ROUGHNESS ASSESSMENT IN PAVEMENT MANAGEMENT AT NEW YORK METROPOLITAN AREA AIRPORTS

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INTRODUCTION

The Port Authority of New York and New Jersey (Port Authority) operates four airports within the New York Metropolitan Area: John F. Kennedy International, LaGuardia, Newark Liberty International and Teterboro. The airfield pavement network at these airports consists of roughly 19 miles of runway and 63 miles of taxiway. The replacement cost of these pavements is approximately $1 billion. To maintain safe pavements, operate efficiently, and preserve its investment, the Port Authority utilizes pavement management systems to identify pavements in need of maintenance or rehabilitation.

The Port Authority's pavement management system has always included functional pavement ratings using pavement condition indices and structural remaining life analyses. Recently, the Port Authority has added roughness assessment to its pavement management activities. Aircraft simulation and straightedge analysis are used to assess runway roughness. Taxiway roughness is assessed using a profilometer and International Roughness Index or aircraft simulation.

This paper describes the methodology the Port Authority employs for roughness assessment, how it is incorporated into pavement management activities, and how results can impact pavement rehabilitation design.

PORT AUTHORITY PAVEMENT MANAGEMENT SYSTEMS

The Port Authority uses computer software based pavement management systems to develop pavement management plans for the New York Metropolitan Area's four airports. Like most pavement management systems they include the pavement's material composition, layer thicknesses, construction history, traffic data, pavement condition surveys, structural remaining life analysis, maintenance and rehabilitation (M&R) strategies, and cost data. Material composition, layer thickness and construction history are updated annually as projects are completed. Traffic data is updated every five years. Pavement condition surveys are performed at least once every three years; in accordance with ASTM D5340.Inspection data is used to determine the pavement condition index (PCI). Structural remaining life is computed using elastic layer and F806-R805 programs. Maintenance and rehabilitation strategies are based on Port Authority experience. Construction cost data for the M&R activities is updated annually. Condition index is the primary trigger of M&R activities. Each year the Port Authority uses its pavement management systems to develop five-year pavement maintenance and rehabilitation plans for its airports.

EVOLUTION OF ROUGHNESS ASSESSMENT AT THE PORT AUTHORITY

Roughness assessment a Port Authority airports was first performed by airline pilots. Typically runways were deemed too rough when a pilot felