump or dip.

- **Type 2—Short Wavelength.** A clear cutoff length that defines short versus long wavelength roughness does not exist; however, short wavelength roughness can be defined as roughness that minimally impacts the aircraft as a whole. Each strut tends to react to the localized roughness independently, e.g., the response at the main landing gear (MLG) has a minimal effect on the response at the nose landing gear (NLG) for Type 2 roughness and vice versa.

- **Type 3—Long Wavelength.** Long wavelength roughness can be defined as bumps and dips that excite the aircraft's rigid body modes of vibration (pitch and plunge). This type of roughness couples the MLG and NLG responses. The MLG response will impact the NLG response and vice versa.

Types 1 and 2 roughness are the primary concerns for taxiways since speeds are low and controllable. However, all three roughness types can affect aircraft response on runways where speed is high during takeoff and landing.

Multiple analysis tools are used to locate and quantify the three types of roughness. The tools are defined as:

- **Profile Index (PI)-100:** A 100-foot-*simulated* profilograph with a 1-inch blanking band locates and quantifies single- and multiple-event Type 3 (longer wavelength) roughness.

- **PI-25:** A 25-foot profilograph with a 0.4-inch blanking band locates and quantifies single- and multiple-event Type 2 roughness.

- **12-foot Rolling Straightedge (RSE):** Pavement profile deviations from a 12-foot RSE using a threshold of 0.4 inches locates and quantifies Type 1 roughness. Single bumps and dips like a faulted slab can be washed out when looking at an index such as PI-100, PI-25, or BBI over a larger pavement section. A deviation threshold of 0.4 inches is consistent with the *must grind* threshold for new pavement acceptance.

- **Boeing Bump Index (BBI):** BBI is computed to be consistent with the current AC 150/5380-9. This tool is also used to detect single-event bumps and dips with wavelengths greater than 100 feet.

Limits of acceptability (Tables 1 and 2) were developed empirically in Phase 1 using measured profile data collected over the past 30 years and profile data used in the FAA's pilot simulator study (Hudspeth, Stapleton, & Sparkman 2017). Each analysis tool has limits that define what is acceptable (green), excessive (yellow), and unacceptable (red).

Table 1. Limits of Acceptability for Runways

PI-100 (1-Inch BB)	**PI-25 (0.4-Inch BB)**	**12-Foot RSE**	**BBI**
Red > 35	Red > 35	Red > (ABS 0.8)	Red > 1.2 Unacceptable
Yellow 20–35	Yellow 20–35	Yellow (ABS 0.4–0.8)	Yellow 1.0–1.2 Excessive
Green < 20	Green < 20	Green < (ABS 0.4)	Green < 1.0 Acceptable

ABS = Absolute value
BB = Blanking band

Table 2. Limits of Acceptability for Taxiways

PI-25 (0.4-Inch BB)	**12-Foot RSE**
Red > 35	Red > (ABS 0.8)
Yellow 20–35	Yellow (ABS 0.4–0.80)
Green < 20	Green < (ABS 0.4)

ABS = Absolute value
BB = Blanking band

Runway and taxiway limits are the same except taxiways do not include PI-100 or BBI analyses because speeds are low and controllable.

It is important to note that the BBI-recommended actions regarding excessive and unacceptable pavement sections differ from MER-recommended actions. The MER method is intended to be a pavement management tool. The BBI method is concerned with fatigue and safe aircraft operations.

The BBI method-recommended actions (Boeing, 1995): "Roughness that occurs in the 'unacceptable' range will require immediate closure in the affected locations, while roughness in the ‘excessive’ range will require immediate repair, but not closure.” This description also contains information regarding the development and limitations of the Boeing method.

MER-recommended actions: A MER analysis is a pavement management tool. The limits in Tables 1 and 2 were established empirically using measured profile data. Roughness labeled in the acceptable MER range requires no further action until the next pavement management cycle. Roughness labeled in the excessive or unacceptable MER ranges requires additional evaluation to determine if/when/what corrective action is required. The additional evaluation in ProFAA can include remeasuring the profile in the affected areas, comparing the profile to other lines of survey, aircraft simulation, and engineering judgement.

2. APPROACH

2.1 UPDATES TO PROFAA

The MER vision developed in Phase 1 included:

- Evaluation of the entire runway or taxiway in 500-foot sections using the tools: PI-100, PI-25, 12-foot RSE, and BBI
- Results presented in a color-coded plot
- “Drill-down” capability to examine the results of each analysis tool
- Plotting options such as ability to remove end-to-end grade for better scaling
- Ability to shift the profile starting location
- Ability to save the results in a Microsoft® Excel® spreadsheet

There were six objectives for Phase 2. These objectives were:

1. Incorporate the concept and pavement evaluation tools developed in Phase 1 into ProFAA.
2. Modify ProFAA to include an automated screening procedure that will display color coded results with drill down capability.
3. Prepare narrative for inclusion of the methodology developed with this research into FAA AC 150/5380-9.
4. Investigate the potential application of this methodology into FAA AC 150/5370 “Standards for Specifying Construction of Airports” (Sections P401 and P501).
5. Investigate the benefit of establishing a baseline profile for tracking pavement contour changes over the life of the pavement.

6. Investigate potential impact of the BAA research results on specific FAA advisory circulars.

Previous versions of ProFAA included the ability to compute the PI, the RSE, and the BBI. Only minor changes listed below needed to be made to these tools.

- PI-25 uses a blanking band (BB) of 0.4 inches instead of the default value of 0.2 inches in a typical ProFAA PI computation. The existing third-order Butterworth low-pass filter of 0.5 feet/cycle to 10 feet/cycle was retained.

- The 12-foot RSE uses a deviation threshold of 0.4-inches, whereas the default straightedge threshold in ProFAA is 0.25 inches. A 10-feet/cycle, fourth-order Butterworth low-pass filter was applied to the profile before applying the 12-foot RSE.

- BBI is computed identically for a taxiway as it is for a runway, except that the maximum index is tabulated for each 500-foot section.

PI-100 was developed by modifying the PI-25 algorithm. Figure 1 is an illustration of a simulated 100-foot-long profilograph. PI-100 uses a blanking band of 1.0 inch. The PI-100 uses a third-order Butterworth low-pass filter at 10 feet/cycle.

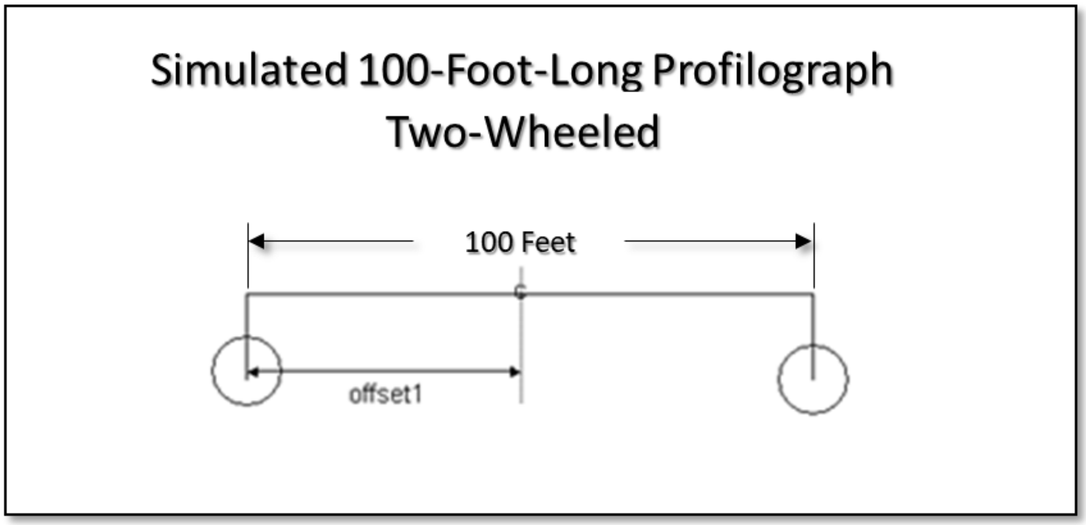


Figure 1. Illustration of a Simulated 100-Foot-Long Profilograph

To accomplish Phase 2 goals, the necessary changes to ProFAA were made to adjust for the MER analysis findings. The following summarizes a typical application of the MER operation in ProFAA.

- The operation button in ProFAA “Read File” is unchanged.

- A new operation button called “MER” has been added.

- Selecting MER prompts the user to identify the profile as a “Runway” or “Taxiway.”

- If “Runway” is selected, PI-100, PI-25, 12-foot RSE, and BBI are computed.
- If “Taxiway” is selected, PI-25 and 12-foot RSE are computed.
- The color-coded results are automatically presented in 500-foot sections.
- The elevation profile is plotted immediately below the color-coded plot. This provides the user with a visual reference of the roughness in each section.
- The PI-100 results are plotted below the profile plot for full pavement length.
- The PI-25 results are plotted below the PI-100 plot for full pavement length.
- The 12-foot RSE results are plotted below the PI-25 plot for full pavement length.
- The BBI results are plotted below the 12-foot RSE plot for full pavement length. (PI-100 and BBI are not computed for taxiways)

Features in ProFAA include:

1. **Hover function:** Hovering the cursor over any color-coded section will present the computed values for each analysis tool. This enables the user to see at a glance which evaluation tool, PI-100, PI-25, 12-foot RSE, or BBI, is acceptable, excessive, or unacceptable.
2. **Drill-down function:** Left clicking on a section will bring up a plot of that section of the profile and a plot of the selected tool results for that section. For example:
    a. Left clicking on PI-100 will display the PI-100 plotted results for that section.
    b. Left clicking on PI-25 will display the PI-25 plotted results for that section.
    c. Left clicking on 12-foot RSE will display the 12-foot RSE plotted results for that section.
    d. Left clicking on BBI will display the BBI plotted results for that section.
3. **User select buttons**: Just above the profile plot are four options that the user can select.
    a. **Output to Excel function:** This allows the user to move the computed values to a clipboard for exporting. This will open MS Excel and display it as “book 1.” The user can rename and save the file.
    b. **Shift Profile 250 feet:** This feature shifts the profile 250 feet and recomputes each analysis. In some cases, roughness events can split sections. This feature compensates for that possibility.
    c. **Undo Shift:** This feature shifts the profile back to the original profile.

d. **Remove Grade from Profile:** This feature allows the user to remove the end-to-end grade in the section selected. It provides a better scale for visualizing the roughness events in that section.

The MER method in ProFAA was initially checked against a set of profiles with known roughness. This set consisted of nine runway profiles and three taxiway profiles. These profiles were run through ProVAL to get *truth* values for each index. During the development of each index in the MER method, the index trace generated by ProFAA was tested against the one generated by ProVAL. This was done using three methods. The first was to overlay the two traces. The second was to compare the elevation spectra of each trace. The third was to perform a linear comparison using both traces and check the results of the linear fit. Figure 2 shows a sample of this comparison. After all indexes were implemented, the truth values generated by ProVAL were compared to the ones being generated by ProFAA. This is shown for the PI-100 in Table 3. These values were compared and used to further develop each index. For this example, cells that contain unacceptable PI-100 values are shaded red, and acceptable values are shaded green.

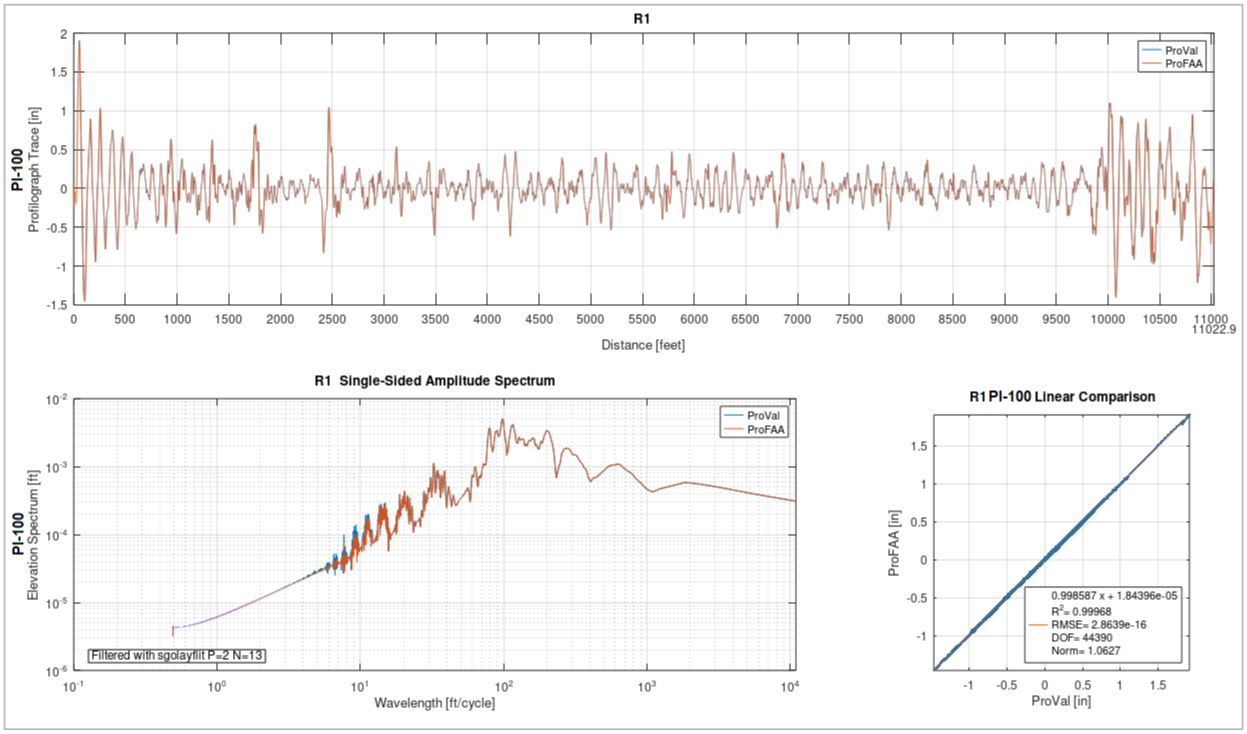


Figure 2. ProFAA-ProVAL PI-100 Comparison for Runway R1

Table 3. ProFAA-ProVAL PI-100 Comparison for Runway R1

	Distance		**PI-100**		
Section Number	**Start**	**End**	**ProVAL (C)**	**ProFAA MER (D)**	**Difference (C-D)**
1	0	500	55.41	53.71	+1.70
2	500	1,000	2.58	2.48	+0.10
3	1,000	1,500	1.25	2.77	-1.52
4	1,500	2,000	5.45	9.43	-3.98
5	2,000	2,500	9.09	9.42	-0.33
6	2,500	3,000	0.00	0.00	0.00
7	3,000	3,500	0.62	0.85	-0.23
8	3,500	4,000	0.00	0.00	0.00
9	4,000	4,500	1.23	1.70	-0.47
10	4,500	5,000	0.00	0.00	0.00
11	5,000	5,500	0.67	1.06	-0.39
12	5,500	6,000	0.00	0.00	0.00
13	6,000	6,500	0.00	0.00	0.00
14	6,500	7,000	0.00	0.00	0.00
15	7,000	7,500	0.00	0.00	0.00
16	7,500	8,000	0.35	0.63	-0.28
17	8,000	8,500	0.00	0.00	0.00
18	8,500	9,000	0.00	0.00	0.00
19	9,000	9,500	0.00	0.00	0.00
20	9,500	10,000	2.62	3.88	-1.26
21	10,000	10,500	42.68	44.11	-1.43
22	10,500	11,000	16.58	19.31	-2.73

After all comparisons appeared reasonable, additional profiles were selected from a database of in-service runways and taxiways and used to test the MER method in ProFAA. This database contained both concrete and asphalt runways and taxiways. For these profiles, ProFAA's MER method was tested in two ways. The first was to exercise the program so that bugs in the software would be uncovered. The second was to verify the results against the expectations for each runway. For example, a newly constructed runway is expected to be all green, and a runway with known roughness is expected to show red and yellow sections. The software was tested until all uncovered issues were resolved, and no further issues were uncovered after repeated testing with different profiles.

2.2 REVIEW FAA AC 150/5380-9

Because FAA AC 150/5380-9, *Guidelines and Procedures for Measuring Airfield Pavement Roughness,* is directly connected to ProFAA, changes made in ProFAA require changes to the AC. Recommended changes were documented by inserting comments throughout a digital MS

Word® document version of the AC and forwarded to the FAA. The recommended changes are summarized in Section 4. Two suggested chapters were added to the AC that describe the MER process and provide a step-by-step example on its use.

2.3 IMPACT ON OTHER RELATED ADVISORY CIRCULARS

The potential impacts on other related ACs were also considered. Each was reviewed with respect to the MER analysis added to ProFAA. These included:

- AC 150/5380-6, *Guidelines and Procedures for Maintenance of Airport Pavements* (FAA, 2014a)
- AC 150/5380-7B, *Airport Pavement Management Program (PMP)* (FAA, 2014b)
- AC 150/5300-13A, *Airport Design* (FAA, 2022)

2.4 EVALUATE ADDITIONAL PROFILE DATA

It was determined that the MER method would need to be evaluated against new profile data. The purpose of this task was to field-test the limits of acceptability established in Phase 1 with additional sets of measured profile data. Each profile was evaluated with the MER process in ProFAA as they became available. Ten runway profiles were analyzed. This task also tests the robustness of the MER method and the systems used to calculate it.

2.5 EVALUATION OF BASELINE SURVEY CONCEPT

This research included a task to identify/evaluate the benefits of establishing a baseline profile for tracking roughness growth and identifying areas needing corrective action. A proactive pavement management program (PMP) using a baseline profile to maintain acceptable levels of pavement smoothness will extend the life of the pavement and minimize dynamic loading to the aircraft. To accomplish this task, four case histories where the baseline concept had been in use for multiple years were examined.

3. RESULTS

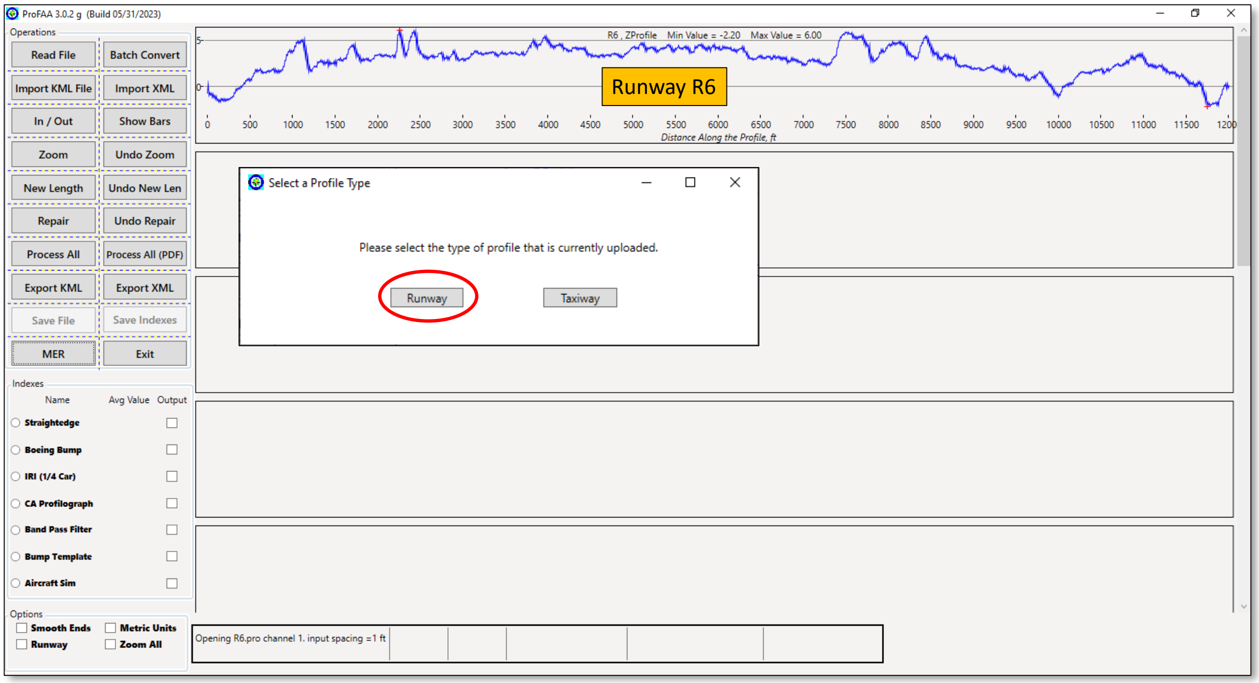
3.1 USING THE MER OPERATION IN PROFAA

The updated version of ProFAA now includes the MER operation. An additional “MER” button was added, as shown in Figure 3.

Figure 3. The MER Operation Button Added to Opening Screen in ProFAA

The following example describes a typical application of the MER operation in ProFAA. The selected profile, Runway R6, was measured with a walking profiler. Runway R6 is known to have a dynamic subgrade, and pilots have complained about roughness. Appendix A includes results of additional profiles, including known rough and smooth runways.

Figure 4 shows the ProFAA opening screen after selecting the profile to be analyzed and the MER operation. The Select Profile Type window will pop up when the MER button is selected. Runway R6 was selected for this example because it demonstrates how two bump events were detected with the PI-100 analysis tool. The orange comment boxes in Figures 4 and 5, which designate Runway R6, PI-100, PI-25, 12-foot RSE, and BBI, are intended as a highlight for the report; they do not appear as part of the actual ProFAA plot.



Please select the type of profile that is currently uploaded.

Opening R6.pro channel 1. input spacing =1 ft

Figure 4. ProFAA Opening Screen after a Runway Profile has been Selected

The color-coded results are displayed in 500-foot sections as shown in Figure 5. The results for PI-100, PI-25, the 12-foot RSE, and BBI analyses are also plotted automatically.

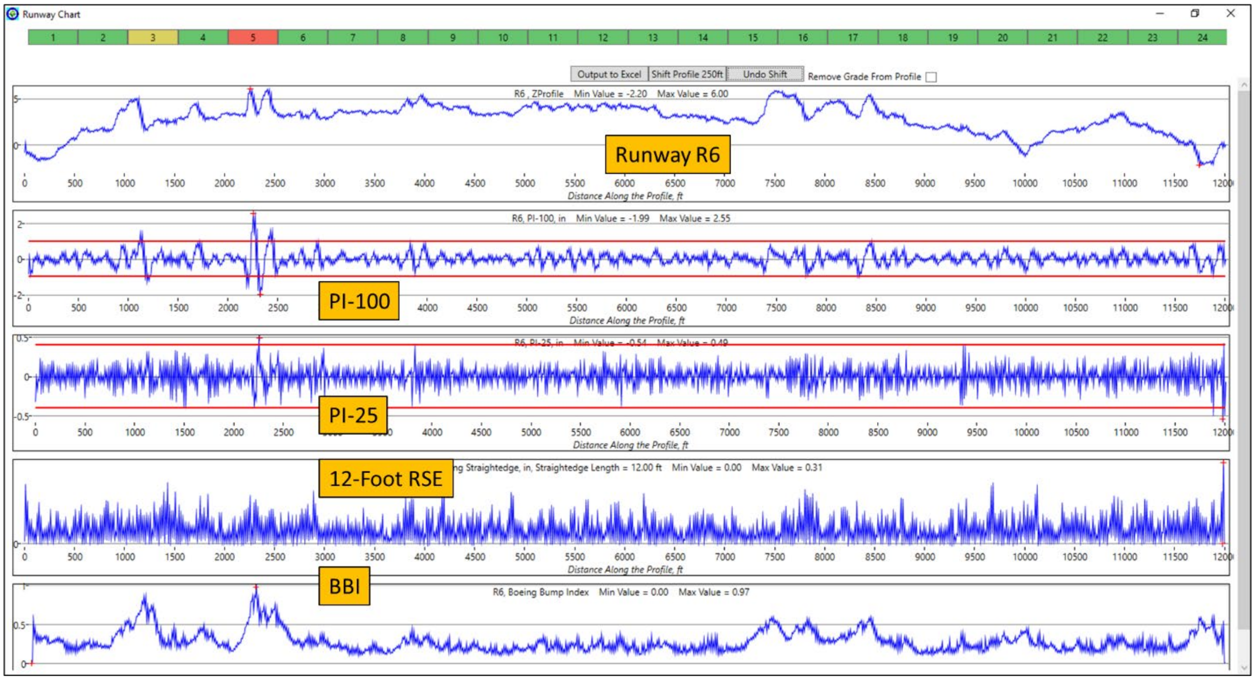


Figure 5. ProFAA MER Plot of Runway R6

Figure 6 is a screenshot that demonstrates the left-click function on Section 5. It displays the PI-100, PI-25, 12-foot RSE, and BBI results for that section and the plot of the profile in that section. Left clicking again, this time on PI-100, will plot the PI-100 results for that section. Similarly, the user can left click on PI-25, 12-foot RSE, or BBI to view those results.

Runway Chart

R6 , ZProfile Min Value = -2.20 Max Value = 6.00

R6, Boeing Bump Index Min Value = 0.00 Max Value = 0.97

ProFAA MER Analysis - Drill Down

(Runway) R6: Section 5: 2000 ft - 2500 ft

PI-100	PI-25	RSE	BBI
58.5	8.68	0.169	0.97375

MER Status: Unacceptable

R6 , ZProfile Min Value = 3.02 Max Value = 6.00

R6, PI-100, in Min Value = -1.99 Max Value = 2.55

Figure 6. Screenshot Showing the Left-Click Function on Section 5

In some cases, a bump or series of bumps can split two 500-foot sections, which can alter the results. Shifting the starting location by 250 feet will compensate for this situation. Figure 7 shows that the user has several buttons to select from: “Shift Profile 250ft,” “Undo Shift,” and “Remove Grade from Profile.” When the user elects to shift the profile 250 feet, a new plot is generated. Undo shift reverts to the original plot. When the “Remove Grade from Profile” box is selected, the end-to-end grade of the profile in that 500-foot section is removed, which allows for a better scale in some cases.

The user can also export the results for the entire runway to an MS Excel file by selecting “Output to Excel.” Table 4 was generated automatically when Output to Excel was selected. These data can be saved in any directory selected by the user.

A comma-separated value (CSV) output feature is also available. All the computed values for an MER computation (PI-100, PI-25, 12-foot RSE, and BBI) are saved in four separate CSV files once “Output to Excel” is selected, as shown in Figure 8. Each index’s data is stored in the directory that was used to load the initial profile.

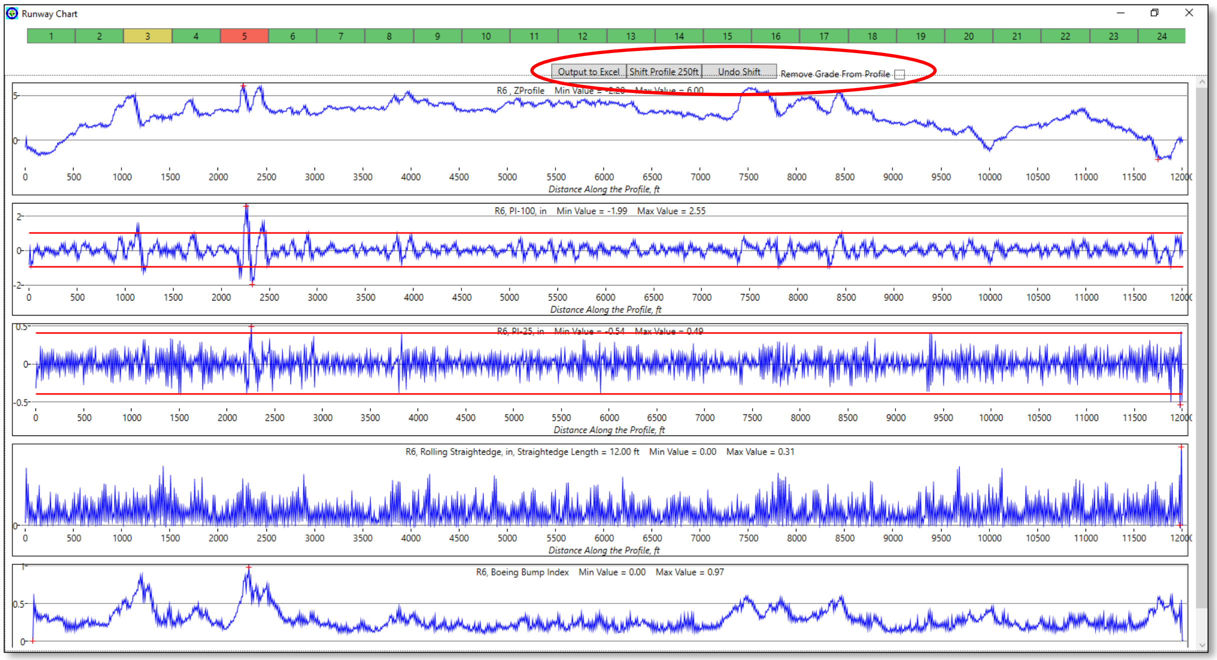
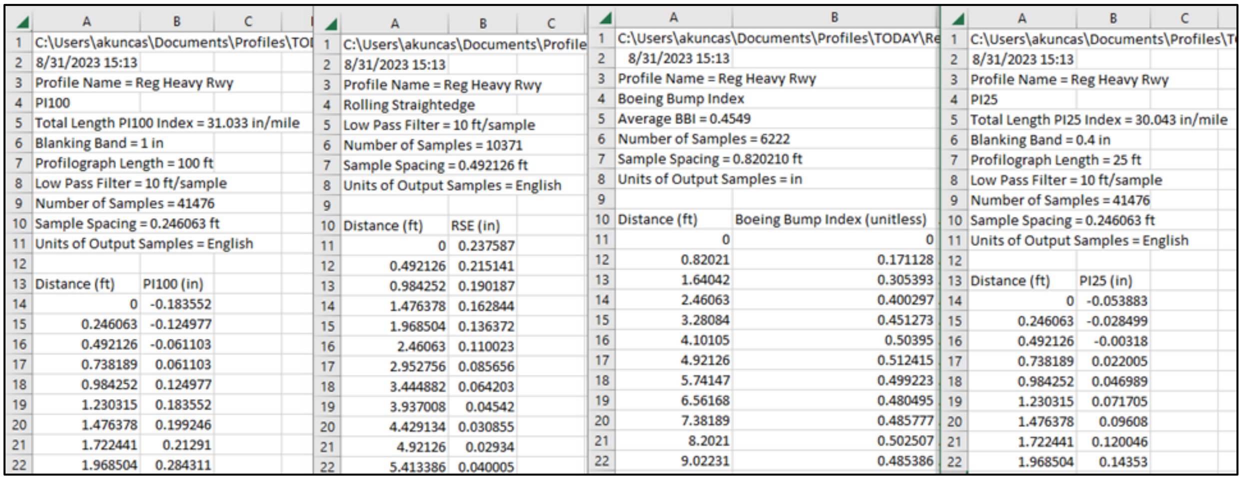


Figure 7. Shift Profile Option

Table 4. Excel Output for Runway R6

Runway Section For: R6	PI-100	PI-25	12-FOOT RSE	Max. BBI
Section #: 1, 0–500 ft	1.77	0.88	0.211	0.57206
Section #: 2, 500–1,000 ft	7.58	0	0.149	0.56221
Section #: 3, 1,000–1,500 ft	21.47	3.02	0.218	0.85974
Section #: 4, 1,500–2,000 ft	6.63	3.7	0.182	0.49105
Section #: 5, 2,000–2,500 ft	58.5	8.68	0.169	0.97375
Section #: 6, 2,500–3,000 ft	11.71	2.86	0.186	0.54988
Section #: 7, 3,000–3,500 ft	0	0	0.121	0.27238
Section #: 8, 3,500–4,000 ft	14.64	4.17	0.162	0.44325
Section #: 9, 4,000–4,500 ft	0	0	0.186	0.32426
Section #: 10, 4,500–5,000 ft	0	0	0.181	0.24454
Section #: 11, 5,000–5,500 ft	6.83	0	0.132	0.34665
Section #: 12, 5,500–6,000 ft	2.26	2.5	0.153	0.37177
Section #: 13, 6,000–6,500 ft	0	0.36	0.176	0.35552
Section #: 14, 6,500–7,000 ft.	0.6	0	0.118	0.34679
Section #: 15, 7,000–7,500 ft	6.98	0.39	0.126	0.59172
Section #: 16, 7,500–8,000 ft	8.36	1.4	0.191	0.56736
Section #: 17, 8,000–8,500 ft	10.22	0.71	0.147	0.59218
Section #: 18, 8,500–9,000 ft	1.63	1.89	0.159	0.35068
Section #: 19, 9,000–9,500 ft	0	3.94	0.156	0.38594
Section #: 20, 9,500–10,000 ft	4.64	0.36	0.217	0.44591
Section #: 21, 10,000–10,500 ft	4.29	0	0.209	0.43833

Runway Section For: R6	PI-100	PI-25	12-FOOT RSE	Max. BBI
Section #: 22, 10,500–11,000 ft	0	0.33	0.166	0.35699
Section #: 23, 11,000–11,500 ft	0	0	0.154	0.35375
Section #: 24, 11,500–12,000 ft	17.07	8.69	0.308	0.58447



	A	B	C
1	C:\Users\akuncas\Documents\Profiles\TO		
2	8/31/2023 15:13		
3	Profile Name = Reg Heavy Rwy		
4	PI100		
5	Total Length PI100 Index = 31.033 in/mile		
6	Blanking Band = 1 in		
7	Profilograph Length = 100 ft		
8	Low Pass Filter = 10 ft/sample		
9	Number of Samples = 41476		
10	Sample Spacing = 0.246063 ft		
11	Units of Output Samples = English		
12			
13	Distance (ft)	PI100 (in)	
14	0	-0.183552	
15	0.246063	-0.124977	
16	0.492126	-0.061103	
17	0.738189	0.061103	
18	0.984252	0.124977	
19	1.230315	0.183552	
20	1.476378	0.199246	
21	1.722441	0.21291	
22	1.968504	0.284311	

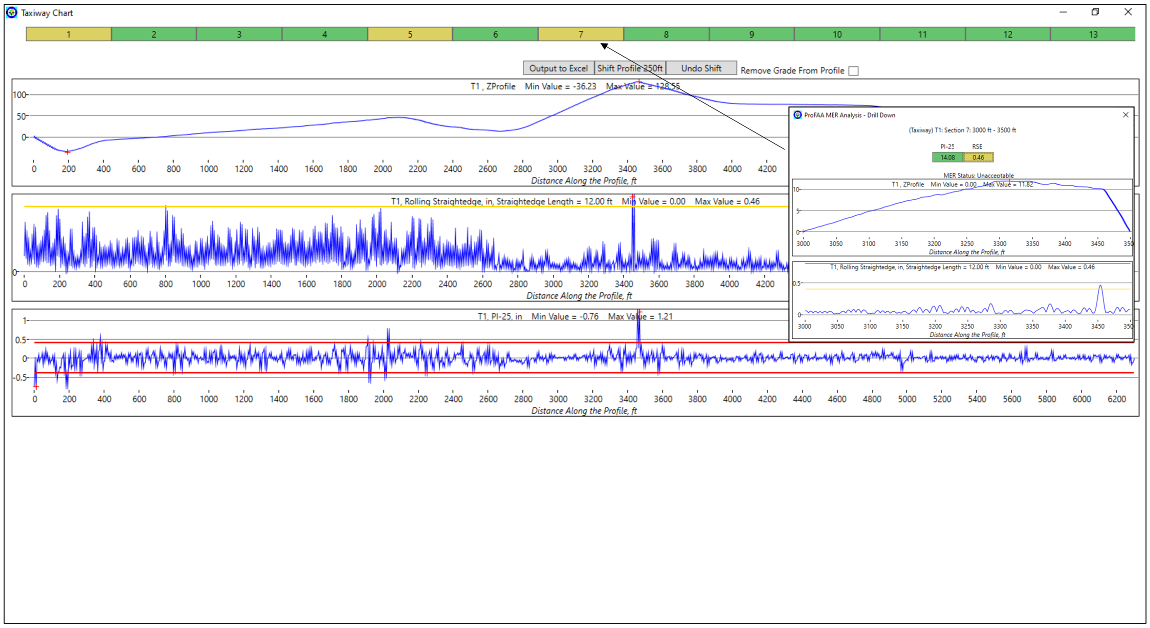
	A	B	C
1	C:\Users\akuncas\Documents\Profile		
2	8/31/2023 15:13		
3	Profile Name = Reg Heavy Rwy		
4	Rolling Straightedge		
5	Low Pass Filter = 10 ft/sample		
6	Number of Samples = 10371		
7	Sample Spacing = 0.492126 ft		
8	Units of Output Samples = English		
9			
10	Distance (ft)	RSE (in)	
11	0	0.237587	
12	0.492126	0.215141	
13	0.984252	0.190187	
14	1.476378	0.162844	
15	1.968504	0.136372	
16	2.46063	0.110023	
17	2.952756	0.085656	
18	3.444882	0.064203	
19	3.937008	0.04542	
20	4.429134	0.030855	
21	4.92126	0.02934	
22	5.413386	0.040005	

	A	B
1	C:\Users\akuncas\Documents\Profiles\TODAY\Re	
2	8/31/2023 15:13	
3	Profile Name = Reg Heavy Rwy	
4	Boeing Bump Index	
5	Average BBI = 0.4549	
6	Number of Samples = 6222	
7	Sample Spacing = 0.820210 ft	
8	Units of Output Samples = in	
9		
10	Distance (ft)	Boeing Bump Index (unitless)
11	0	0
12	0.82021	0.171128
13	1.64042	0.305393
14	2.46063	0.400297
15	3.28084	0.451273
16	4.10105	0.50395
17	4.92126	0.512415
18	5.74147	0.499223
19	6.56168	0.480495
20	7.38189	0.485777
21	8.2021	0.502507
22	9.02231	0.485386

	A	B	C
1	C:\Users\akuncas\Documents\Profiles\T		
2	8/31/2023 15:13		
3	Profile Name = Reg Heavy Rwy		
4	PI25		
5	Total Length PI25 Index = 30.043 in/mile		
6	Blanking Band = 0.4 in		
7	Profilograph Length = 25 ft		
8	Low Pass Filter = 10 ft/sample		
9	Number of Samples = 41476		
10	Sample Spacing = 0.246063 ft		
11	Units of Output Samples = English		
12			
13	Distance (ft)	PI25 (in)	
14	0	-0.053883	
15	0.246063	-0.028499	
16	0.492126	-0.00318	
17	0.738189	0.022005	
18	0.984252	0.046989	
19	1.230315	0.071705	
20	1.476378	0.09608	
21	1.722441	0.120046	
22	1.968504	0.14353	

Figure 8. Screenshot of Excel CSV Output

Taxiway analyses consist of PI-25 and the 12-foot RSE computations only because speeds are low and controllable on taxiways. The results of the Taxiway T1 analysis, shown in Figure 9, indicate mild Type 1 roughness in several sections. Left clicking on the RSE in section 7 shows the 12-foot RSE exceeds the 0.4-inch maximum deviation threshold.



(Taxiway) T1: Section 7: 3000 ft - 3500 ft

PI-25	RSE
14.08	0.46

MER Status: Unacceptable

Figure 9. Taxiway T1 Showing Mild Type 1 Roughness

3.2 REVIEW OF FAA AC 150/5380-9

A thorough review was conducted of AC 150/5380-9, *Guidelines and Procedures for Measuring Airfield Pavement Roughness* (FAA, 2009)**.** The primary purpose of the review is to provide recommendations regarding the changes made to ProFAA, and how the addition of the MER module in ProFAA will impact this AC.

A summary of the recommended changes to FAA AC 150/5380-9 is as follows:

Report Forward:

> *This AC provides guidance and procedures for airfield pavement roughness evaluation using measured profile data only. Both isolated and repeated events can be identified using the criteria herein. The FAA's roughness evaluation software ProFAA is used in the evaluation.*

Chapter 1 Paragraph 1.1:

> *Airport pavement roughness evaluation is conducted in two parts.*
> *Part 1 is the familiar/current Boeing Bump Method or Boeing Bump Index (BBI). This evaluation method considers isolated (single) bump events. It is intended to avoid severe roughness events that could cause damage to the aircraft. This method requires that "unacceptable" sections of the runway be closed immediately. Part 1 applies to runways only.*
>
> *Part 2 refers to a multiple-event roughness (MER) evaluation tool and is used to evaluate multiple bumps and dips in succession. MER is a screening process that enables the user to make informed decisions whether corrective action is suggested as part of Pavement Management. Part 2 considers single and multiple bump events and applies to runways and taxiways. Pavement sections identified as "acceptable" have met roughness screening requirements. The periodic roughness assessment is complete. Pavement sections that are "excessive" or "unacceptable" in Part 2 are required to be evaluated using additional tools in ProFAA such as aircraft simulation that predict aircraft dynamic response.*

Chapter 1 Paragraph 1.2a. It is recommended to add the following to 1.2a:

> *Airport pavement roughness can be described by the way the roughness impacts the aircraft's response.*
>
> *Aircraft response to airport pavement roughness can be broken into three categories: shock, short-wavelength, and long-wavelength responses.*
>
> ***Type 1, Shock:*** *Shock is the result of encountering a sharp change in elevation such as a single step-type bump, a faulted slab, spall, or very short-wavelength bump or dip. Shock loading is typically too fast for the struts and tires*

(suspension system) to fully react to the roughness. Tire size and tire pressure will impact the aircraft's response.

Type 2, Short-Wavelength: *There is no clear cutoff length that defines short- versus long-wavelength roughness. However, short-wavelength roughness can be defined as roughness that minimally impacts the aircraft's rigid body modes of vibration (pitch and plunge), e.g., the response at the MLG to Type 2 roughness has a minimal effect on the response at the NLG and vice versa. Each strut tends to react to the localized roughness independently.*

Type 3, Long-Wavelength*: Long-wavelength roughness can be defined as bumps and dips that can excite the aircraft's rigid body modes of vibration (pitch and plunge). This type of roughness couples the MLG and NLG responses, e.g., the response at the MLG can significantly affect the response of the NLG and vice versa. This type of response is caused by bumps and dips like runway intersections with crowns, vertical curves, or changes in grade.*

Types 1 (shock) and 2 (short-wavelength) are likely to be the primary concern for taxiways since speeds are low and controllable. During takeoff and landing operations, all three types of roughness can affect aircraft response on runways where aircraft speeds can reach takeoff velocity.

Chapter 1 Paragraph 1.2c. It is recommended to rewrite Paragraph 1.2c as follows:

The FAA defines profile roughness as surface profile deviations present over a portion of the runway that causes airplanes to respond in ways that can increase fatigue on airplane components, reduce braking performance, impair cockpit operations, and/or cause discomfort to passengers. Response depends on airplane size, weight, and aircraft velocity. Even when roughness does not cause discomfort to passengers, it could affect the fatigue life of airplane components or decrease operational safety of the airplane. Depending upon airplane characteristics and operating speed, an airplane may be excited into harmonic resonance due to profile roughness that can increase inertial forces or vibrations within the airplane structure. One example is resonant response in a four-wheel truck pitch mode, which elevates friction in the pivot joint.

The FAA groups airfield pavement roughness into two categories, Single-Event Roughness and Multiple-Event Roughness.

1) ***Single-Event Roughness.***

These are bumps and dips that are isolated single events that occur over 100 meters (328 feet) or less. They can induce structural fatigue damage and cause dynamic loading on the pavement. This type of roughness is the focus of the BBI approach for roughness assessment. Elevation changes can occur as an abrupt vertical step/spall (Type 1 or 2) or as a more gradual deviation from a planned pavement profile (Type 3).

*2) **Multiple-Event Roughness (MER).***

MER is the result of several bumps or dips in succession. Aircraft loads can build nonlinearly, particularly if the aircraft speed and bump length resonate with the aircraft's natural frequencies of vibration.

The MER method was developed to detect multiple-event roughness using measured profile data only. The MER analysis is a screening process to be used as a pavement management tool. It is designed to extend pavement life by locating and quantifying areas that might require corrective action. The MER method can be applied to runways and taxiways.

Chapter 1 Paragraph 1.2i. It is recommended to add Paragraph 1.2i introducing ProFAA.

> ***1.2i. ProFAA Roughness Evaluation Software:*** *ProFAA is a pavement evaluation tool designed to aid users in locating and quantifying airport pavement roughness that is acceptable, excessive, or unacceptable. ProFAA uses a number of tools to do that; the BBI, various straightedge algorithms, the MER tool, and aircraft simulation. Aircraft simulation in ProFAA predicts the dynamic response of an aircraft operating on that surface at a constant speed.*

Chapter 1 Paragraph 1.2j. It is recommended to add Paragraph 1.2j discussing profile measurements.

> ***1.2j. Profile Measurement:*** *Assessing an airport pavement for roughness levels is dependent on a quality profile data of the runway or taxiway. A variety of commercially available profilers are capable of accurately measuring elevation and distance down the runway. True profilers are capable of measuring changes in grade and will capture all wavelengths. High-speed inertial profilers measure a "relative" profile. Inertial profilers are fast and very repeatable, but high-pass filtering can impact the accuracy in locating Type 3 roughness. When using inertial profilers, high-pass filtering should be avoided during the measurements. Paragraph 2.2 discusses profile requirements in more detail.*

Chapter 2 was left intact except for minor typos and minor content corrections.

Chapter 3 was updated to reflect changes to ProFAA regarding the computation of the BBI. These included updating charts and deleting areas that are no longer supported by ProFAA.

Chapter 4 was added to this AC. Chapter 4 describes the MER process and the concept of operation.

Chapter 5 was added to this AC. Chapter 5 is a step-by-step example demonstrating the procedure of conducting an MER analysis in ProFAA.

Review of AC 150/5380-9 highlighted the need for additional testing of inertial profilers and their ability to capture wavelengths that impact MER and BBI results. Appendix B contains the results of a limited test comparing an inertial profiler using a pre-measurement filter of 0.0, to two different walking profilers. The results indicate that long wavelength measurements are possible with inertial profilers. However, additional testing is necessary to confirm their use for airport pavement roughness evaluation applications.

3.3 IMPACT ON OTHER RELATED ADVISORY CIRCULARS

3.3.1 Impact on AC 150/5380-6C, *Guidelines and Procedures for Maintenance of Airport Pavements* (Dated 10/10/2014)

Researchers reviewed AC 150/5380-6, *Guidelines and Procedures for Maintenance of Airport Pavements*, to determine the impact of the MER process. This AC focuses primarily on inspection and general maintenance procedures. It defines the various types of pavement failures, such as rutting and shoving for asphalt pavements, and cracking and joint failure for rigid pavements. It describes various pavement repair methods and recommends a proactive PMP that references AC 150/5380-7, *Airport Pavement Management Program (PMP).*

After review, it was concluded that the MER process has minimal direct impact on AC 150/5380-6. The impact that the MER process might have on pavement management is more applicable to AC 150/5380-7.

3.3.2 Impact on AC 150/5380-7B, *Airport Pavement Management Program (PMP)* (Dated 10/10/2014)

Researchers also reviewed AC 150/5380-7B for potential impacts from the MER process. It was determined that the MER process added to ProFAA will have an impact on airport pavement management practices. The primary purpose of the review was to provide recommendations regarding the changes made to ProFAA, and how the addition of the MER module in ProFAA will impact this AC. A suggested approach was to include the MER process into a proactive PMP regarding pavement roughness detection, quantification, and corrective action. Figure 10 depicts the version of the proactive PMP.

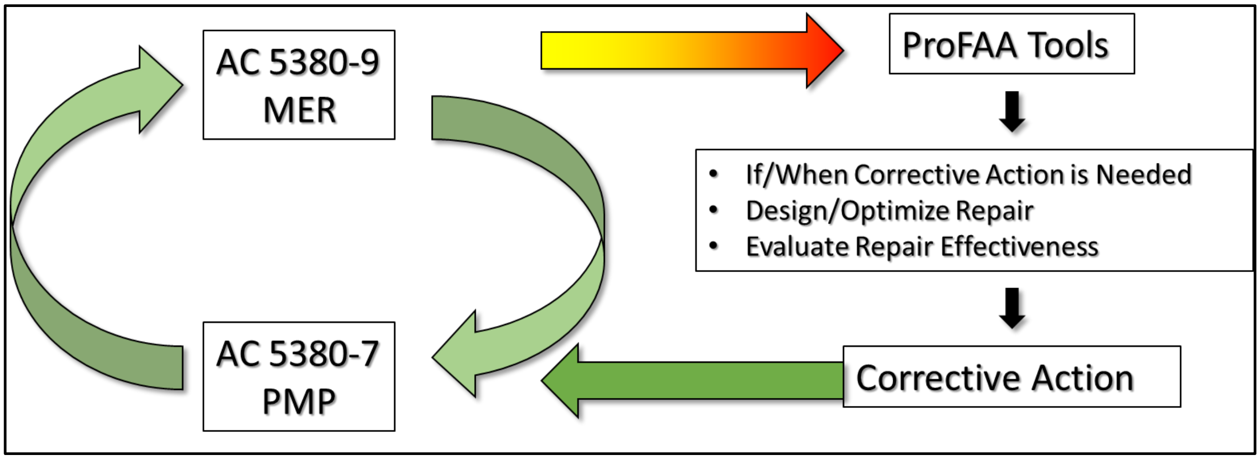


Figure 10. Proactive Approach for Pavement Management Regarding Roughness

The following changes were recommended.

Paragraph 2.3.2.2 Roughness: Paragraph 2.3.2.2 could be rewritten as follows:

> *Roughness measurements can be included as part of the periodic PM assessment. Recent improvements in profile measurement methods and analysis techniques enable airport pavements to be proactively maintained at acceptable smoothness levels. AC 150/5380-9,* Guidelines and Procedures for Measuring Airfield Pavement Roughness*, contains procedures for assessing pavement roughness using measured profile data only. That process is described in the added Section 3.4, Roughness Assessment Method.*

Recommended Adding Section 3.4 to this AC:

Paragraph 3.4 describes a new approach envisioned for airport pavement roughness assessment. The proposed language says:

> *AC 150/5380-9, "Guidelines and Procedures for Measuring Airfield Pavement Roughness," contains a procedure for proactively maintaining airfield pavements with acceptable levels of smoothness. It works in conjunction with the FAA's airfield pavement evaluation software (ProFAA) and is referred to as the Multiple Event Roughness (MER) evaluation tool.*
>
> *Airport pavement roughness can be described by the way the roughness impacts the aircraft's response and can be broken into three categories: shock, short wavelength, and long wavelength response.*

As such, it recommends a procedure for proactively maintaining airfield pavements to an acceptable level smoothness. The AC works in conjunction with the FAA's updated airfield pavement evaluation software (ProFAA) with the new operation referred to as the MER evaluation tool.

The recommended changes should define the three types of roughness based on how they impact aircraft response. The MER procedure in ProFAA should be illustrated showing how runway and taxiway roughness can be located and quantified in a color-coded plot. It should also suggest how AC 150/5380-9, AC 150/5380-7, and ProFAA can work together to proactively monitor and maintain acceptably smooth airport pavements. It describes how the synergistic approach can aid in decision-making regarding if, how, and when corrective action is needed. This concept is illustrated in Figure 10.

3.3.3 Impact on AC 150/5300-13A, *Airport Design* (Dated 3/31/2022)

The MER tool in ProFAA can be used in airport pavement design. For example, runway intersections with crowns for water dispersal are felt by the aircraft as bumps. Using the MER tool to determine if the bump is acceptable could be an assurance tool that would flag potential errors in design.

In addition, the MER tool could be used to evaluate designs for runway repairs or rehabilitation. Appendix C contains an example where a rehabilitation design review using the MER tool in ProFAA would have prevented construction of a pavement that was immediately determined to be unacceptable from a roughness standpoint.

3.4 EVALUATE ADDITIONAL PROFILE DATA

To further test the process and the limits, the MER method in ProFAA was applied to other runway profiles as they became available. Appendix A contains the MER results for 10 runways that were analyzed in the past 2 years. All the profiles analyzed were measured with walking profilers; either the SurPRO or the Auto Rod & Level (AR&L). The conclusion resulting from the additional runway MER analyses was that they were consistent with the methodology and limits of acceptability established in the MER development phase. A few exceptions (almost always the 12-foot RSE) were generally detected on otherwise smooth pavements. The RSE is usually the reason the limit was exceeded. It is not uncommon to capture a profile data anomaly that impacts the RSE analysis, particularly when using a walking profiler. In the case of a false positive in the MER analysis, it is recommended to conduct additional analysis. This could mean remeasuring the section(s) in question or comparing it to other lines of survey for consistency. For those pavement sections that exceed the limits of other MER evaluation tools, aircraft simulation is recommended.

3.5 EVALUATION OF BASELINE SURVEY CONCEPT

Long-term profile tracking and comparing the data to a baseline survey can be useful in extending pavement life and reducing loads on the aircraft that use those surfaces. Tracking “roughness growth” can also be used to estimate when corrective action will be needed. Appendix D contains the results of four case histories whose profiles were tracked for multiple years and compared to a baseline survey.

4. CONCLUSIONS

4.1.1 ProFAA Modification

The FAA's airport pavement roughness evaluation program, ProFAA, has been modified to include the multiple-event roughness (MER) operation. The MER operation is capable of locating and quantifying single- and multiple-event roughness using measured profile data only. The MER assessment tool applies to runways and taxiways. The results are presented in a color-coded plot of the pavement in 500-foot sections. The MER operation supports pavement management programs (PMPs).

4.1.2 Impact on Advisory Circular 150/5380-9 (Dated 9/30/2009)

Advisory Circular (AC) 150/5380-9, *Guidelines and Procedures for Measuring Airfield Pavement Roughness,* and ProFAA are designed to work together. A review of the AC was conducted to determine the impact that the MER operation has on the AC content.

The new approach for the pavement evaluation process is divided into two parts.

- Part 1 is the familiar Boeing Bump Method or Index (BBI). This evaluation method considers isolated (single) bump events. It is intended to detect severe roughness events that could impact safe operations or cause damage to the aircraft. This method requires that unacceptable sections of the runway be closed until repairs are made. Part 1 applies to runways only.

- Part 2 applies to runways and taxiways. It is the MER evaluation tool and is used to evaluate single and multiple bumps and dips in succession. MER is part of a process that enables the user to make informed decisions regarding the need for corrective action. Pavement sections that are flagged as excessive or unacceptable in Part 2 require further evaluation prior to making decisions regarding corrective action. Things to consider in the enhanced evaluation: examine the measured profile data, compare the profile to other lines of survey, or remeasure the affected pavement sections, if necessary. In addition, ProFAA has other tools to assist in determining if, when, and what corrective action is needed. Aircraft simulation can be used to predict the dynamic response of the aircraft. It can also be used to determine the effectiveness of a proposed repair design.

Two chapters were recommended to add to the AC.

- Chapter 4 is a description of the MER evaluation concept.

- Chapter 5 is a step-by-step application of the MER operation.

4.1.3 Field Testing the MER Concept

The MER operation in ProFAA was applied to 10 recently measured runways, to field-test the limits of acceptability that were established empirically in Phase 1 of this research. The process was successful with a few exceptions with the RSE analysis. The 12-foot RSE is the most sensitive analysis method of all four tools regarding exceeding the acceptable limit. The reason is often an anomaly in the measured profile data.

4.1.4 Impact on Other Related Advisory Circulars

A review was conducted on three related ACs:

- AC 150/5380-6C, *Guidelines and Procedures for Maintenance of Airport Pavements.* (FAA, 2014a). The MER operation had very little impact on this AC.
- AC 150/5380-7B, *Airport Pavement Management Program (PMP)* (FAA, 2014b). The MER operation could have a significant impact on this AC.
- AC 150/5300-13B, *Airport Design*. (Dated 3/31/2022). The MER operation could have an impact on this AC by evaluating pavement designs.

Note: Microsoft® Word® versions of AC 150/5380-9 and AC 150/5380-7B containing the recommended changes were sent to the FAA William J Hughes Technical Center and to the FAA Standards office (AAS-100) as non-published Technical Notes (TNs). These technical notes contained the suggested changes to each of the ACs regarding how they were impacted by the MER process. The TNs are written such that the suggested changes can be accepted, rejected, or modified by AAS-100. Copies of these TNs are also retained by APR Consultants, Inc. (APR).

5. RECOMMENDATIONS

5.1.1 ProFAA Upgrade

If a runway or taxiway is flagged as excessive or unacceptable using the MER process, it is necessary to conduct further analyses to determine if, when, and what corrective action is needed. This can include conducting aircraft simulations. The current version of ProFAA can only conduct constant-speed taxi simulations. It is recommended that ProFAA be modified to simulate more realistic operations that include takeoff and landing.

The current version of ProFAA simulates five different (mostly older) aircraft. It is recommended that ProFAA be upgraded to represent a cross section of modern aircraft. The recommended aircraft would be classes (generic versions) representing:

- General Aviation
- Regional Jet
- Narrow-Body Commercial Jet
- Middle-Market Class Commercial Jet
- Wide-Body Class Commercial Jet
- Very Large Class Commercial Jet

Gross weight and wheel spacing are the primary components that define the classes. The data required to simulate the generic versions would be based on actual aircraft data that fall into that particular class.

5.1.2 ADVISORY CIRCULARS 150-5380-9 and 150-5380-7

- It is recommended that FAA AC 150/5380-9, *Guidelines and Procedures for Measuring Airfield Pavement Roughness*, be updated to reflect the changes made to ProFAA.

- It is recommended that FAA AC 150-5380-7, *Airport Pavement Management Program (PMP)*, be updated to include a statement that the MER process can provide a proactive approach for pavement management that links the ACs to the MER process in ProFAA as described in Figure 1.

- It is recommended that FAA AC 150-5300-13B, *Airport Design*, include a statement that the MER operation in ProFAA provides a tool that can be used to evaluate airport pavement designs.

5.1.3 Inertial Profilers

- It is recommended that inertial profilers be evaluated for their ability to capture long wavelength roughness (recommend up to 200 feet) required for BBI and MER analysis. Initial studies (Appendix B) indicate that removing all premeasurement filters can capture wavelengths required for MER and BBI analyses.

6. REFERENCES

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APPENDIX A—EVALUATION OF ADDITIONAL PROFILES

The multiple-event roughness (MER) process and limits of acceptability were developed empirically using the measured profile data from 72 runways and taxiways, and profile data from the FAA's pilot simulator study (Hudspeth, Stapleton & Sparkman, 2017) where the profiles were also rated subjectively.

To further test the process and the limits, the method was applied to other runway profiles as they became available.

This appendix contains the results for 10 runways that were analyzed in the past 2 years. All the profiles analyzed were measured with walking profilers, either the SurPRO or the Auto Rod & Level (AR&L).

The pavements are identified as:

- **R201**

  Figure A-1 shows R201, an asphalt runway that received a new overlay in 2022. R201 is a smooth pavement except for a 0.43-inch deviation from the 12-foot rolling straightedge (RSE) that was detected in section 7. To confirm this issue, one option would be to remeasure that section to confirm and then decide on appropriate corrective action.

(Runway) R201CL _2022: Section 7: 3000 ft - 3500 ft

PI-100	PI-25	RSE	BBI
0	1.66	0.426	0.71751

MER Status: Excessive

Figure A-1. MER Analysis Results of Runway R201

- **R202**

Figure A-2 shows R202, a smooth asphalt runway that has been recently resurfaced. This will serve as a new baseline for future comparisons. This runway is built on reclaimed ground; differential settlement is expected for this runway.

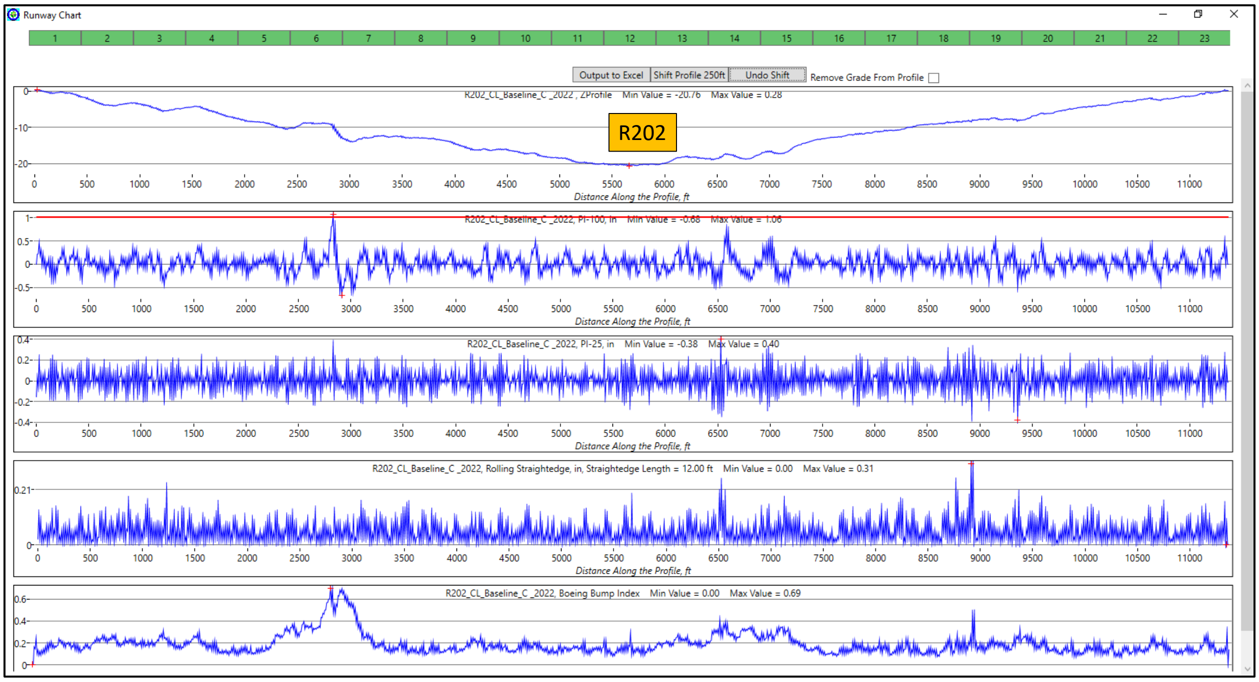


Figure A-2. MER Analysis Results of Runway R202

- **R203**

Figure A-3 shows R203, a Portland concrete cement (PCC) runway that underwent significant corrective action several years ago. Takeoff simulations using the software program, Airport Pavement Roughness Assessment Software (APRas), resulted in excessive response at the Cockpit (CP) vertical acceleration and Center of Gravity (CG) vertical acceleration. This was runway is R6 from Phase 1, which had significant corrective action several years ago. This runway is built on expansive clay material and has experienced differential settlement in the past. The MER analysis found it to be excessive in many areas and unacceptable in several others. APRas 100-knot taxi and takeoff and landing simulations found it excessive in multiple locations. This indicates that it continues to experience differential settlement. The R203 profile was measured using a SurPRO (centerline only) in 2022. R203 likely ranks high for corrective action.

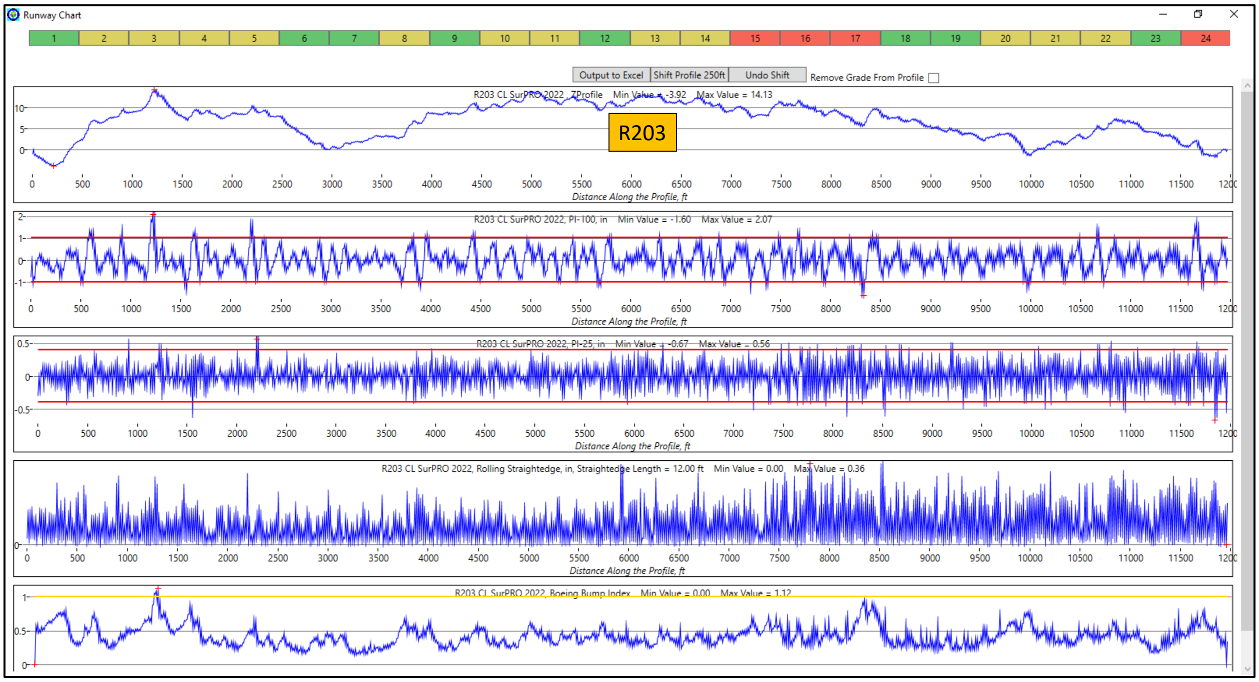


Figure A-3. MER Analysis Results of Runway R203

- **R204**

Figure A-4 shows R204, a smooth PCC runway. The profile was measured with a SurPRO. APRas 100-knot taxi and takeoff and landing simulations found it acceptable.

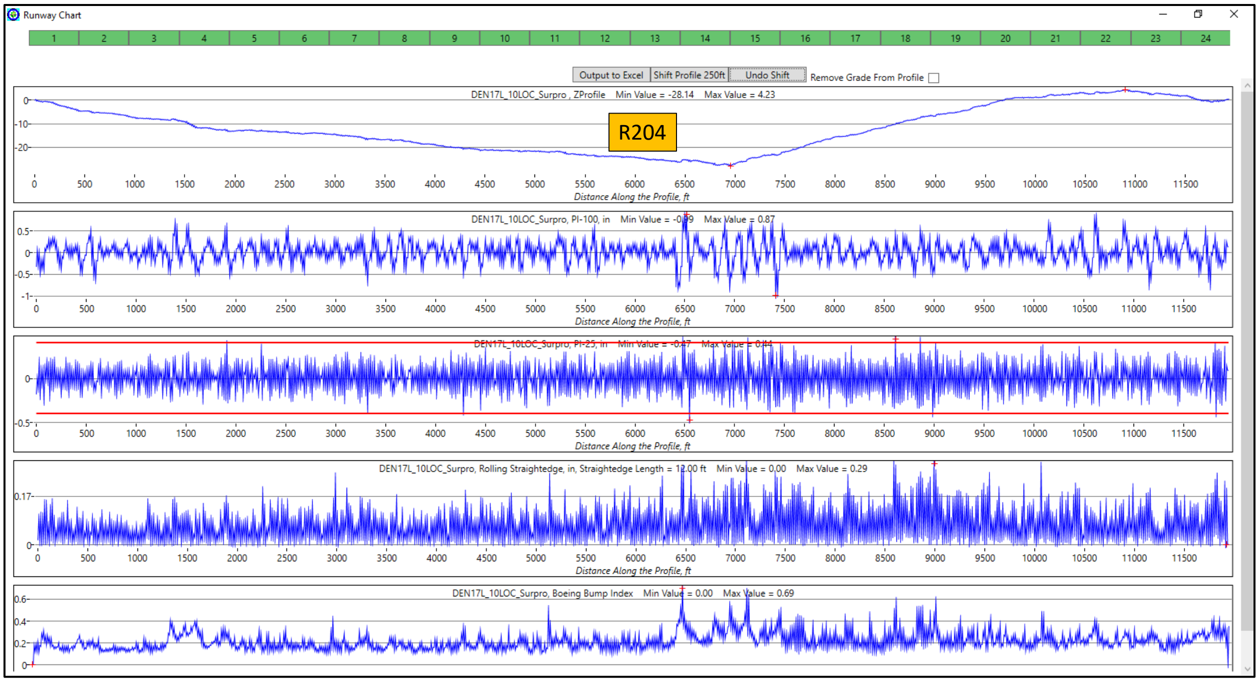
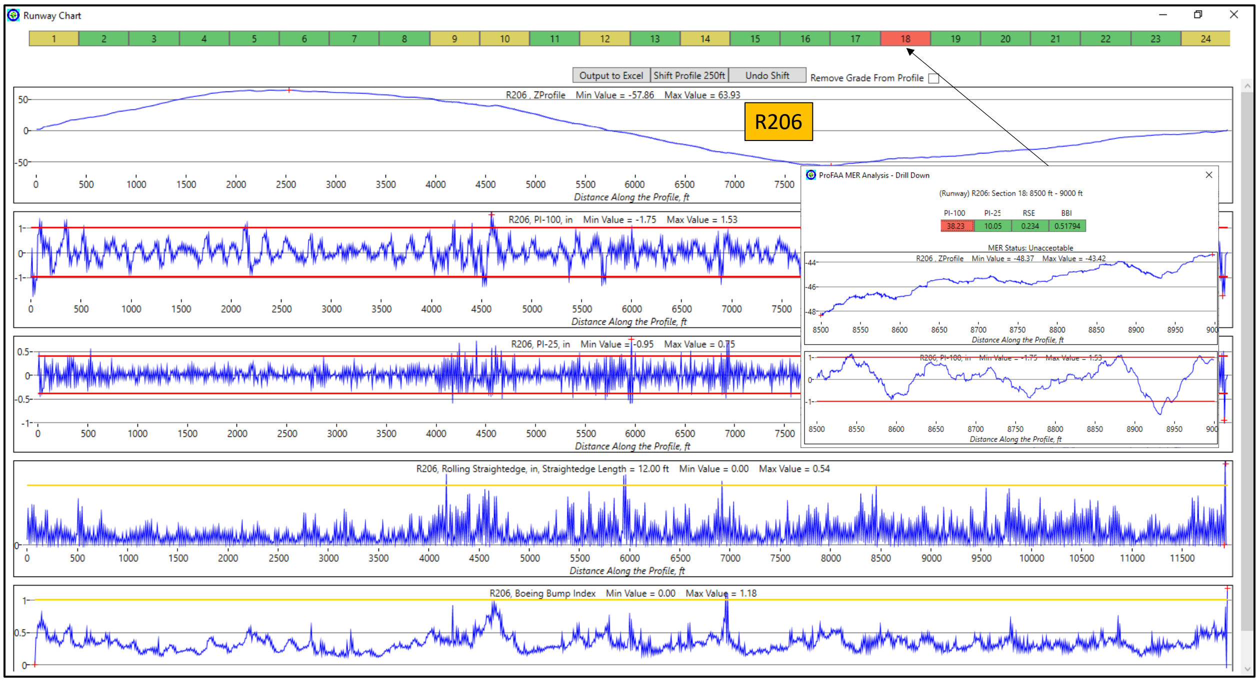


Figure A-4. MER Analysis Results of Runway R204

- **R206.**

  Figure A-5 shows R206, a PCC runway found to have excessive roughness that would require additional analysis to determine if corrective action is needed. There were multiple Type 3 bumps in Section 18. APRas 100-knot taxi and takeoff and landing simulation found it to produce excessive responses, particularly in the cockpit, in multiple locations. Additional analysis is recommended for this runway.



(Runway) R206: Section 18: 8500 ft - 9000 ft

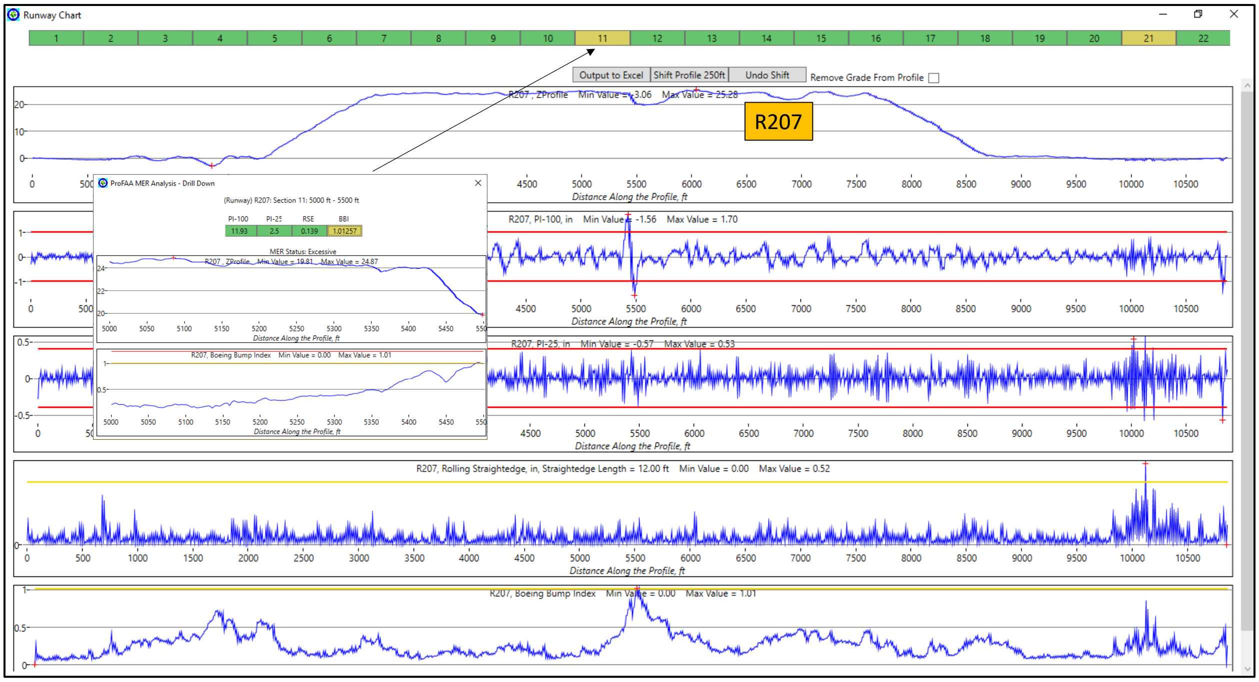
PI-100	PI-25	RSE	BBI
38.23	10.05	0.234	0.51794

MER Status: Unacceptable

Figure A-5. MER Analysis Results of Runway R206

- **R207**

Figure A-6 shows R207, a runway with visible settlement in the profile when first measured in 2022. This runway is built on reclaimed ground, so differential settlement was expected. It has several visible dips and bumps in the profile, but they are very long wavelengths, which did not trigger PI-100 or PI-25 limits. However, one area in section 11 triggered an excessive BBI. It also produced an excessive response in APRas simulations. As a result of the APRas findings, this runway had corrective action and was analyzed again as R208.



(Runway) R207: Section 11: 5000 ft - 5500 ft

PI-100	PI-25	RSE	BBI
11.93	2.5	0.139	1.01257

MER Status: Excessive

Figure A-6. MER Analysis Results of Runway R207

- **R208**

The MER analysis found R207 to exceed the BBI limit of acceptability. It had a very long wavelength dip caused by significant settlement, which was corrected in 2023. Figure A-7 shows the results of the MER analysis of R208 after repair of the long dip. Section 3 triggered a 12-foot RSE. That area was not repaired so it is considered a data anomaly. This runway will be remeasured and analyzed annually.

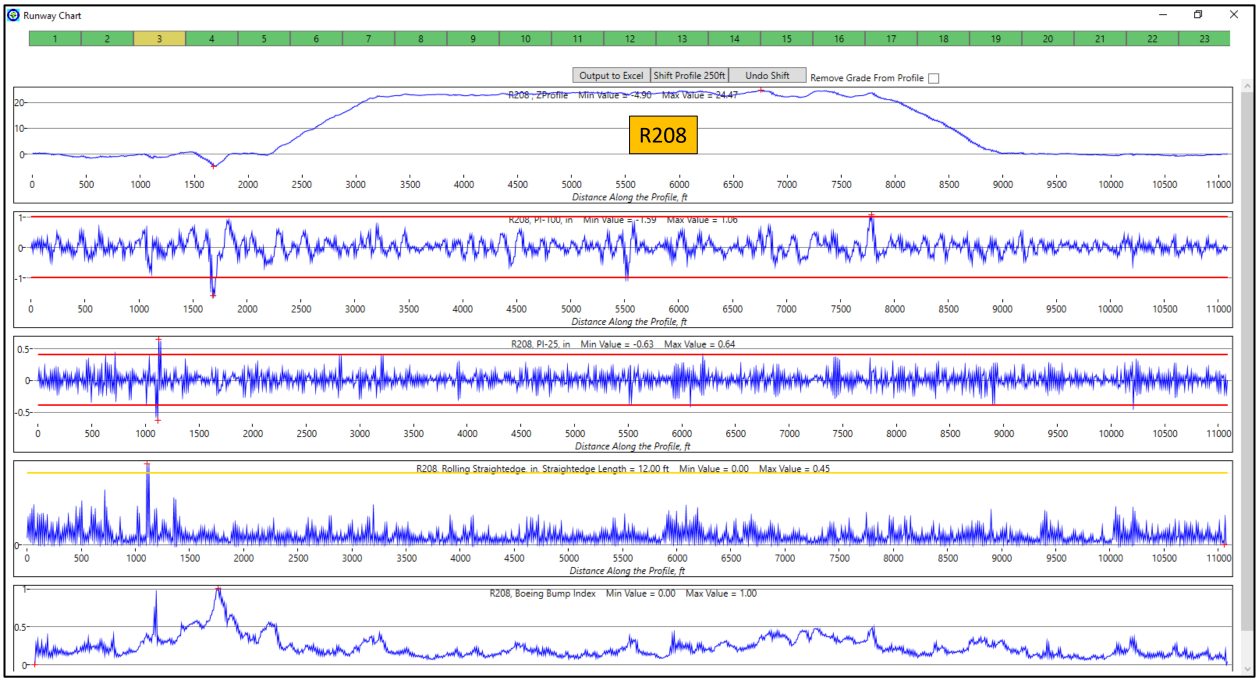


Figure A-7. MER Analysis Results of Runway R208

- **R209**

Figure A-8 shows R209, an asphalt runway, is one of three parallel runways. The MER analysis found three areas that exceeded the RSE threshold and one area that barely exceeded the PI-100 acceptable threshold. APRas found the runway to be acceptable for taxi, takeoff, and landing operations from both ends of the runway. The user would have been prompted to remeasure the four sections before making any corrective action decisions.

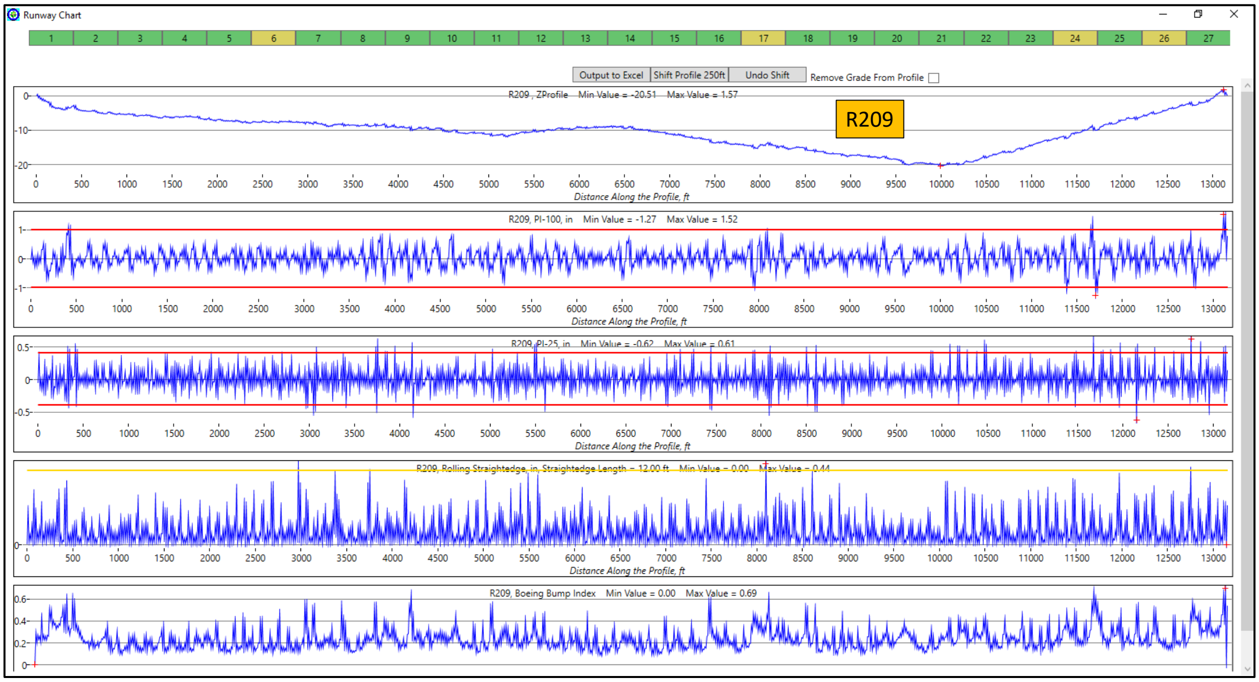


Figure A-8. MER Analysis Results of Runway R209

- **R210.**

  Figure A-9 shows R210, the second of three asphalt runways. MER evaluation showed all sections are acceptable. APRas found the runway to be acceptable for takeoff, landing, and taxi from both ends of the runway using several aircraft types.

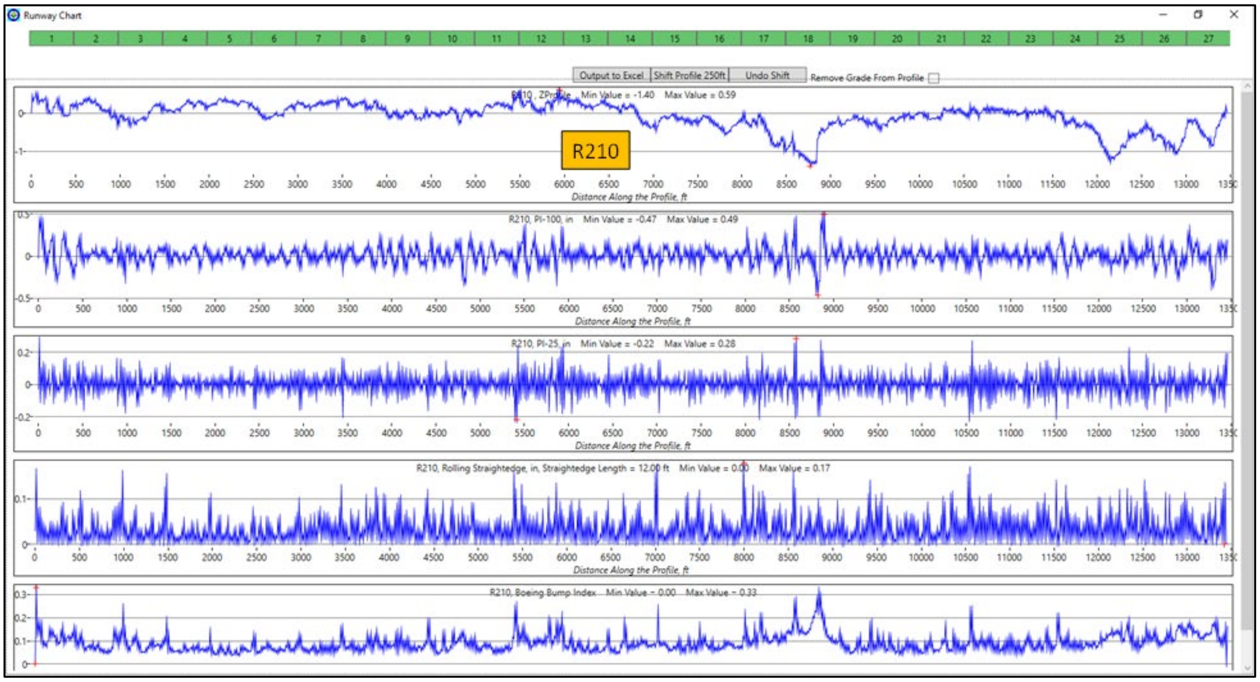


Figure A-9. MER Analysis Results of Runway R210

- **R211**

  Figure A-10 shows R211, the third of three asphalt runways. MER screening shows all sections are acceptable. APRas found the runway to be acceptable for takeoff, landing, and taxi from both ends of the runway using several aircraft types.

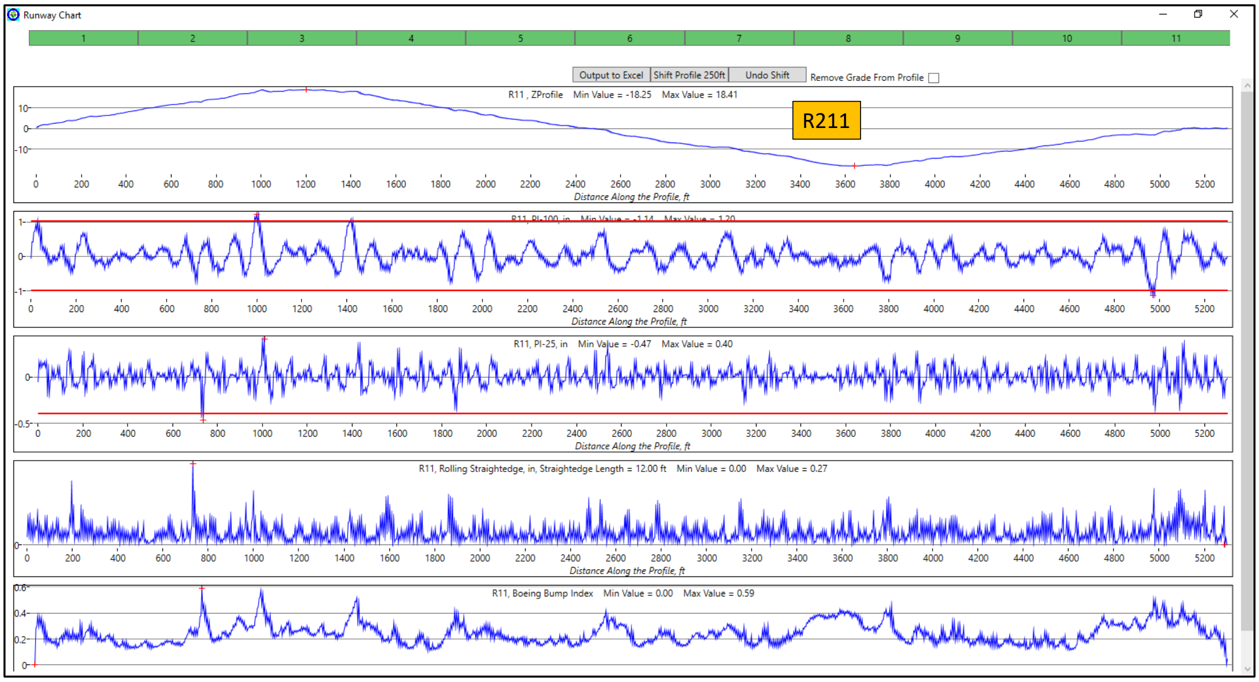


Figure A-10. MER Analysis Results of Runway R211

In conclusion, the additional runways that were analyzed were consistent with the limits of acceptability established in the MER development. A few exceptions (almost always the 12-foot RSE) were generally detected on otherwise smooth pavements. The RSE is the most sensitive analysis method of all four tools when the acceptable limit is exceeded. There are several potential reasons for this. It is not uncommon to capture a profile data anomaly that impacts the RSE analysis, particularly when using a walking profiler. The impact of a false flag in the MER analysis is that some additional analysis is recommended. This could be remeasuring the section(s) in question or comparing them to other lines of survey for consistency. For pavements that exceed the limits on multiple evaluation tools, aircraft simulation is recommended.

<u>REFERENCE</u>

Hudspeth, S., Stapleton, S., Ballew, J., & Sparkman, J. (2017). Final surface roughness study data collection (DOT/FAA/TC-18/8). https://www.airporttech.tc.faa.gov/Products/Airport-Safety-Papers-Publications/Airport-Safety-Detail/boeing-737-800-final-surface-roughness-study-data-collection

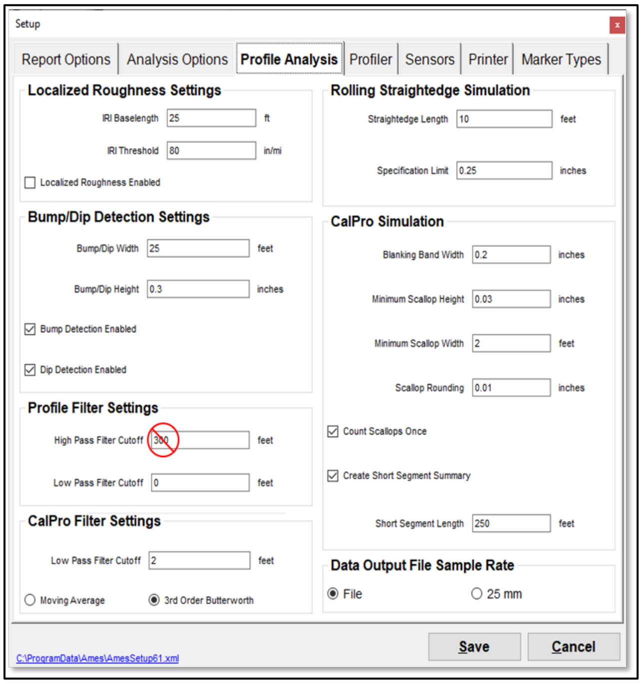
APPENDIX B— COMPARISON OF AMES INERTIAL PROFILER TO A SURPRO 4000 AND AN AUTO ROD & LEVEL-EXTENAL REFERENCE

This Appendix contains the results of a limited road test to compare inertial to true profilers.

PROFILER COMPARISON STUDY – TECHNICAL NOTE

Purpose:

The purpose of this technical note is to document the results of a limited profiler comparison study to evaluate the impact of using “no filtering” when measuring a profile using the AMES 8200 inertial profiler.



Localized Roughness Settings

IRI Baselength 25 ft

IRI Threshold 80 in/mi

☐ Localized Roughness Enabled

Bump/Dip Detection Settings

Bump/Dip Width 25 feet

Bump/Dip Height 0.3 inches

☑ Bump Detection Enabled

☑ Dip Detection Enabled

Profile Filter Settings

High Pass Filter Cutoff 300 feet

Low Pass Filter Cutoff 0 feet

CalPro Filter Settings

Low Pass Filter Cutoff 2 feet

○ Moving Average ● 3rd Order Butterworth

Rolling Straightedge Simulation

Straightedge Length 10 feet

Specification Limit 0.25 inches

CalPro Simulation

Blanking Band Width 0.2 inches

Minimum Scallop Height 0.03 inches

Minimum Scallop Width 2 feet

Scallop Rounding 0.01 inches

☑ Count Scallops Once

☑ Create Short Segment Summary

Short Segment Length 250 feet

Data Output File Sample Rate

● File ○ 25 mm

C:\ProgramData\Ames\AmesSetup61.xml

Figure B-1. Screenshot of AMES Software Showing “No Filter”

Background:

AMES Engineering suggested selecting the “no filter” option in their software if the goal is to capture longer wavelength roughness (Figure B 1). The concern was that the default setting of 300 feet may have an impact on the results when conducting an MER (Multiple-Event Roughness) analysis.

The Test Site:

The test was conducted on March 13, 2023, on an active county road in Clark County, Ohio. (Figure B-2). Even though traffic was very light, it was not practical to lay out a reference line to follow. Another reason this site was chosen was that it had visible Type 2 and Type 3 roughness.

Figure B-2. Photo of Lower Valley Pike Test Site

The test site was manually measured to be 1,035 feet in length. The intention was to measure at least two 500-foot sections to be compatible with an MER analysis.

The AMES profiler had approximately 300 feet to accelerate to 30 MPH (test speed) and unlimited space to decelerate. Reflective tape (Figure B-3) was used to trigger the AMES start and stop locations.

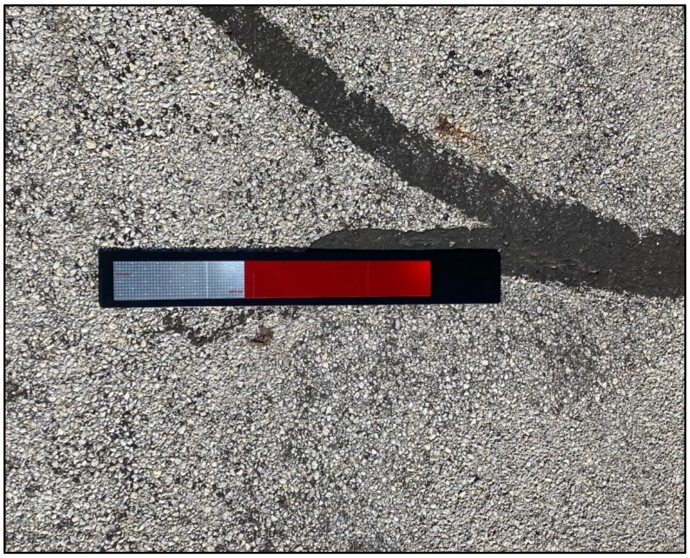


Figure B-3. Reflective Tape that Triggers AMES Profiler

Three profile measurement units (Figure B-4) used in this limited test were:

- The Auto Rod & Level
- The SurPRO 4000
- The AMES 8200 Inertial profiler

Figure B-4. Photo of All Three Profiling Devices

Three passes were made between the road's wheel paths (approximate centerline) with each device.

Results:

Figure B-5 is a plot of the profiles measured with all three units with the end-to-end grade removed. This shows very good correlation between profiling units. Figure B-6 is the same plot with the end-to-end grade included. The AMES inertial profiler does not carry the grade changes for the full 1,035-foot test section. Table B-1 shows the actual change in elevation in 1,000 feet (two 500-foot sections) for three passes of each unit. Table B-2 shows the distance traveled by each unit for the full 1,035-foot test section for three passes of each unit.

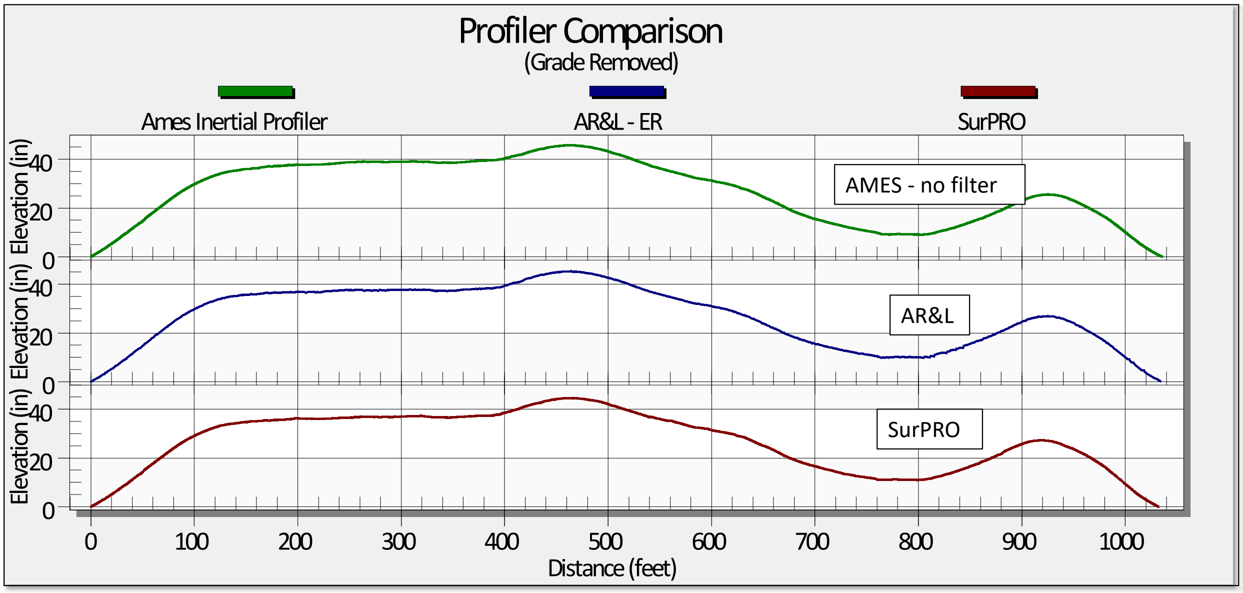


Figure B-5. Plot of All Three Profilers with the End-to-End Grade Removed

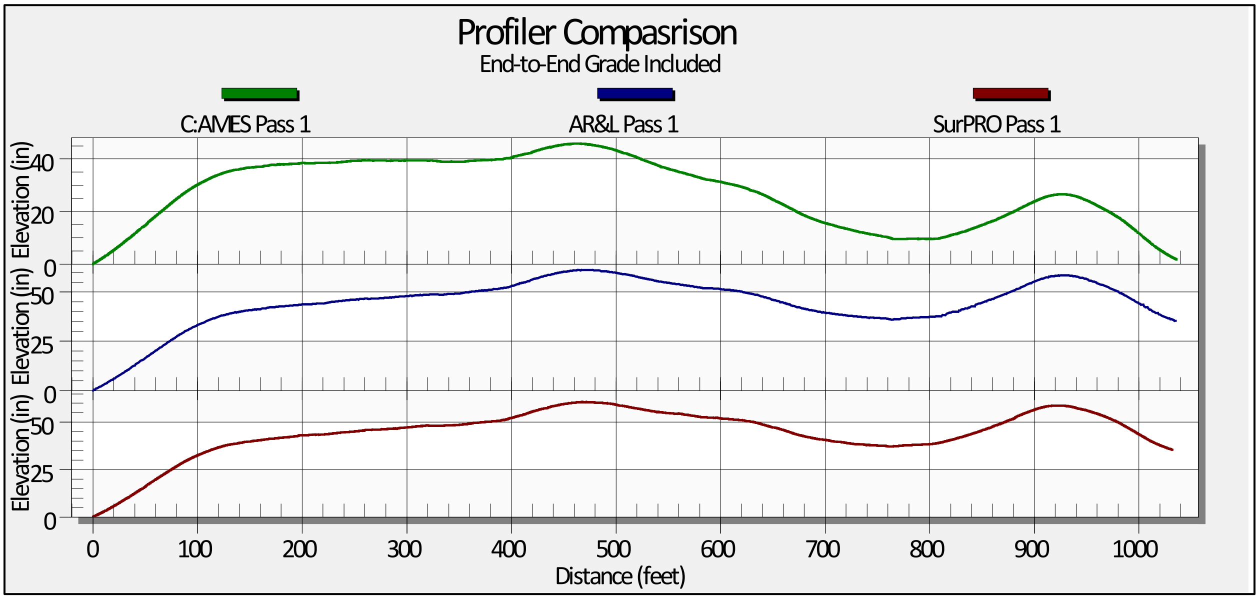


Figure B-6. Plot of All Three Profilers with the End-to-End Grade Included

Table B-1. End-to-End Change in Elevation at 1,000 Feet

0 to 1,000 Feet Change in Elevation (Inches)			
	Pass 1	Pass 2	Pass 3
AR&L – ER	44.42	43.40	43.70
SurPRO	43.60	44.30	43.20
Ames 8200	12.80	10.49	8.60

AR&L–ER = Auto Rod & Level–External Reference

Table B-2. Distance Traveled for the 1,035-Foot Test Section

Measured Distance Comparison (Feet)			
	Pass 1	Pass 2	Pass 3
AR&L – ER	1,036	1,035	1,036
SurPRO	1,032	1,031	1,032
Ames 8200	1,036	1,036	1,036

AR&L–ER = Auto Rod & Level–External Reference

Figure B-7 shows the repeatability between passes for the AR&L. Figure B-8 shows the repeatability between passes for the SurPRO. Figure B-9 shows the repeatability between passes for the AMES.

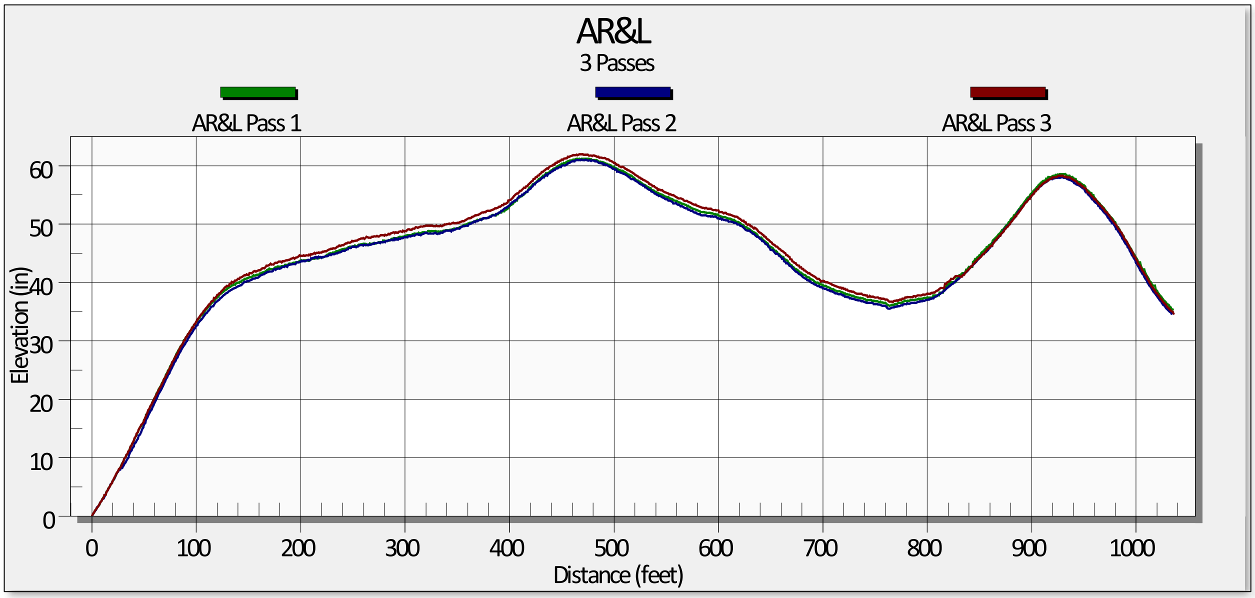


Figure B-7. Plot of Three Passes with the AR&L

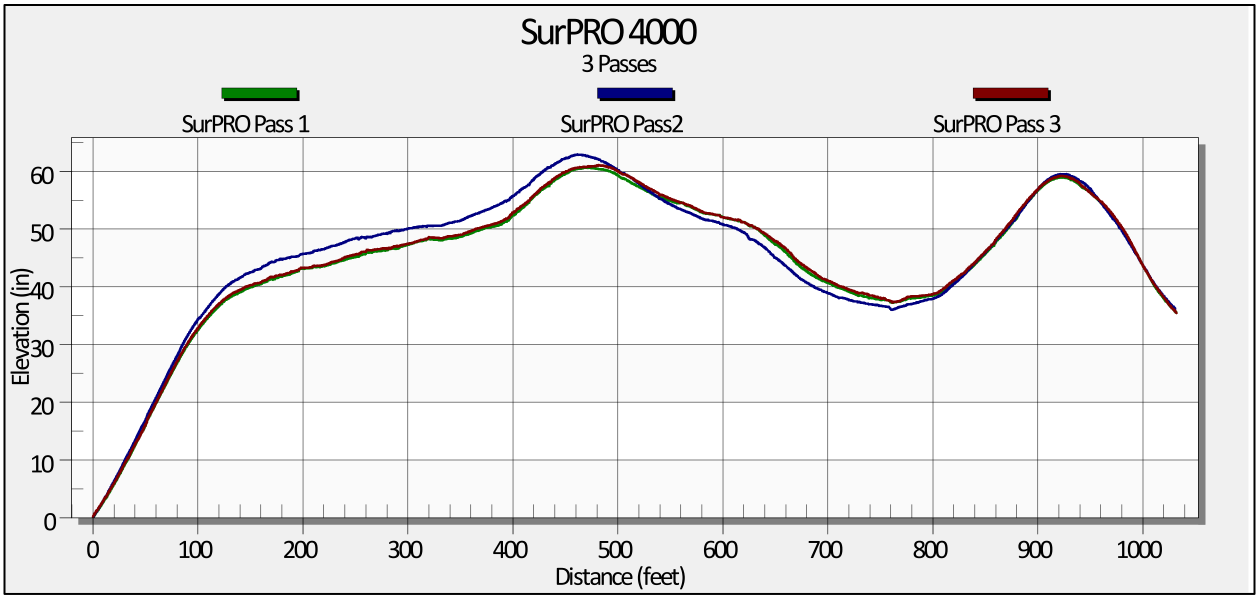


Figure B-8. Plot of Three Passes with the SurPRO

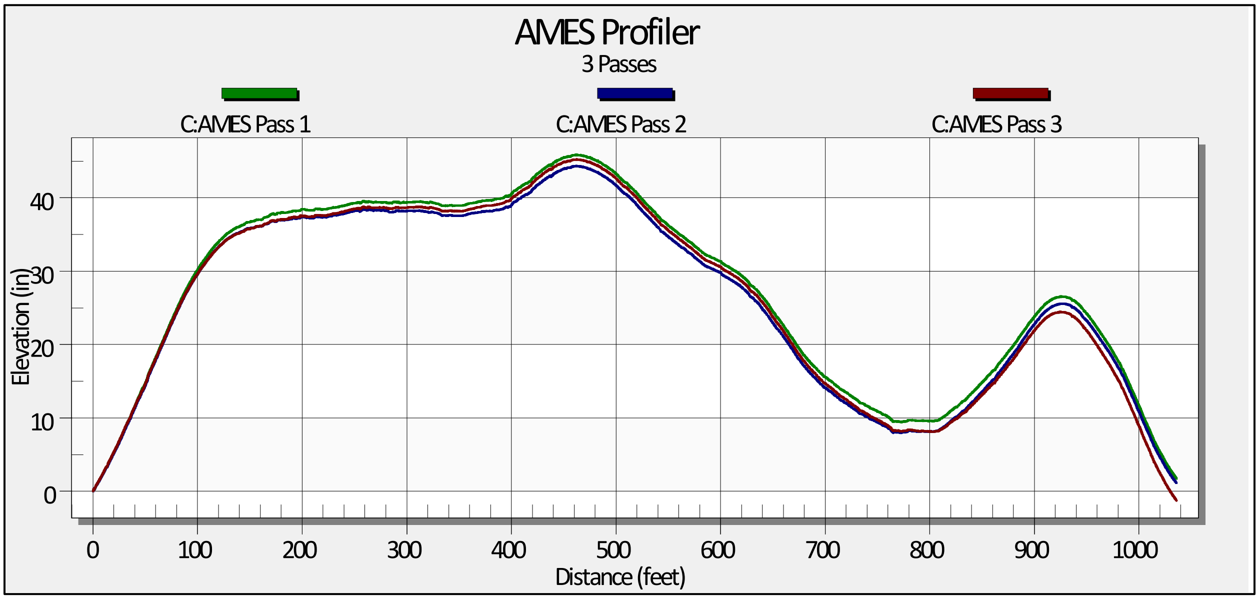


Figure B-9. Plot of Three Passes with the AMES Inertial Profiler

Table B-3 shows the results of the MER analysis conducted using ProVAL. The primary reason this limited test effort was conducted was to determine if high-speed inertial profile data could be used to conduct an MER analysis with sufficient accuracy to locate and quantify airport pavement roughness. The MER analysis was conducted for all three passes of each profiler.

Profile index (PI)-100, developed to find Type 3 roughness, is the primary concern. This section of road had visible longer wavelength (Type 3 roughness) with significant grade changes. As a result, it was a good test site for this limited evaluation. The computed PI-100 values for each pass for each unit were very repeatable. The MER results using the AMES data agreed with the true profiler results. Comparison of PI-100 results for each profiler type shows excellent agreement between the true profilers and the AMES unit for pavement sections one and two. All profilers show sections one and two to be unacceptable for PI-100.

PI-25 comparisons were also very good. All profilers show section 1 acceptable and section 2 excessive. The 12-foot RSE (rolling straightedge) showed some disagreement.

Table B-3. Results of an MER Analysis for Three Passes of Each Profiler Type

AR&L										
		PI 100			PI 25			12-Ft RSE		
Start	Stop	Pass 1	Pass 2	Pass 3	Pass 1	Pass 2	Pass 3	Pass 1	Pass 2	Pass 3
0	500	118.51	119.68	114.4	14.76	14.21	13.66	0	0	0
501	1,000	169.64	167.45	162.75	26.93	23.23	31.68	821’ (.42”)	0	833’ (.51”)
AMES										
		PI 100			PI 25			12-Ft RSE		
Start	Stop	Pass 1	Pass 2	Pass 3	Pass 1	Pass 2	Pass 3	Pass 1	Pass 2	Pass 3
0	500	113.82	115.00	110.89	9.28	10.92	12.55	0	0	0
501	1,000	163.00	163.08	164.17	22.70	23.23	23.23	0	0	0
SurPRO										
		PI 100			PI 25			12-Ft RSE		
Start	Stop	Pass 1	Pass 2	Pass 3	Pass 1	Pass 2	Pass 3	Pass 1	Pass 2	Pass 3
0	500	121.44	129.68	120.27	18.01	18.02	16.92	0	0	0
501	1,000	128.17	153.65	161.52	25.87	26.39	32.21	0	761’ (.43”)	0

Conclusions:

The conclusions of this limited test suggest that the AMES inertial profiler data can be used to conduct an MER analysis. Although not evaluated in this report, it is likely that aircraft simulations can also be conducted using AMES profile data. The reasoning is that most aircraft gear spacing is less than 100 feet, which appears to be a wavelength the Ames unit can capture with sufficient accuracy.

The AMES unit fails to track end-to-end grade changes as accurately as true profilers. Consequently, using the AMES profiler to establish a baseline is not recommended unless the data can be updated periodically with true profiler data.

Recommendation:

It is recommended that additional testing be conducted on a runway(s) and/or taxiway with all three types of roughness and with changes in grade. It is also recommended that the test plan include inertial profilers made by other manufacturers as well as scanning laser technology and other promising profile measurement methods.

APPENDIX C—SAMPLE APPLICATION OF THE PROFAA MULTIPLE-EVENT ROUGHNESS PROCESS TO ADVISORY CIRCULAR 150/5300-13A

The following is a case history example of how a multiple-event roughness (MER) analysis of a profile design could have been used to prevent a costly reconstruction.

In this case history, a Portland concrete cement (PCC) runway, which had just had an extensive rehabilitation completed, was immediately reported by pilots as unacceptably rough. The rehabilitation design required tie-ins to meet existing grade. The paving contractor was successful in meeting those design requirements; however, the design did not meet overall (long wavelength) grade control requirements. Figure C 1 is a plot of the as-built.

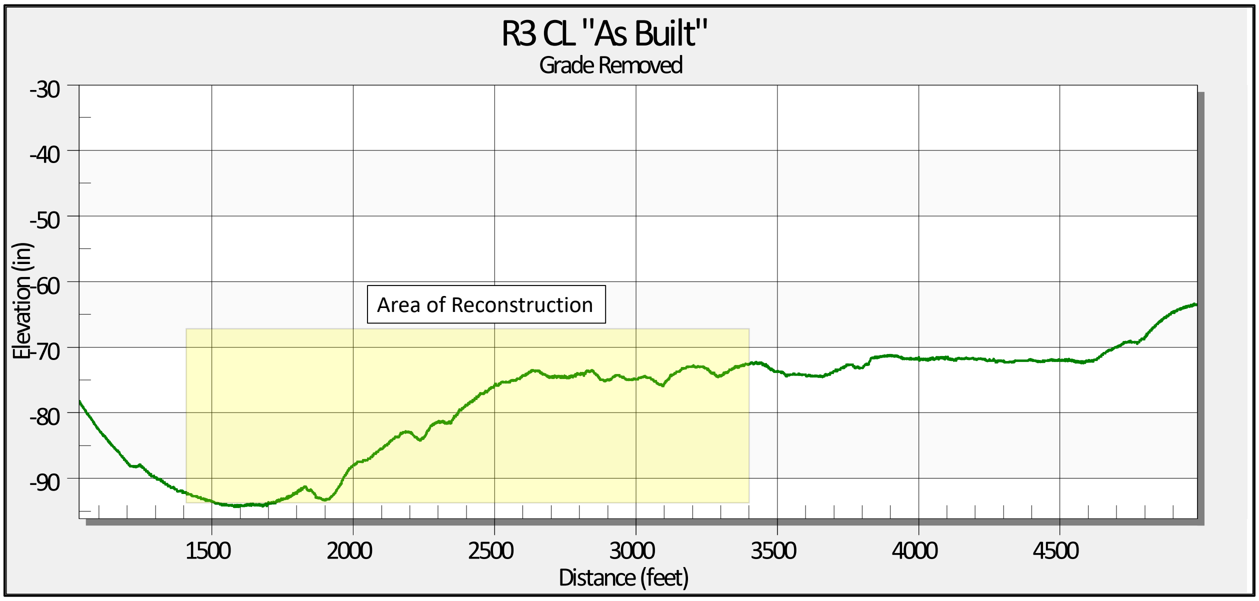


Figure C-1. Profile Plot of As-Built: Contractor Required to Meet Existing Grades

Table C-1 contains the results of the MER analysis that would have detected the rough areas in the design phase and led to a redesign, which could have prevented a costly reconstruction and delay in opening that runway. Note that the paving contractor met the 12-foot straightedge requirements for smoothness as called for in Advisory Circular (AC) 150/5370-10H. The long wavelength roughness that caused the pilot complaints was detected with the Profile Index (PI)-100 (long wavelength Type 3 roughness) assessment. Had an MER analysis been required as part of the AC 150/5370-10 acceptance testing, this runway design would have been found unacceptable.

Table C-1. MER Analysis of Runway Rehabilitation Project

		Red > 35		**Red > (ABS .8)**	**Red > 1.2 Unacceptable**
		Yellow 20 to 35		**Yellow (ABS .4 to .8)**	**Yellow 1.0 to 1.2 Excessive**
Distance (Feet)		**Green < 20**		**Green < (ABS .4)**	**Green < 1.0 Acceptable**
Start	**Stop**	**PI-100**	**PI-25**	**12-Foot RSE**	**BBI**
0	500	0.00	1.76	<ABS .4	Acceptable
500	1,000	3.26	1.35	<ABS .4	Acceptable
1,000	1,500	6.88	3.19	<ABS .4	Acceptable
1,500	2,000	26.16	5.81	<ABS .4	Acceptable
2,000	2,500	38.88	7.21	<ABS .4	Acceptable
2,500	3,000	23.84	4.46	<ABS .4	Acceptable
3,000	3,500	39.37	4.88	<ABS .4	Acceptable
3,500	4,000	12.97	7.90	<ABS .4	Acceptable
4,000	4,500	0.00	0.60	<ABS .4	Acceptable
4,500	5,000	7.28	4.64	<ABS .4	Acceptable
5,000	5,500	2.00	8.91	<ABS .4	Acceptable
5,500	6,000	2.02	5.36	<ABS .4	Acceptable
6,000	6,500	1.96	1.85	<ABS .4	Acceptable
6,500	7,000	0.00	0.00	<ABS .4	Acceptable
7,000	7,500	0.00	0.00	<ABS .4	Acceptable
7,500	8,000	0.00	0.00	<ABS .4	Acceptable
8,000	8,500	0.00	0.00	<ABS .4	Acceptable
8,500	9,000	0.34	0.79	<ABS .4	Acceptable
9,000	9,500	0.34	7.78	<ABS .4	Acceptable
9,500	10,000	1.68	1.42	<ABS .4	Acceptable
10,000	10,500	0.00	0.67	<ABS .4	Acceptable
10,500	10,980	14.31	0.39	<ABS .4	Acceptable

The MER analysis tool in ProFAA can also be used to determine the smoothness acceptability for intersecting runways with crowns, panel replacements, changes in grade, or other pavement design issues.

It is recommended that FAA AC150/5300-13B include a comment recognizing the MER function in ProFAA and that it can be used as a smoothness acceptability check of pavement designs.

APPENDIX D—CASE HISTORIES DEMONSTRATING THE VALUE OF ESTABLISHING A BASELINE PROFILE

D.1 INTRODUCTION

Airfield pavements are significant investments in terms of cost to construct them and their economic potential. As such, it is logical to implement reasonable practices to ensure that these pavements remain in service for as long as possible. Recognizing this, a variety of techniques have been used to monitor elements of the pavement's health. These techniques typically comprise a pavement management system, pavement condition inspections, and falling weight and heavy falling deflectometer evaluations. These techniques are useful to monitor specific aspects of the pavement's health and are conducted at frequent intervals throughout the pavement's life.

True profile measurements are used to monitor a pavement's profile shape change as it ages. Bumps and dips can be measured regardless of amplitude or wavelength. Using this method, the profile shape can be tracked. When changes occur, analysis techniques can be used to determine if the changes have adverse effects on aircraft ride quality.

The four case studies presented here show runways whose profiles runways have been monitored over time. Each runway had a baseline profile and profile updates measured in subsequent years. Analytical comparisons were made between the data sets. The comparison process involved three profile analyses that were conducted on the baseline and on each subsequent profile update for each case study. These analyses were:

- Visual Profile Comparison: The plotted profile of the baseline was compared to each profile update and a visual analysis was conducted to see the changes that occurred over time.

- Aircraft Simulation: For the baseline and each profile update, a 737-800 was simulated performing a 90-knot constant speed taxi. Peak responses and their locations were recorded and compared to determine if the profile shape changes were degrading ride quality of the runway.

- 100-Foot Straightedge Analysis: The baseline profile and each profile update were assessed with an analytical 100-foot straightedge using a 1-inch reference line. By comparing the deviations from baseline to the various updates, profile shape changes were visually identified and could be measured allowing the user to calculate the pavement's annual rate of change.

Finally, any profile analysis is only as good as the profile data used in the analysis. As such, preliminary research was conducted comparing the amplitudes and wavelengths captured by true profilers such as APR Consultants, Inc.'s (APR) Auto Rod & Level (AR&L) – External Reference (ER) and International Cybernetics Corporation's (ICC) ICC's SurPRO, and those captured by inertial profilers such as the Ames Engineering 8200.

The results of this study showed that profile shape change was identifiable and quantifiable in all four case studies when using these three forms of analysis. In all cases but one, profile shape changes affected aircraft ride quality over time. By comparing aircraft simulation and deviation from a straightedge, the user could quantify the profile deterioration over time. Additionally, once the rate of change was determined, projected shape changes could be made by modifying the profile using the calculated rate of change. Aircraft simulation could then be made on the modified profiles to determine when aircraft responses would become unacceptable and require corrective action.

D.2 PROFILE CHARACTERISTICS

When delivered, an airfield pavement is generally smooth and acceptable. However, over time and with continuous use, these pavements often develop roughness that, at a minimum, can result in pilot and passenger complaints, but can also develop into a safety concern. As a pavement ages, its profile can change shape with the subtle development of bumps and dips. As these bumps and dips continue to develop, there is an increased risk that they will produce dynamic aircraft response and increase the dynamic loading on the pavement. This cycle can lead to premature pavement failure. However, by establishing a baseline profile, these changes can be detected, monitored, and corrected before the pavement experiences excessive loading.

D.3 Profile Shape Change

An airfield pavement is subjected to a difficult environment throughout its life, yet is expected to provide a surface for safe operations for up to 40 years. It must support the static loads of operating aircraft, some of which are more than 1,000,000 lb, but they must also hold up under extreme hot and cold weather conditions. In addition, the pavement must also perform acceptably when the materials in the structure’s subgrade settle due to compaction or expand due to moisture content or freezing temperatures.

Subsurface materials and conditions can have a big impact on the long-term stability of the pavement’s surface. While efforts are made to stabilize the subsurface materials, environmental conditions, such as temperature or moisture, can also play a significant role in the changes of an airfield profile. Establishing a pavement’s true profile baseline will not alter or deter these changes, but it can determine the effect these changes will have on the maintenance planning of this pavement throughout its useful life.

Since 1993, the baseline comparison process has been used to provide understanding of the changes a pavement can experience. Throughout this appendix, four case studies will be reviewed to demonstrate the use of a baseline profile for comparison purposes.

Case Study 1: One airport uses profile monitoring on several runways that are built on a mix of reclaimed land amid existing bedrock. This airport exhibited significant amounts of differential settlement where portions of runway were built using fill materials. However, other areas, where bedrock was present during construction, remained stable. These variable profiles often result in excessive dynamic loading from operating aircraft and can lead to pilot and passenger complaints.

Case Study 2: At another airport, the runway network was built over a subsurface that consists of expansive clays. When moisture interacts with these clays, swelling develops and creates bumps in the runway that often result in excessive dynamic loading from operating aircraft and often produce pilot and passenger complaints.

Case Study 3: At the third airport, the baseline monitoring technique was used to quantify profile shape changes due to pavement settlement over an underground utility tunnel. This area can produce unacceptable aircraft responses when encountered in certain conditions.

Case Study 4: In this case, a runway was rehabilitated and resurfaced in the early 2000s. This runway was built in the 1940s over an area that was swampy and consisted of compressible materials in the subgrade. During the rehabilitation process, grout pillars were incorporated into the design to prevent settlement once the new overlay was placed. Over time, the pavement did settle, but the pillars floated creating a dimpling effect in the runway's surface. Over time, the differential rates of settlement create a ride-quality concern for this runway.

D.3.1 Indications of Profile Shape Change

While there can be detrimental effects on the pavement's structure due to changes in the profile shape, this appendix focuses primarily on the effect profile shape change has on aircraft response. This section of the appendix will show obvious visual signs of settlement in the runway's longitudinal profile by showing "snapshots" of the runway's profile at various points in time.

The first example shows how the baseline profile comparison method was successful in quantifying the effect of differential settlement and helped the airport make decisions about timely pavement repairs. The overall shape of the runway is consistent; however, waviness in the profile is clearly seen 7 years later (Figure D-1). This area, called an "Area of Interest," is a good example of differential settlement. Figure D-2 enlarges the area of interest and is plotted with the overall grade removed. Additionally, elevation reference lines are added to help quantify the change over time.

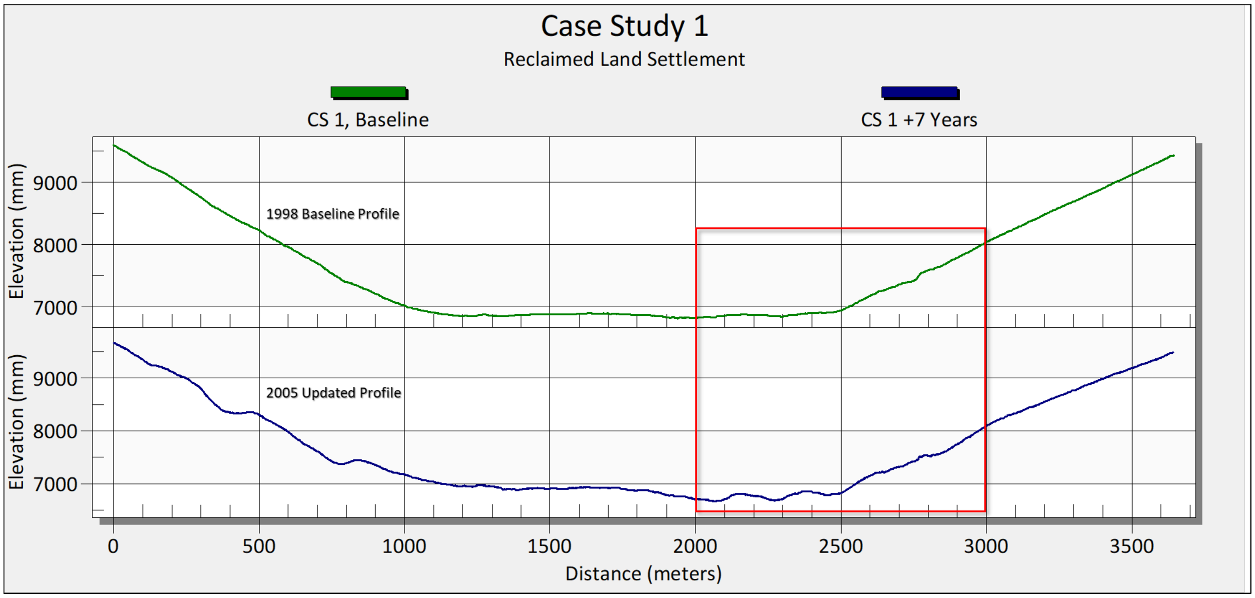


Figure D-1. Case Study 1 Identifying Differential Settlement with Area of Interest Identified

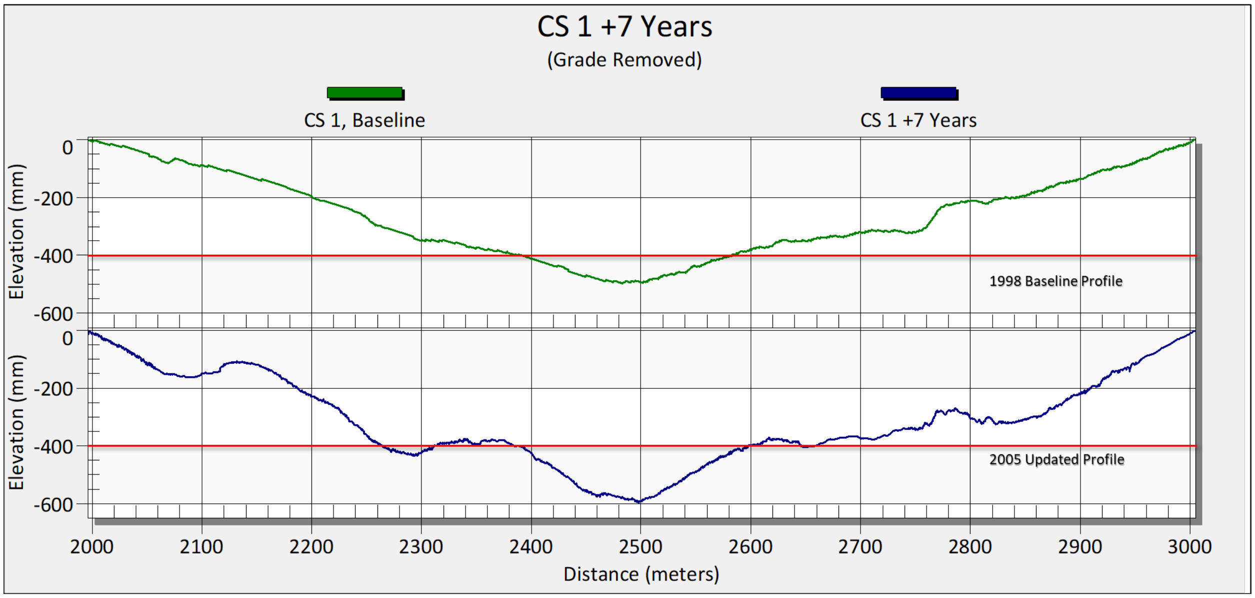


Figure D-2. Case Study 1 Area of Interest Enlarged with Elevation Reference Lines

Case Study 2 is a situation where expansive clays have created back-to-back bumps. As shown in Figure D-3, there are three lines of survey, one each for three separate points in time. The baseline for this runway was measured in 2006. The runway was then rehabilitated (at some point before 2011) and remeasured in 2011. These two bumps have been effectively removed. This runway was measured again in 2017, and the bumps could be seen redeveloping. Figure D-4 enlarges the Area of Interest of this runway.

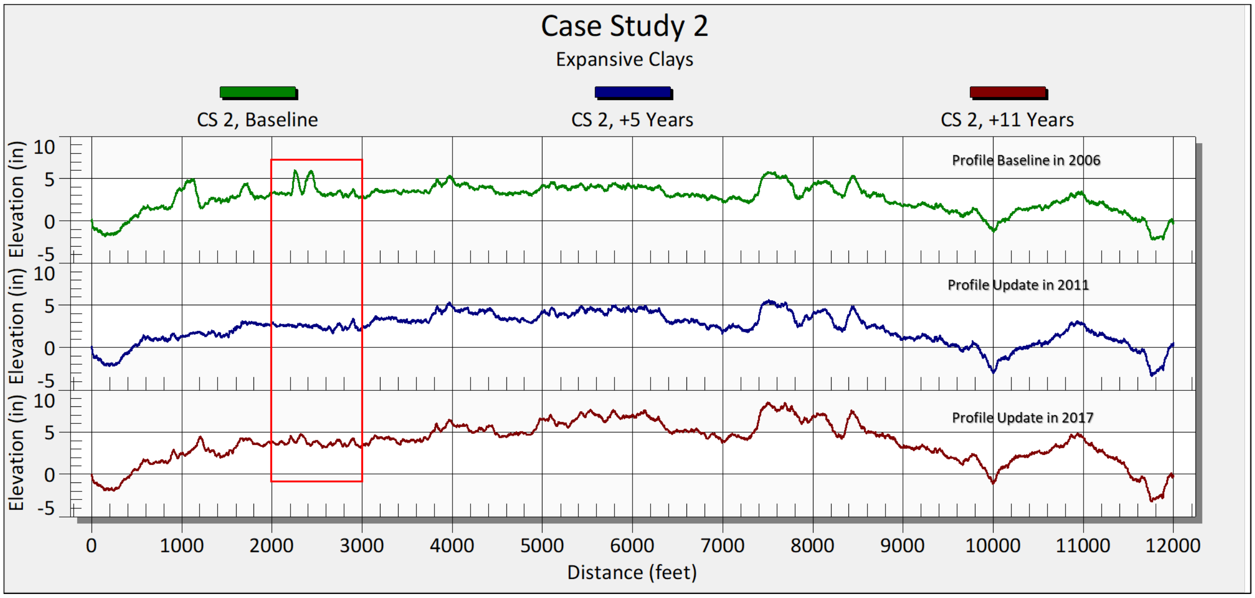


Figure D-3. Case Study 2 Pavement Heaving Due to Expansive Clays in the Subgrade

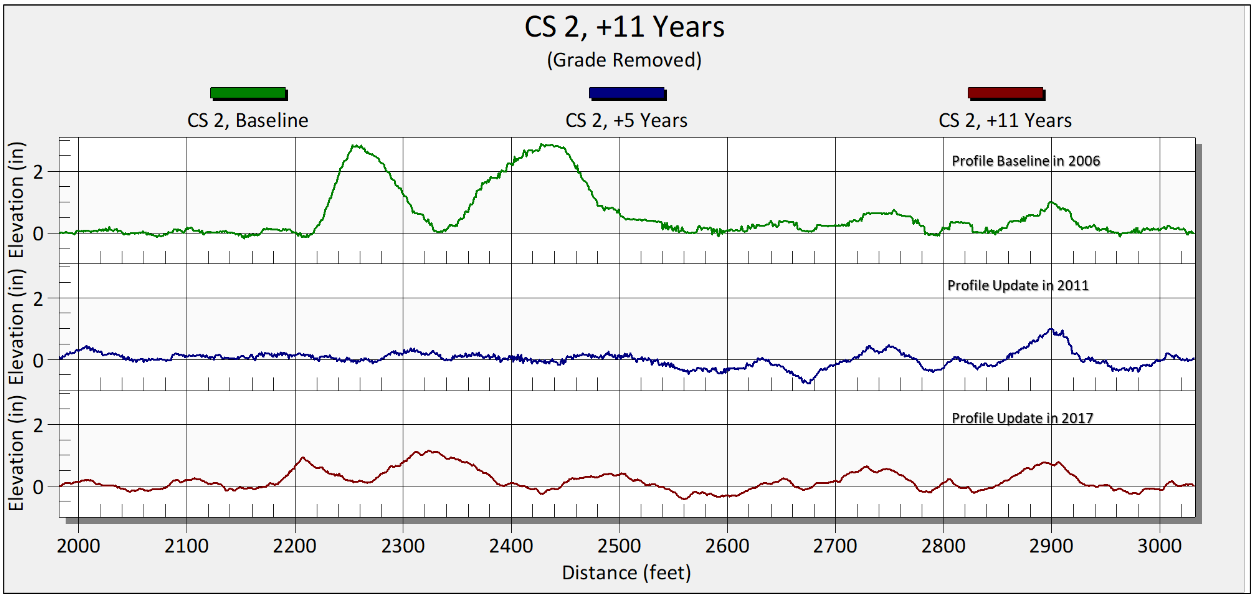


Figure D-4. The Area of Interest Where Expansive Clays Caused Swelling, was Repaired, and Swelling Resumed

Case Study 3 documents the history of settlement occurring on a utility tunnel underneath a runway. The baseline profile of this runway was measured in 2005 and then resurveyed in 2010, 2013, and 2017. Figure D-5 clearly shows the settlement getting deeper with each successive survey. Figure D-6 is an enlarged plot of the Area of Interest for this runway.

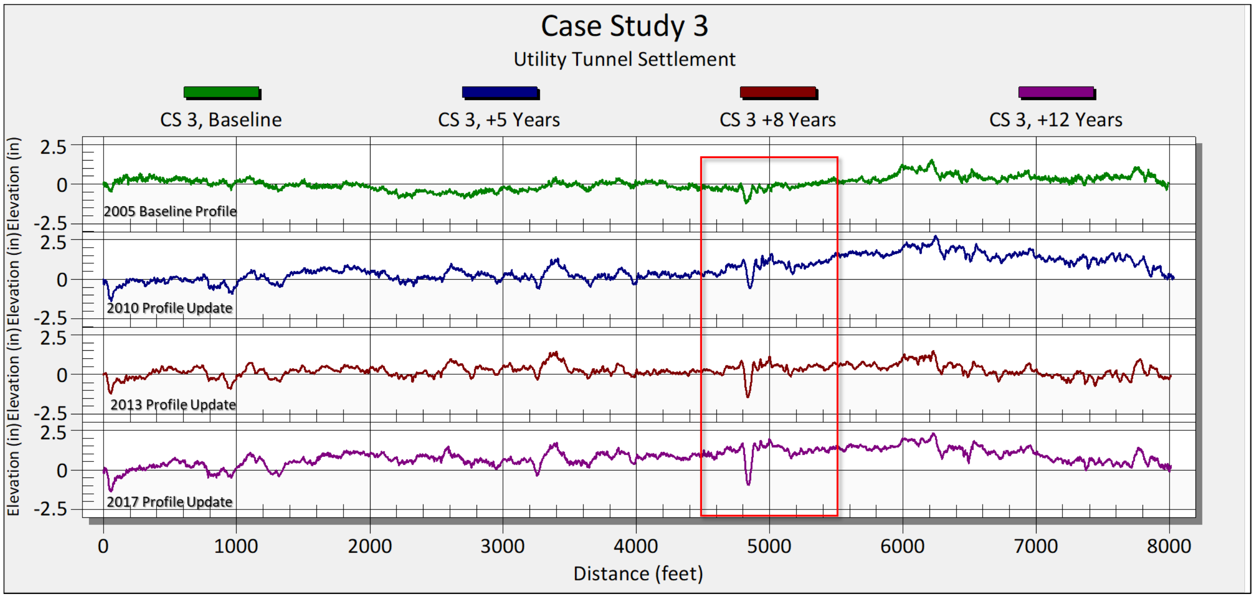


Figure D-5. Case Study 3 Documents the Settlement Occurring Around a Utility Tunnel

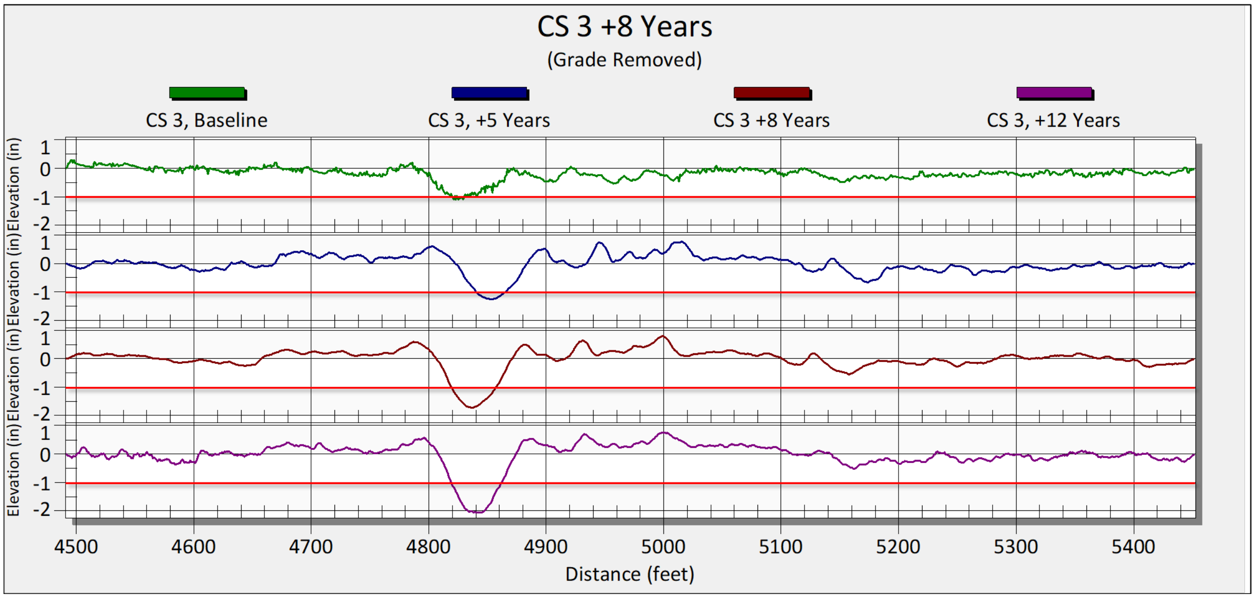


Figure D-6. The Area of Interest for Case Study 3 Plotted with Grade Removed

Case Study 4 involves an asphalt runway built in an area with swampy conditions. In 2006, this runway was rehabilitated and resurfaced. During this process, grout pillars were placed at regular intervals along the runway's length in an area where borings indicated weaker soil conditions. The pillars were intended to provide flotation and prevent the runway's surface from settling. Soon after placement, it was discovered that the pillars themselves floated relative to the pavement's surface while the asphalt pavement surrounding the pillars began to settle. This resulted in dimpling throughout a 1,175-foot-long area. However, the entire area where the pillars were placed still settled significantly compared to the baseline profile. Figure D-7 is a plot of the runway after 9 years of use. Figure D-8 shows the case study 4 baseline profile and dimpling Area of Interest after 9 years.

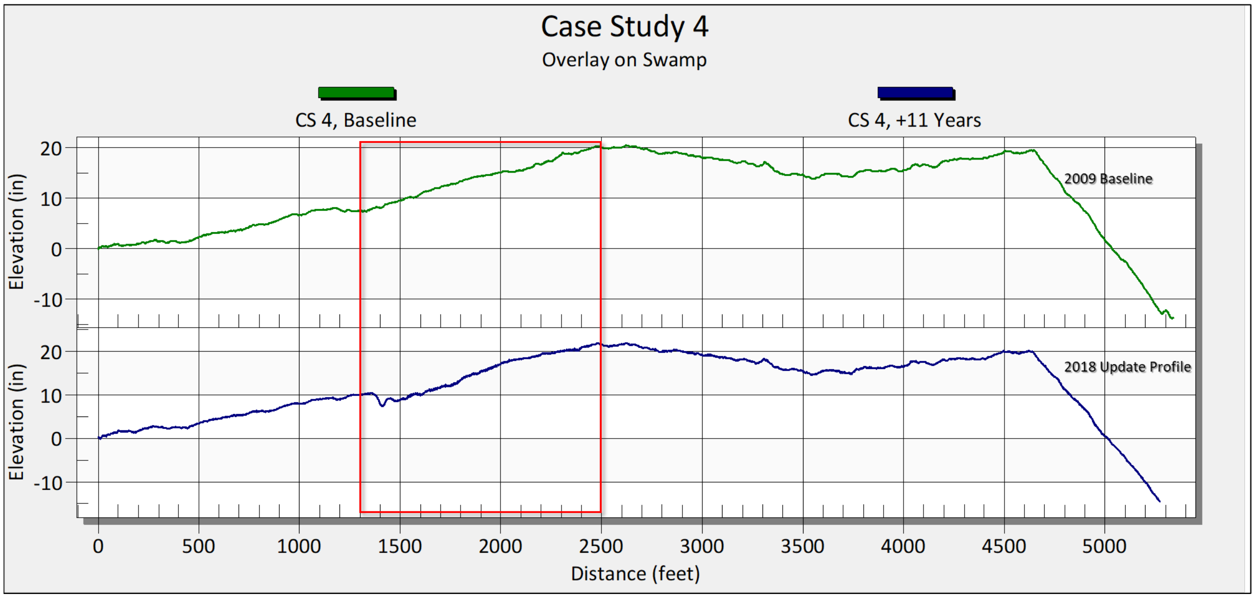


Figure D-7. Case Study 4 Shows Settlement Around the Area of Interest After 9 years

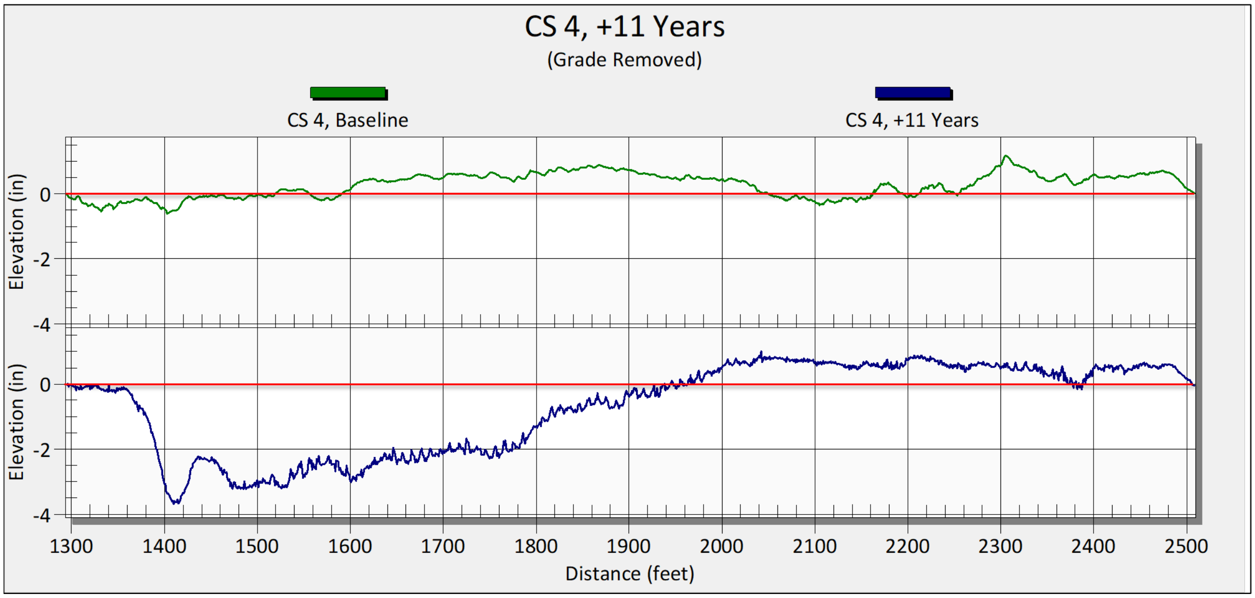


Figure D-8. The Area of Interest for Case Study 4 Showing the Dimpling and Settlement of This Runway

D.3.2 Effects on Aircraft Response

While there are several implications associated with profile shape change, either through settlement or heaving, this portion of the report focuses on the implication it has on aircraft response. To help quantify the effect of profile shape change on aircraft response, this analysis used Airport Pavement Roughness assessment software (APRas). Specifically, each profile was assessed by simulating a 737-800 performing a 90-knot constant speed taxi simulation. Peak accelerations at the cockpit (CP) and the aircraft's center of gravity (CG) were recorded as well as the ride quality factor (RQF), which describes the ride quality value for the entire simulation, not just the peaks. For example, Figure D-9 is a constant-speed taxi simulation plot for the 737-800 as it traverses the baseline profile for Case Study 1. Red circles identify peak responses at the CP and CG of the aircraft. The peak CP acceleration was 0.58G at 1,947 meters and the peak acceleration for the CG was predicted to be 0.42G also occurring at 1,947 meters (as marked). The RQF, also circled in red in the upper right corner of the figure, was calculated to be 2.38.

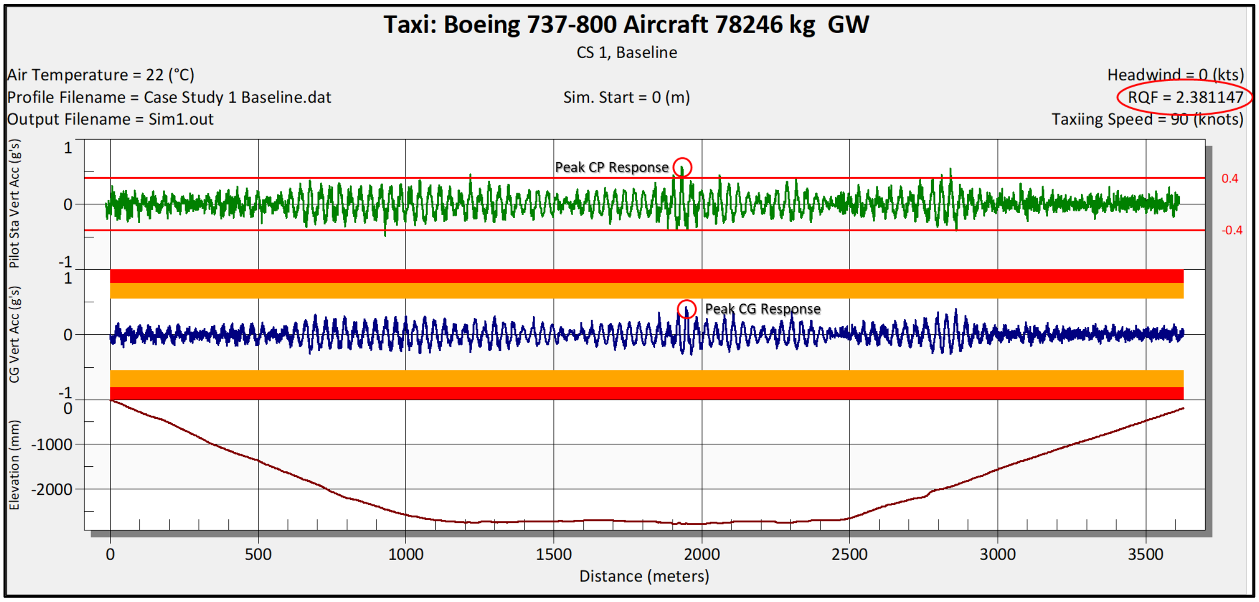


Figure D-9. Plot for 90-Knot Constant-Speed Taxi Simulation for Case Study 1 Baseline Profile

What this simulation shows is that the ride quality for Case Study 1 baseline is considered smooth and acceptable when compared to the criteria used in the Boeing Bump method as discussed in Boeing Document D6-81746 (Boeing Commercial Airplane Group, Airport Technology Organization, 1995).

By comparison, Figure D-10 is a simulation conducted with the same conditions used in Figure D-9. Figure D-10 shows that, while differential settlement occurred, the wavelengths produced by the settlement were too long to produce adverse ride quality for this aircraft.

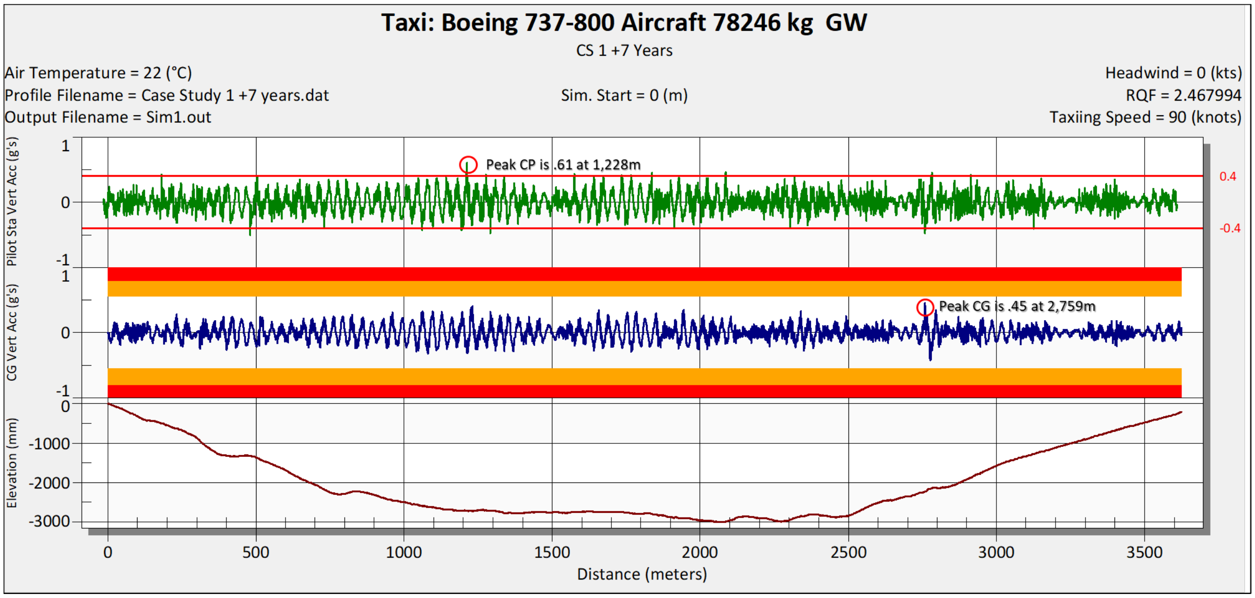


Figure D-10. Plot for 90-Knot Constant-Speed Taxi Simulation for Case Study 1 Profile Measured 7 Years After the Baseline

D.3.3 Aircraft Simulation on Case Study 2

Case Study 2 has the issue of pavement heaving due to subsurface swelling caused by moisture. The first measurement of this runway profile was in 2006. This baseline profile showed two bumps in succession (Figure D-11). Aircraft simulation predicted that these two bumps would produce excessive aircraft responses at the aircraft's CG.

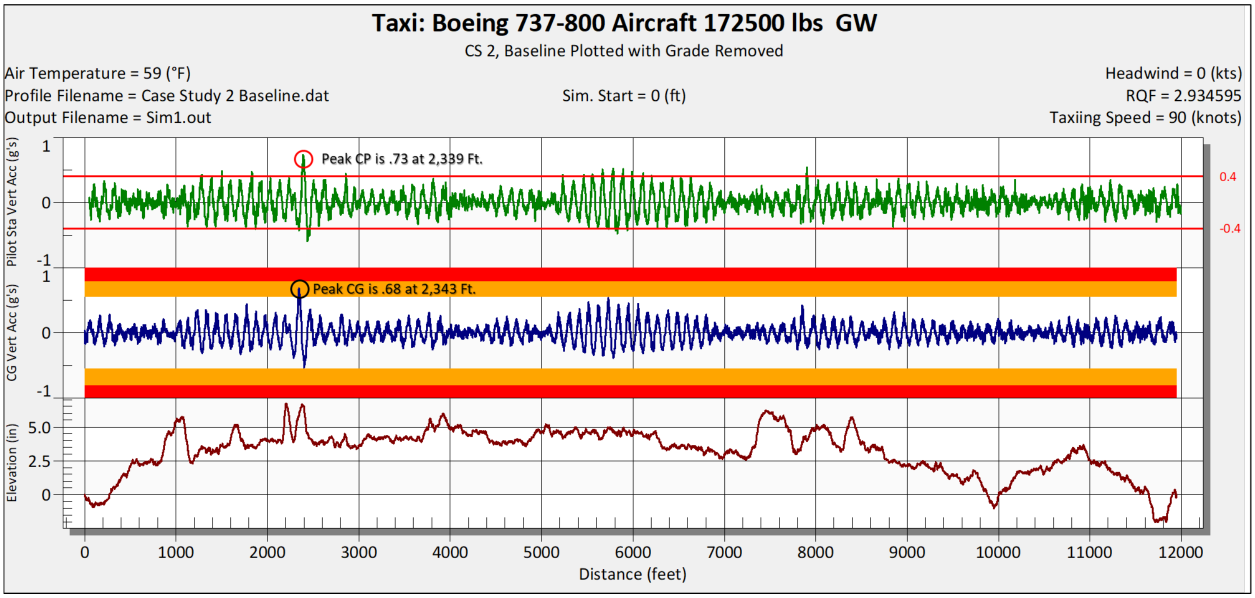


Figure D-11. Plot for 90-Knot Constant-Speed Taxi Simulation for Case Study 2 Baseline Profile

When remeasuring this runway 5 years later, after the affecting panels were removed and replaced (2,000 to 2,500 feet), peak accelerations (Figure D-12), which were considered excessive, were recorded in areas other than that Area of Interest.

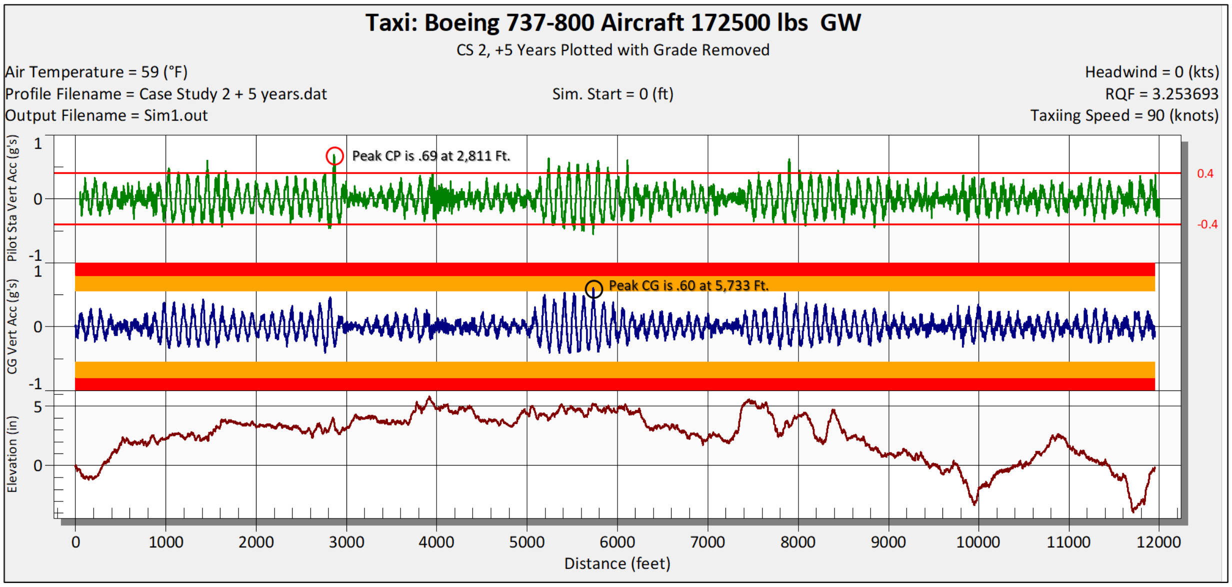


Figure D-12. Plot for 90-Knot Constant-Speed Taxi Simulation for Case Study 2, 5 Years After Baseline

In 2017, 11 years after the baseline, the bumps appear to be developing again. While the responses were predicted to be acceptable at the aircraft's CG, the CP was predicted to produce significant responses (0.75G) while traversing the area of interest. (Figure D-13)

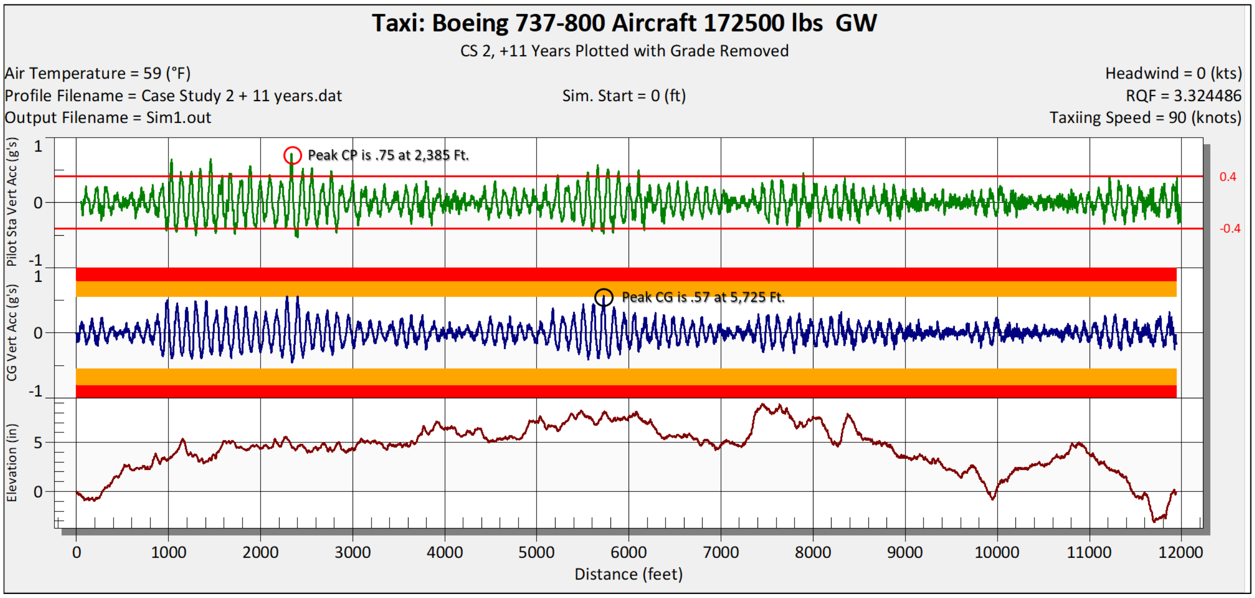


Figure D-13. Plot for 90-Knot Constant-Speed Taxi Simulation for Case Study 2, 11 Years After Baseline

Aircraft simulation results for Case Study 2 show how using aircraft simulation can be useful to determine whether corrective action has been successful. Aircraft simulation would have shown that the predicted aircraft responses were unacceptable and should have triggered corrective action planning. Once corrective action was taken, the ride quality greatly improved in the Area of Interest. Then, after measuring the pavement's profile in a timely interval, these events can be seen developing again, giving authorities time to plan and budget for another round of corrective action.

D.3.4 Aircraft Simulation on Case Study 3

Case Study 3 involves a utility tunnel underneath a runway constructed of PCC. The baseline profile was established of this runway shortly after construction. The Area of Interest for this runway is approximately 4,800 feet from the end of the primary runway. The baseline profile analysis shows peak responses for the CP at around 6,300 feet from the end of the runway and the peak responses from the CG around 6,804 feet from the end of the runway (Figure D-14). These locations of peak loading are outside the current Area of Interest.

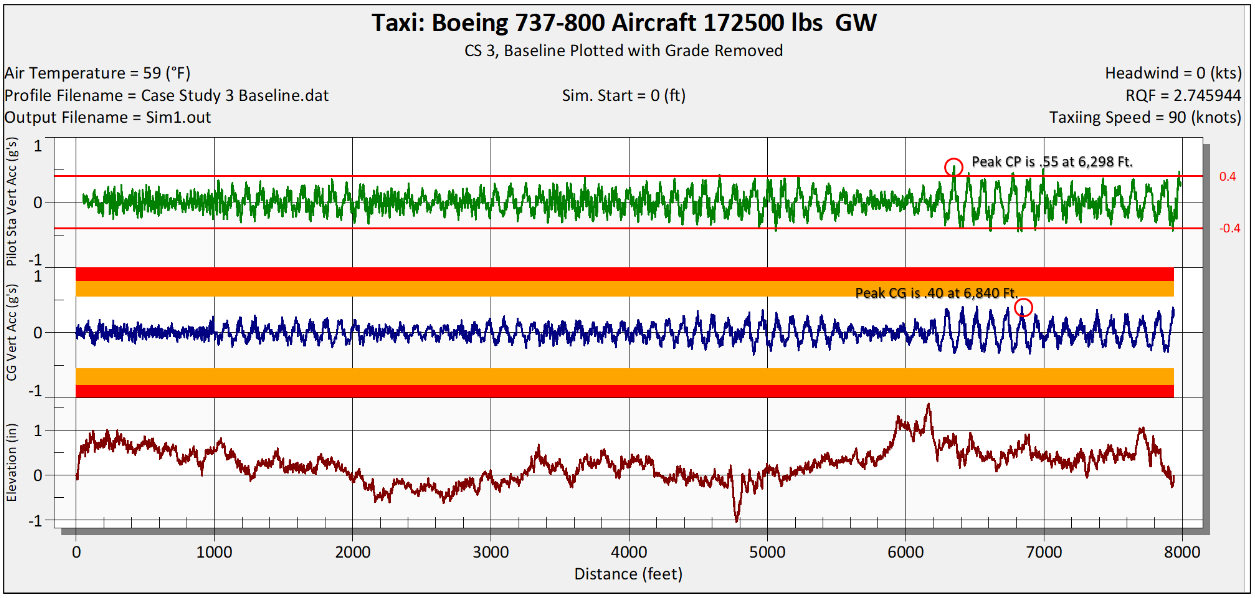


Figure D-14. Plot for 90-Knot Constant-Speed Taxi Simulation for Case Study 3, Baseline Profile

The first profile update was measured 5 years after the baseline was established. As shown in Figure D-15, aircraft simulation predicts that the Area of Interest was now producing peak loads from the CP and the CG. The CG was predicted to produce unacceptable responses based on the thresholds established by Boeing.

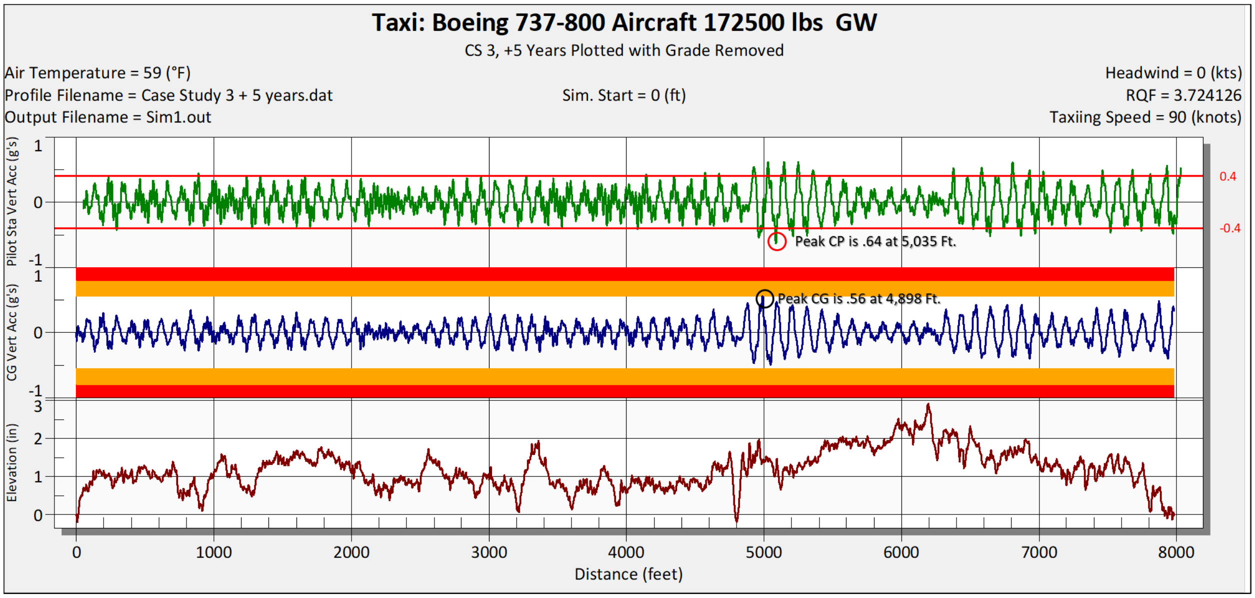


Figure D-15. Plot for 90-Knot Constant-Speed Taxi Simulation for Case Study 3, 5 Years After Baseline

The next update was conducted 8 years after the baseline was established. This update showed increased accelerations at both the CP and CG, as shown in Figure D-16.

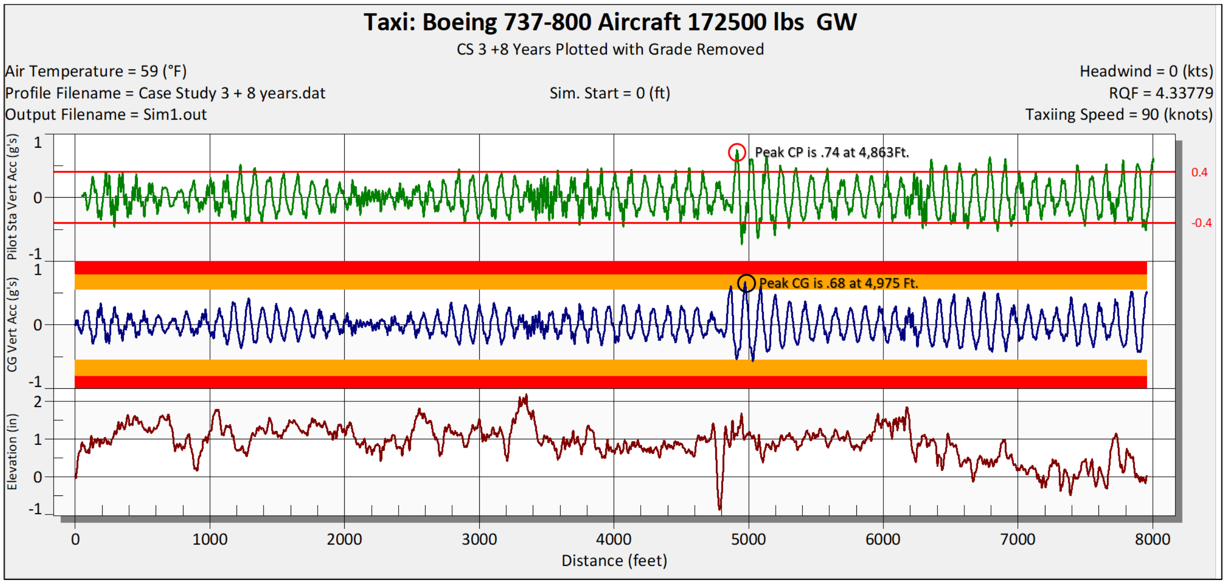


Figure D-16. Plot for 90-Knot Constant Speed Taxi Simulation for Case Study 3, 8 Years After Baseline

A fourth update was then conducted 12 years after the initial baseline profile was measured (Figure D-17). Here, aircraft simulation predicted deteriorating conditions caused by increased settlement surrounding the utility tunnel.

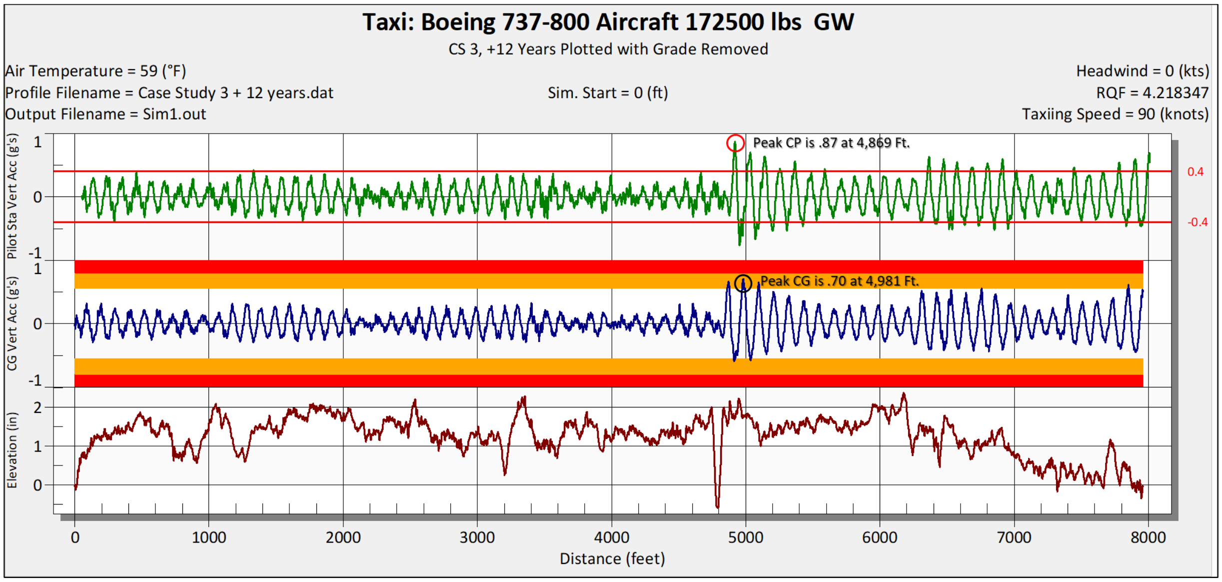


Figure D-17. Plot for 90-Knot Constant-Speed Taxi Simulation for Case Study 3, 12 Years After Baseline

Case Study 3 shows how consistent, iterative profile measurement and analysis can aid an organization in the planning and development of a corrective action plan.

D.3.5 Aircraft Simulation on Case Study 4

Case Study 4 is a runway that was reconstructed over swampy subgrade conditions. An attempt was made to mitigate settlement from the weight of the new overlay, but this attempt failed and resulted in a very dynamic pavement surface consisting of pavement dimpling and areas of large-scale settlement. The Area of Interest for this runway was between 1,200 feet and 2,500 feet from the end of the primary runway. The baseline profile was measured in 2006. At the time, visual evidence of the dimpling was evident but did not have a significant effect on aircraft response (Figure D-18). Also, at the time the baseline profile was established, there was little sign of differential settlement in the Area of Interest.

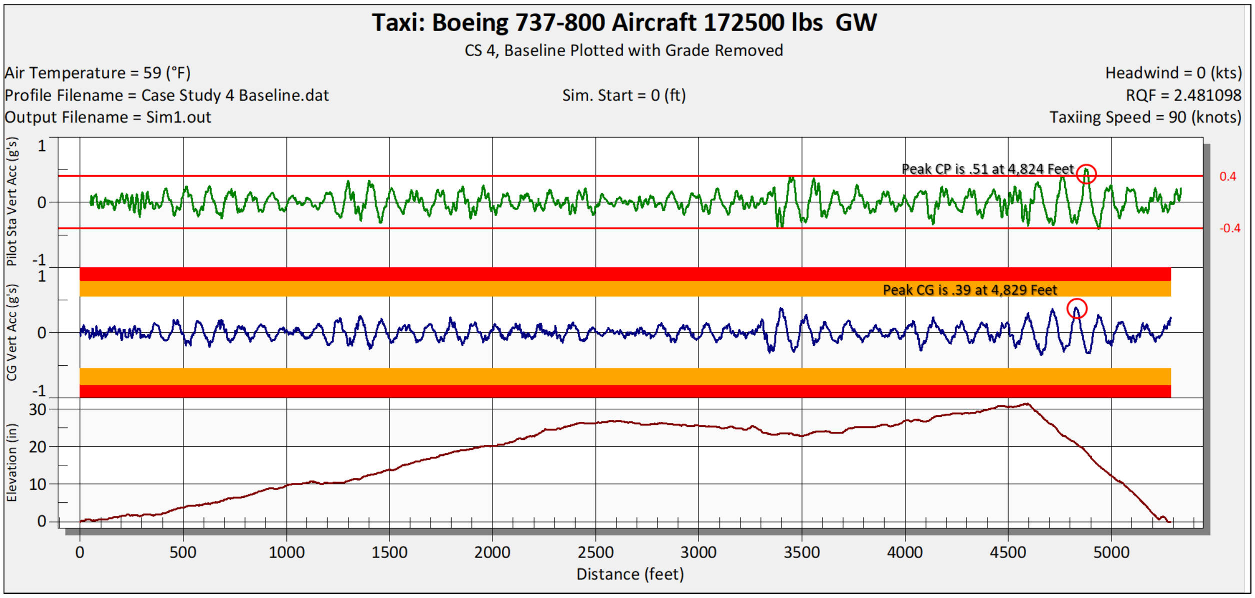


Figure D-18. Plot for 90-Knot Constant-Speed Taxi Simulation for Case Study 4, Baseline Profile

This runway was surveyed and evaluated numerous times between 2006 and 2018; however, only two points in time were assessed, the baseline and the survey data collected 11 years later. As shown in Figure D-19, aircraft responses were predicted to be unacceptable at the aircraft's CG and well over 1.0G at the CP. This was the last survey and analysis conducted prior to another significant reconstruction of this runway to correct the settlement and improve the ride quality.

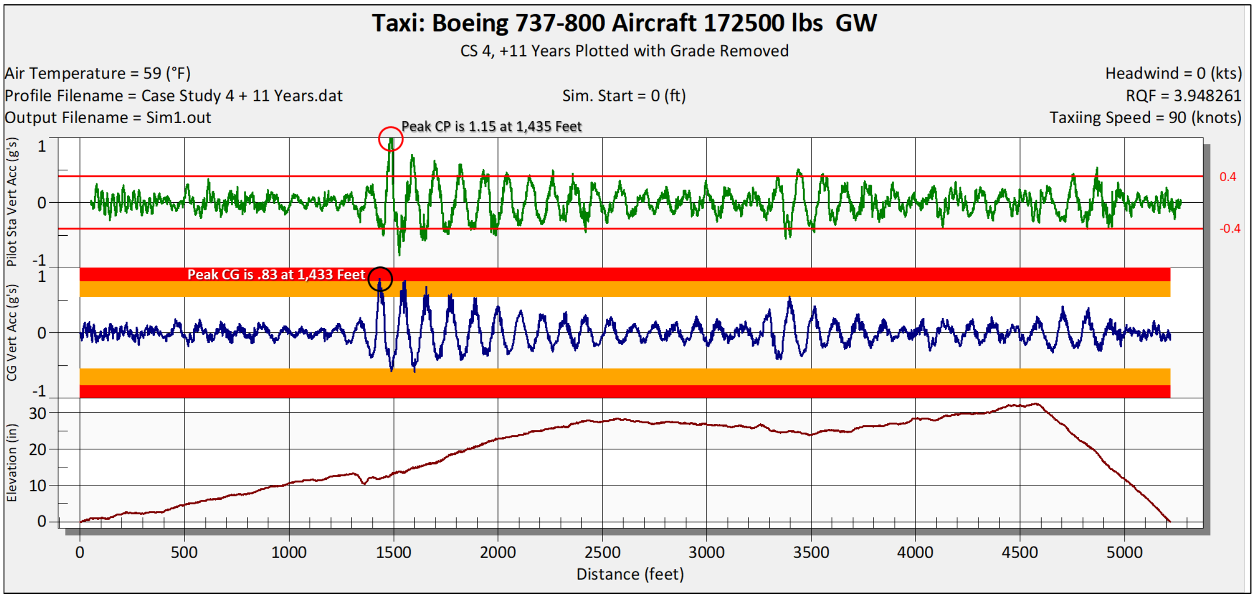


Figure D-19. Plot for 90-Knot Constant-Speed Taxi Simulation for Case Study 4, 11 Years After Baseline

D.4 AIRCRAFT SIMULATION SUMMARY

Aircraft simulation, as shown in this report, is a proven method to determine the effect profile shape change has on aircraft operations and operational safety. Pavement profile surveys and analysis at regular intervals allow an organization to determine if profile shape changes are causing poor aircraft responses and higher dynamic loads on the pavement. As in Case Study 1, changes are occurring to the profile, but the wavelengths are fairly long and do not create a ride quality problem. Conversely, Case Studies 2, 3, and 4 all show how aircraft simulation can be used to track deteriorating conditions and inform the organization on when to make the appropriate pavement repairs before the ride quality is predicted to compromise operational safety.

D.4.1 Quantifying Profile Shape Change

While aircraft simulation can quantify the effect profile shape changes can have on aircraft response, it is not so effective at quantifying the amount of change that has occurred over time. For this, it is best to evaluate the measured profile data using a 100-foot analytical straightedge. This method was used on all the profiles for each case study runway. A 1-inch allowable deviation was used on this analysis to help identify deviations that can cause unwanted aircraft responses. The results were then plotted and compared to the baseline deviations. From these data, changes can be measured. Those measured data, coupled with the interval between profile measurement updates, a rate of change value can be calculated. This ability allows the user to modify the measured profile simulating the shape change that would occur in the coming years and, using aircraft simulation, determine when the profile shape change becomes unacceptable and requires corrective action. It is recognized that profile changes are not necessarily linear.

D.4.1.1 Case Study 1: 100-Foot Straightedge Analysis

When comparing the deviations identified using the baseline profile to the profile update measured 7 years later, three areas show where the profile has changed to the point where the 1-inch allowable deviation is exceeded. One area exceeded the 1-inch threshold in the baseline and, when compared, it appears to have settled further. These plots are shown in Figures D-20 and D-21.

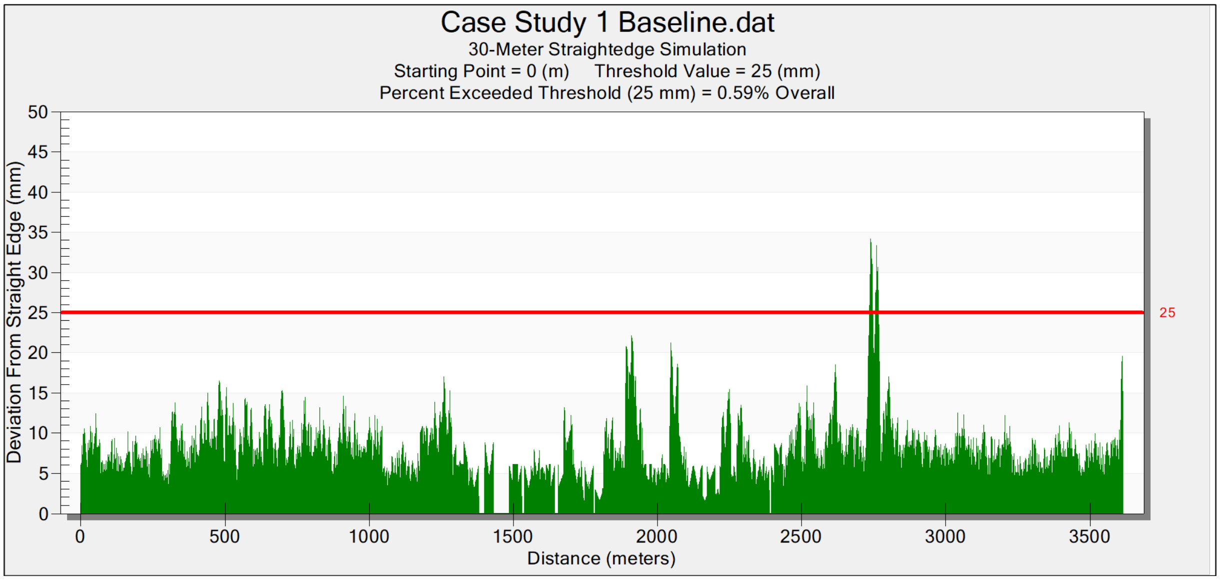


Figure D-20. Plot for 100-Foot Straightedge Analysis for Case Study 1 Baseline Profile

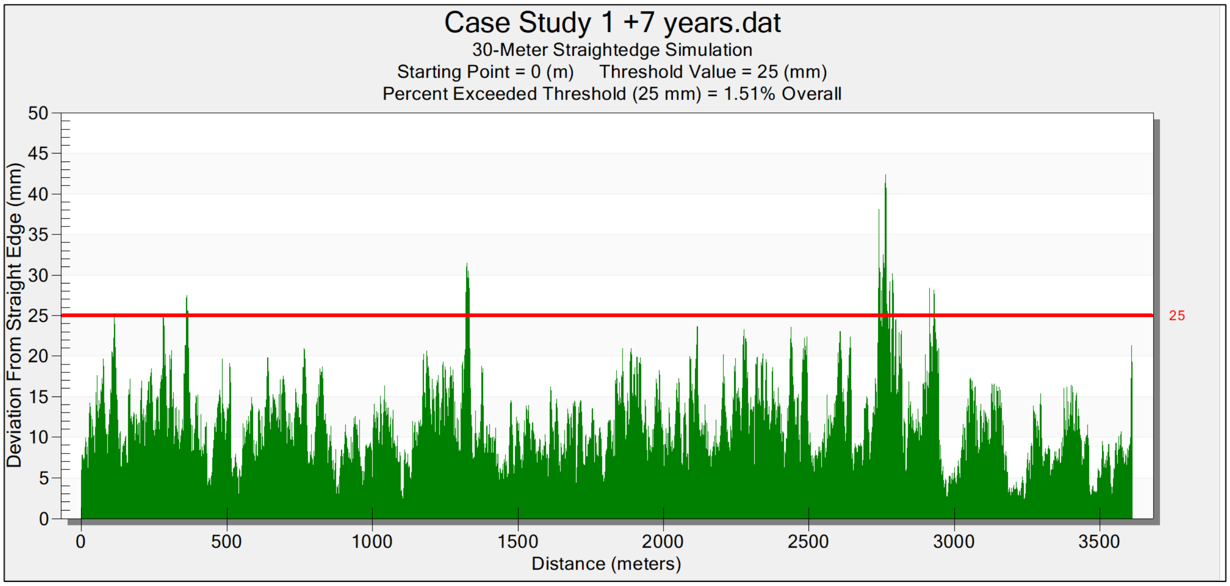


Figure D-21. Plot for 100-Foot Straightedge Analysis for Case Study 1, 7 Years After the Baseline

D.4.1.2 Case Study 2: 100-Foot Straightedge Analysis

Case Study 2 is interesting because it is a baseline profile that works backwards, in a sense. The baseline profile had several bumps in succession, and aircraft simulations show these bumps were causing ride quality complaints. When measured, there were several locations on the pavement that exceeded the 1-inch threshold in the initial 2,500 feet of the runway (Figure D-22). An updated profile was then measured 5 years later. The resulting straightedge analysis shows that those areas in the initial 2,500 feet had greatly improved (Figure D-23). Then, 11 years after the baseline, the runway's profile was measured and evaluated a third time. This analysis shows that two new areas are starting to develop approximately 1,000 feet past the threshold (Figure D-24)

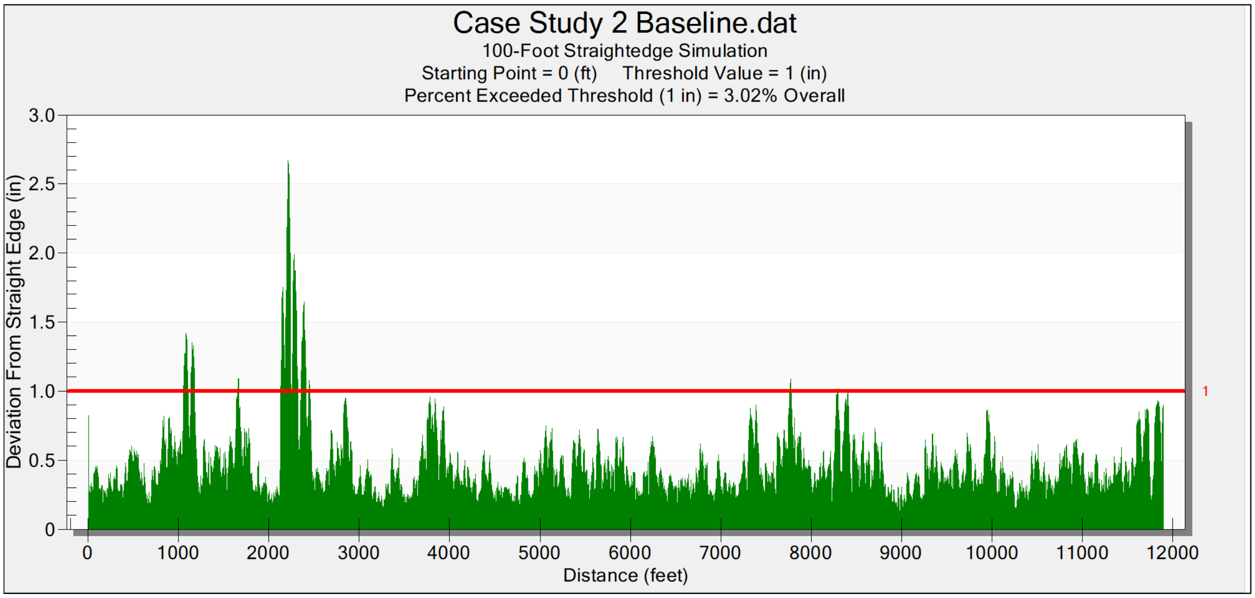


Figure D-22. Plot for 100-Foot Straightedge Analysis for Case Study 2 Baseline Profile

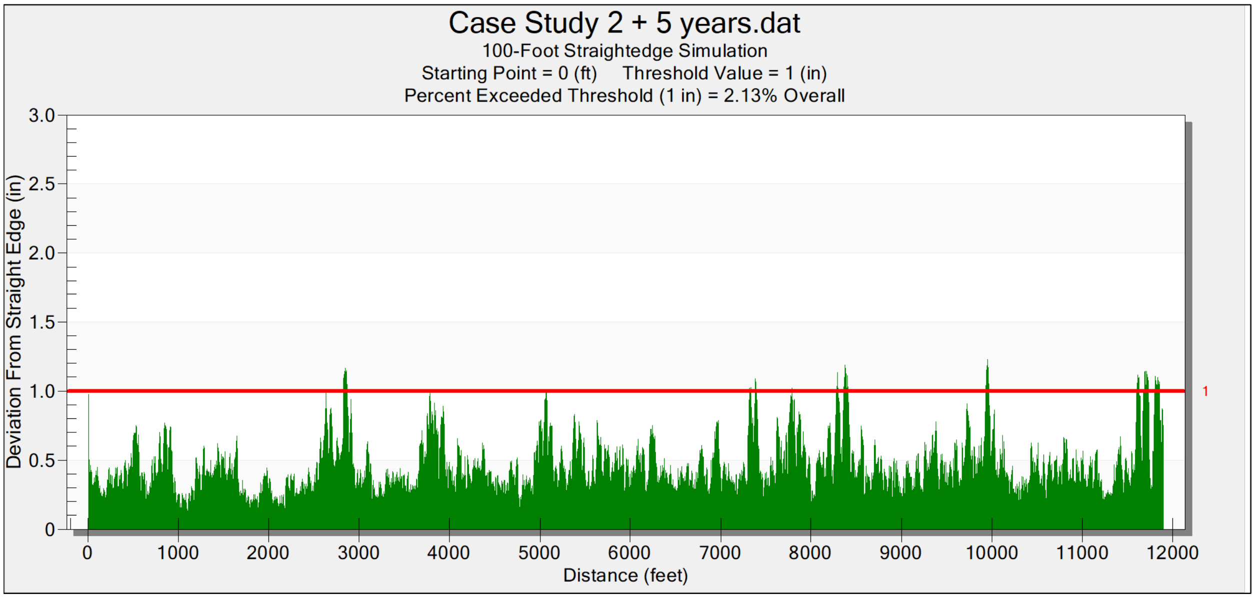


Figure D-23. Plot for 100-Foot Straightedge Analysis for Case Study 2 5 Years After the Baseline

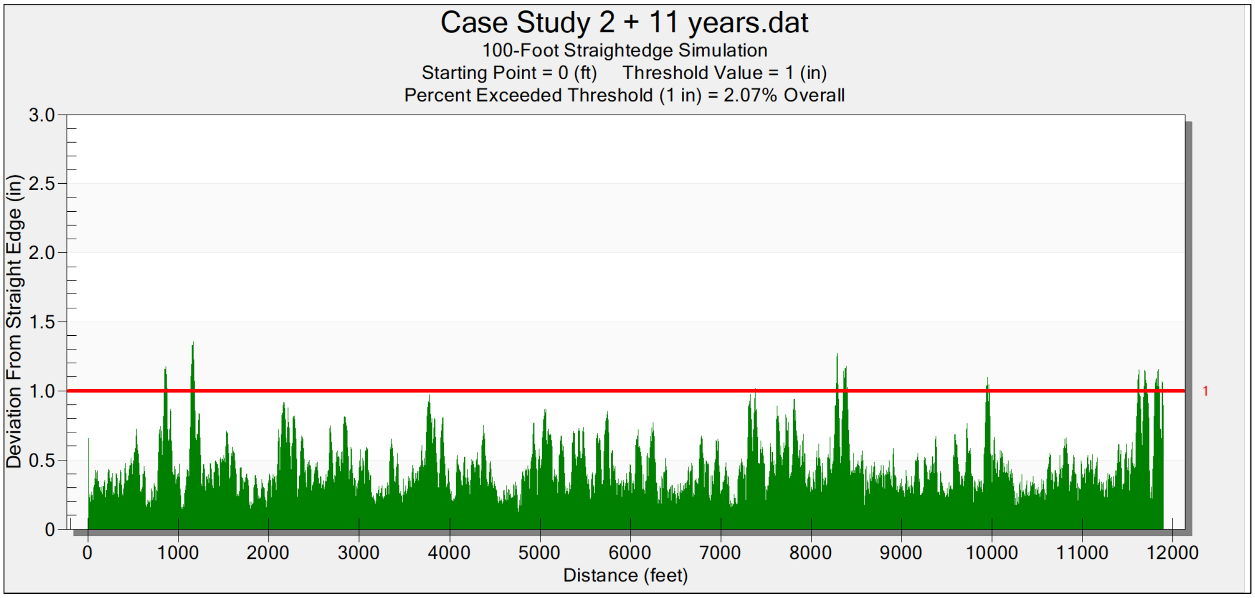


Figure D-24. 100-Foot Straightedge Analysis for Case Study 2, 11 Years After the Baseline

D.4.1.3 Case Study 3: 100-Foot Straightedge Analysis

Case Study 3 involves a utility tunnel underneath the runway. The straightedge analysis offers an excellent perspective on how this method can track profile shape changes and provide measurements of the change and the ability to determine the rate of change. This will enable planners to determine when corrective action should be taken. As shown in Figure D-25, the baseline profile of this runway shows the tunnel to have about 1.175 inches of deviation.

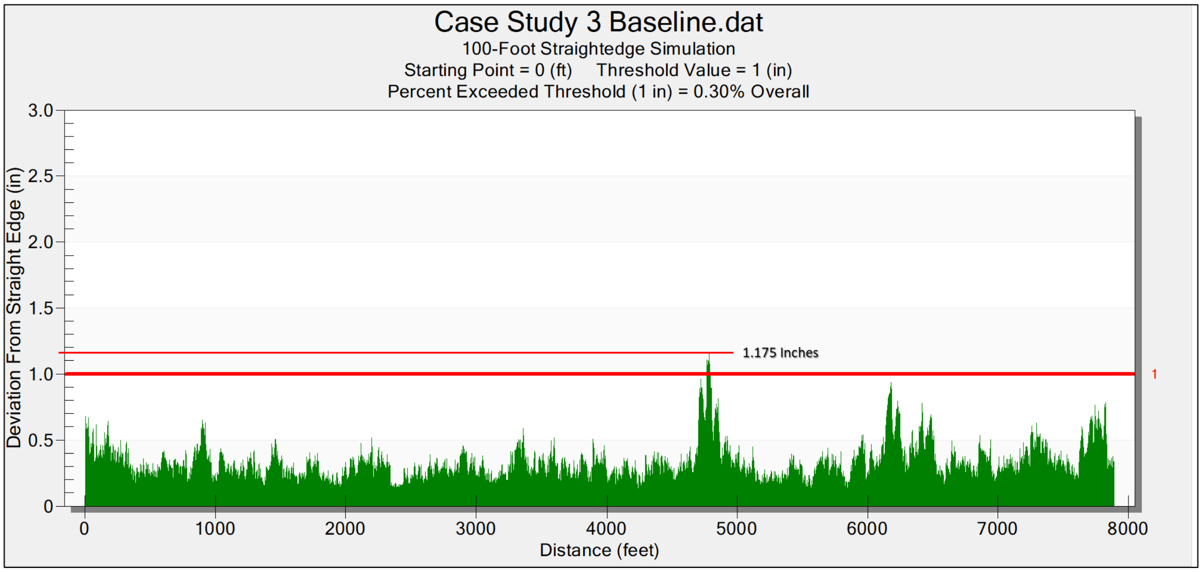


Figure D-25. Plot for 100-Foot Straightedge Analysis for Case Study 3 Baseline Profile

Figure D-26 shows the updated analysis using data measured 5 years after the baseline. Here, the maximum deviation of 1.80 inches. This is a growth of 0.62 inches in 5 years, yielding a rate of change of 0.124 inches per year.

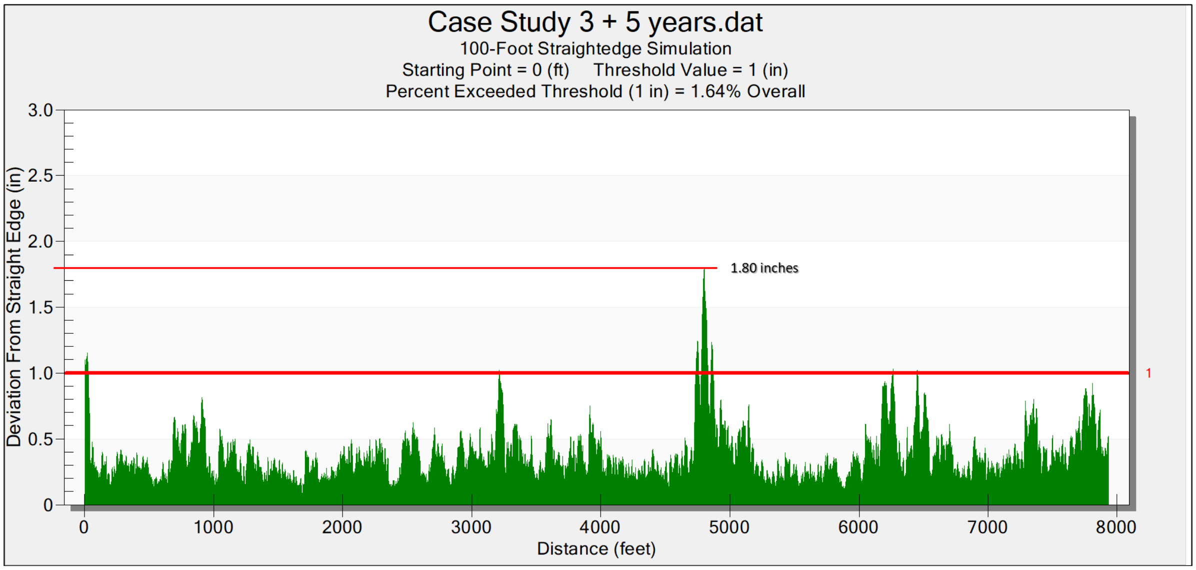


Figure D-26. Plot for 100-Foot Straightedge Analysis for Case Study 3, 5 Years After the Baseline

The next update was measured 8 years after the baseline (Figure D-27). The peak deviation was measured at 2.20 inches, which was an increase of 0.40 inches occurring over 3 years since the last update. This is a rate of change of 0.13 inches per year, which would be a slight acceleration since the 5-year update rate of change.

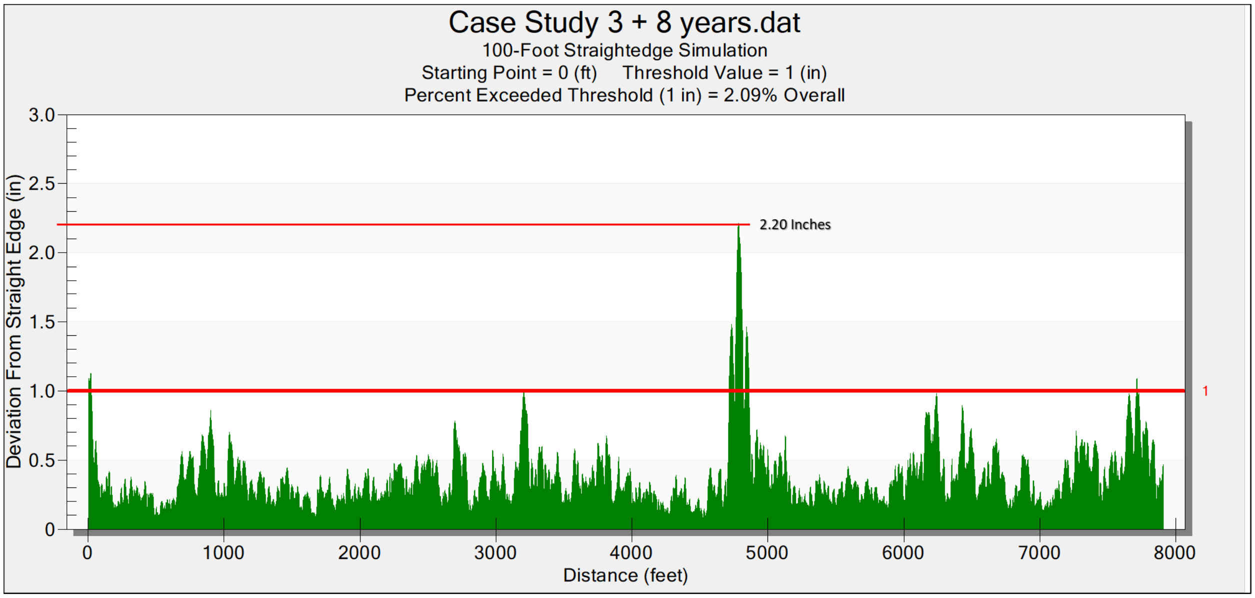


Figure D-27. Plot for 100-Foot Straightedge Analysis for Case Study 3, 8 Years After the Baseline

The final update of this runway was made 12 years after the baseline. It was found to have a maximum deviation of 2.60 inches. This would be an additional 0.40 inches of change over 4 years for a rate of change of 0.10 inches per year (Figure D-28). This would show that the profile shape change has slowed since the last analysis.

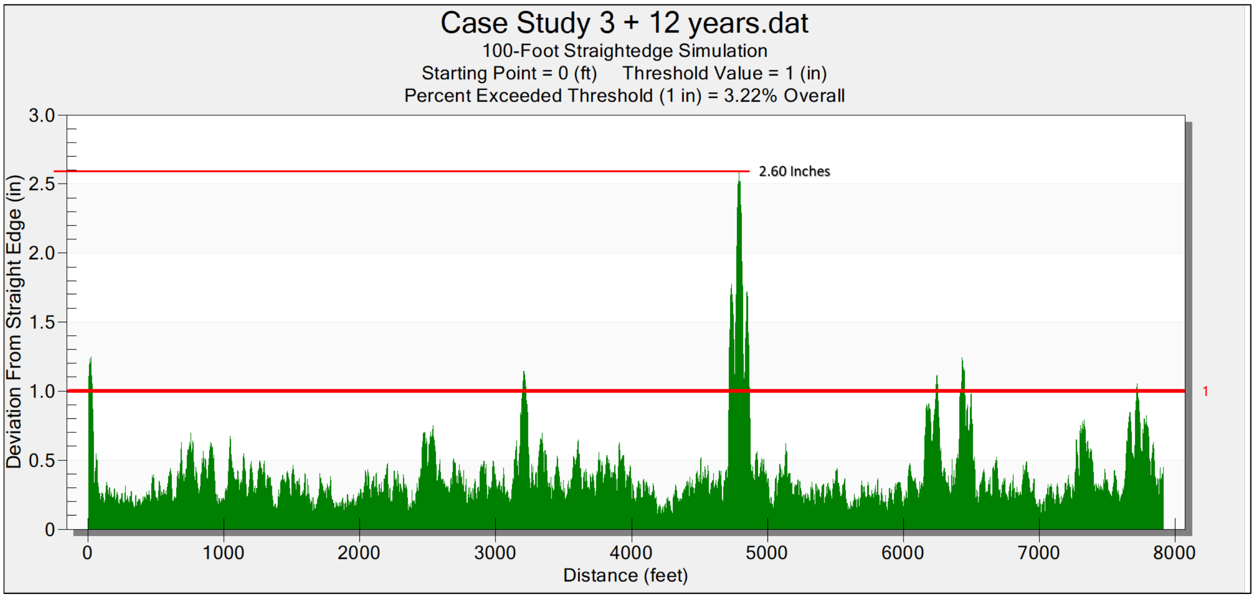


Figure D 28. Plot for 100-foot Straightedge Analysis for Case Study 3, 12 Years After the Baseline

D.4.1.4 Case Study 4: 100-Foot Straightedge Analysis

As discussed, this runway has experienced unique and problematic settlement issues that have been monitored for several years. When evaluating the baseline with the 100-foot straightedge, the Area of Interest, around 1,300 feet, did not show any deviations that approached the 1-inch threshold (Figure D-29). However, when evaluated with the same technique using profile data measured 11 years after the baseline, this technique clearly shows how the pavement has settled, registering a peak deviation of 2.3 inches (Figure D-30). It should be noted that the other issue associated with this runway is a dimpling problem where the grout pillars, inserted to prevent settlement, floated, and the surrounding asphalt pavement settled. These dimpling deformations were not detected in a noticeable way using this technique but would have been visible using a shorter straightedge length.

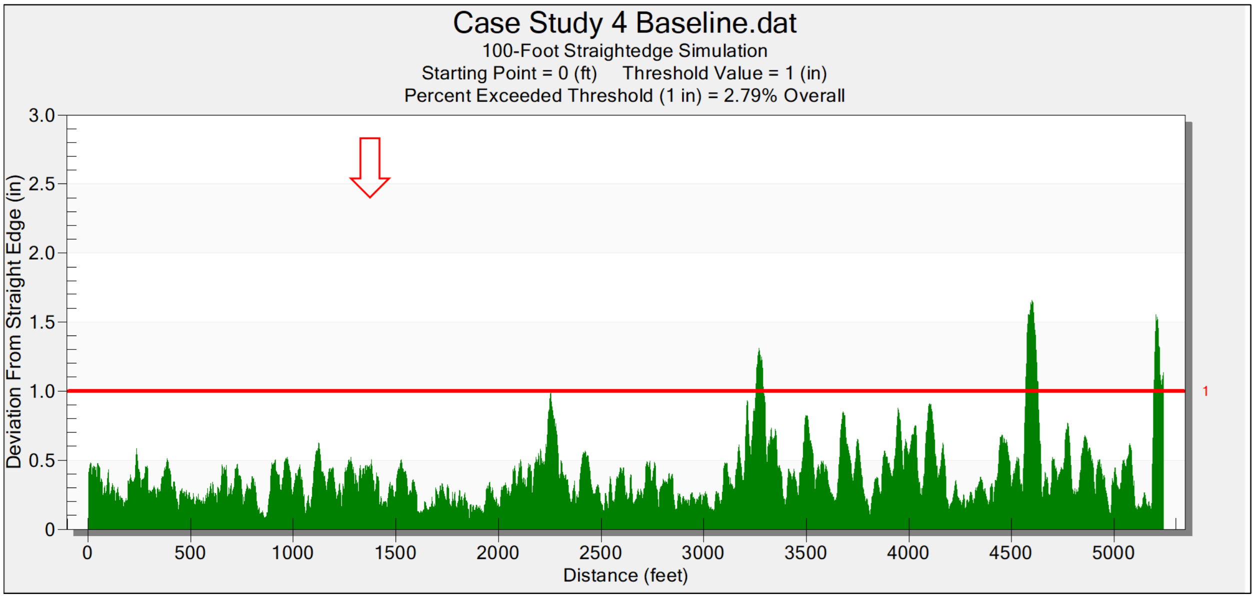


Figure D-29. Plot for 100-Foot Straightedge Analysis for Case Study 4, Baseline Profile

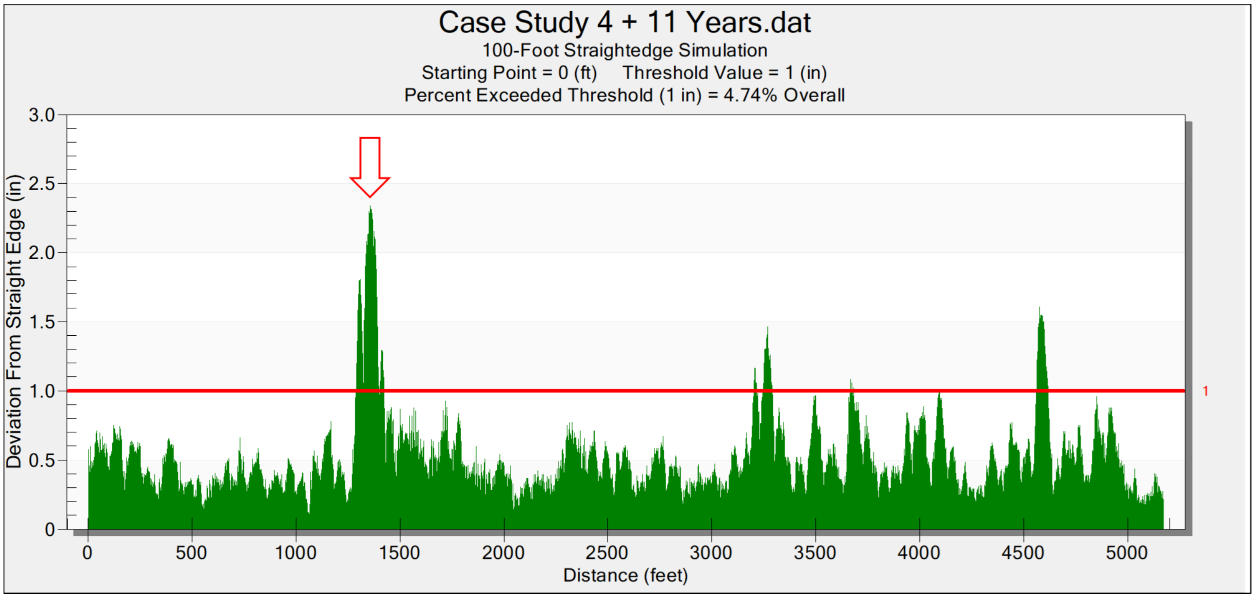


Figure D-30. Plot for 100-Foot Straightedge Analysis for Case Study 4, 11 Years After the Baseline

D.4.2 Profile Measurement by Device Type

To effectively track a runway's profile shape as it changes over time, it is important that very long wavelengths and the pavement's grade be accurately measured. Ideally, it would be best to have the capability to track an infinite wavelength regardless of amplitude.

D.4.2.1 True Profiling Devices and Techniques

Currently, there are off-the-shelf devices that can measure all grade changes and bumps/dips regardless of wavelength or amplitude. As of this writing, APR's AR&L – ER and ICC's SurPRO line of inclinometers (Figure D-31) have demonstrated the ability to track all grade changes regardless of amplitude or wavelength. These units can survey a 10,000-foot (3,048-meter) line of survey in approximately 1 hour and collect an elevation data point at intervals that range from every 2.75 inches (70 mm) up to 1 foot (305 mm).

Figure D-31. The Three Types of Profilers Used in this Comparison Study

Alternative techniques to obtain all grades would be to use a traditional survey crew using a robotic total station (RTS). This method would produce acceptable vertical accuracy but it would be very time-consuming to get acceptable datapoint intervals using this method.

True profile measurement devices and techniques can produce excellent results. The profile data used in the four case studies for this report were all measured with the AR&L – ER and demonstrate this unit's ability to achieve these objectives.

D.4.2.2 Inertial Profiling Devices

Inertial profiling devices are commonly used in the road and highway industries. For this study, the Ames Engineering 8200 inertial profiler was used and is shown in Figure D-31. These units can measure profile data quickly and accurately. However, there are questions about how long a wavelength a typical inertial profiler can measure. (See Appendix B in this report.) Some inertial profilers have settings that allow a user to increase the unit's ability to capture longer wavelengths, but, at this time, the limit of the wavelength is unknown. In testing, comparing the measured profile of an inertial profiler to that of true profilers, the inertial profiler was able to match the dimensions of bump/dip wavelength and amplitudes; but when comparing end-to-end grade, the inertial profiler failed to match the results produced by the true profilers (Table D-1). Figure D-32 shows the comparison between units with the end-to-end grade removed.

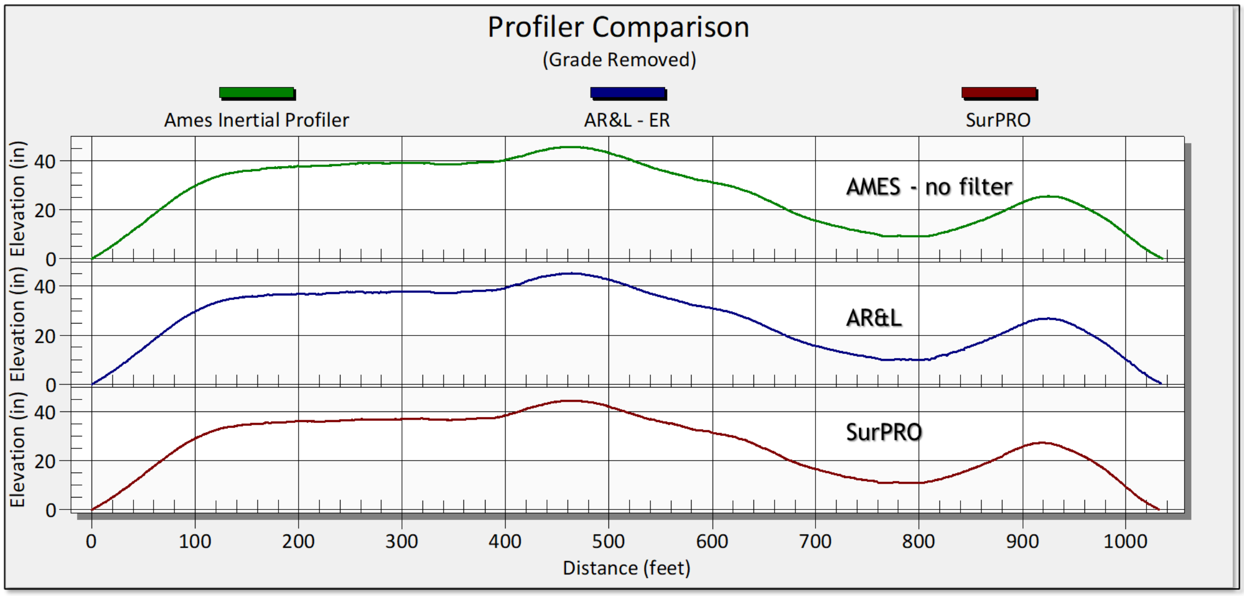


Figure D-32. Profile Comparison Between the Ames 8200 (top), the AR&L–ER (middle), and the SurPRO (bottom) With Overall Grade Removed

Table D-1. End-to-End Elevation Change as Measured by the True Profilers versus the Inertial Profiler

0 to 1,000 Feet Change in Elevation (Inches)			
	Pass 1	Pass 2	Pass 3
AR&L – ER	44.42	43.40	43.70
SurPRO	43.60	44.30	43.20
Ames 8200	12.80	10.49	8.60

Further comparison testing of these profiler units would be beneficial to discovering the limits of an inertial profiler’s wavelength tracking. Additionally, it would be beneficial to test inertial profilers developed by other manufacturers.

D.5 CONCLUSIONS

Runways are a vital asset to the nation’s economy. In addition to the construction costs, runways are critical for local and national commerce. If a runway is closed, even temporarily, that closure can have an impact on the efficient flow of consumers and goods. As such, it is the objective of regulatory agencies to ensure that these pavements are safe and serviceable for as long as possible. To achieve a long service life, the FAA has promoted the development of several pavement inspection techniques, such as pavement condition inspections and structural integrity evaluations carried out by Falling Weight Deflectometer and Heavy Falling Weight deflectometers.

This appendix shows that by establishing a baseline profile, a variety of techniques can be employed by the user to gain visibility into the dynamics of the structure and the development of profile shape changes over time. The overall concern is that profile shape changes can lead to poor aircraft responses which, at a minimum, can initiate pilot and passenger complaints and increase the localized pavement-loading environment, but, if severe enough, could compromise safety for operating aircraft.

This appendix reviewed four case studies to demonstrate how a baseline profile and periodic updates can be used over time to monitor the pavement's profile shape. A variety of analyses were used to identify profile shape changes, assess the impact the changes are having on aircraft ride quality operations, and track profile change growth over time to help planners draft corrective action if needed.

D.5.1 Visual Analysis

In all four case studies, the plotted profile clearly shows area of profile shape changes when comparing the baseline profile to the profile updates that were measured over time. The visual analysis would serve as the initial evaluation to determine the impact of profile shape change. With the right profile evaluation tools, measurements can be made to determine the amount of change that has occurred and the location of where the changes are occurring.

D.5.2 Aircraft Simulation

With the profile measured, aircraft simulation can be used to determine the impact these changes have on aircraft responses. In many instances, the wavelengths of the profile shape changes are long and do not affect aircraft response, as in Case Study 1. However, in every other case study used in this report, aircraft simulation shows how these changes begin to detrimentally affect ride quality. Using thresholds of acceptability, such as those found in Boeing Document Number D6-81746 (1995), airport managers can plan corrective action to improve these conditions.

D.5.3 Straightedge Analysis

While aircraft simulations can help determine the effect profile shape change has on aircraft ride quality, a straightedge analysis of the measured profile data will quantify the dimensions of the profile shape change. For this analysis, a 100-foot-long straightedge was used on all four case studies. This technique allows the user to calculate the rate of change occurring in the amount of time between profile updates. Using the rate of change value, the user could then modify the profile by accelerating the profile's deformation to model the future profile shape. With this modified profile, aircraft simulation can then be used to determine when the profile shape change is severe enough warranting corrective action planning.

D.6 RECOMMENDATIONS

The purpose of this report is to evaluate the benefit of establishing a baseline profile as a standard component of runway construction, overlay, or significant reconstruction. This analysis used four case studies that have experienced a variety of profile dynamics over time. Several different evaluations were conducted on each case study's baseline and subsequent profile updates. The results were reviewed from the perspective of a pavement manager to see if the conclusions would be helpful in making critical maintenance decisions throughout the pavement’s life.

This study shows that establishing a baseline profile is an effective way to monitor a pavement’s health over time and assist in making critical decisions on when to plan corrective action to mitigate excessive dynamic loading on the pavement. The following analytical techniques can be used to provide visibility into the dynamics of the pavement’s profile.

1. **Visually Comparing the Baseline Profile to Profile Updates:** This technique allows the user to visually discern changes that have occurred to the pavement’s profile. Using software that can plot multiple lines of survey at once, the user can identify and quantify profile shape changes that occur as pavement ages.

2. **Aircraft Simulation:** Aircraft simulation allows the user to determine if profile shape changes adversely affect aircraft ride quality over time. Using thresholds of acceptability, predicted aircraft responses will aid the user in making decisions on when to develop corrective actions.

3. **Straightedge Analysis:** This analysis helps the user quantify the profile shape changes over time. Comparing deviations from a straightedge to the baseline profile and subsequent profile updates collected over time allows the user to calculate the rate of change the profile is experiencing. Based on this, projections can be made to help determine when corrective actions are required.

4. **Quality of Profile Data:** Any profile analysis is only as good as the profile data used in that analysis. To adequately identify and quantify the roughness of a pavement, longer wavelengths must be included. Currently, external reference profilers and inclinometers can measure all wavelengths and amplitudes. Inertial profiler’s ability to measure longer wavelengths and amplitudes are limited.

As a result of this study, the following recommendations can be made.

1. Because of the proven benefits documented in this report, it is recommended that a baseline profile become a standard deliverable by the contractor upon completion of a runway’s construction, overlay, or major rehabilitation.

2. ProFAA needs to be enhanced with the ability for viewing multiple sets of profile data at the same time. These enhancements should include an ability to measure profile wavelengths and amplitudes between the sets of profile data.

3. Enhance ProFAA with the ability to manipulate profile data. By including a profile editing module, the user will be able to manipulate profile data using the calculated rate of change information and help determine when corrective action will be required.

4. ProFAA can currently simulate a variety of straightedge lengths, but a new method of reporting the deviations to the straightedge needs to be developed. This method should allow the user to compare deviations from one data set to another and provide the user

with the ability to measure the differences in deviation to determine the rate of change the pavement is experiencing.

5. It is known that aircraft can respond to wavelengths up to 300 feet (91 meters). However, there could be reasons to capture large wavelengths or amplitudes to adequately study the pavement's health. Determine what specific wavelengths and amplitudes would be of interest for effectively monitoring the pavement's health. Knowing these values will help determine what type of profile measurement device will be required to establish the baseline.

D.7 REFERENCE

Boeing Commercial Airplane Group, Airport Technology Organization. (1995, November). *Runway roughness measurement, quantification, and application - Boeing method* (D6-81746). https://www.boeing.com/content/dam/boeing/boeingdotcom/commercial/airports/faqs/roughness.pdf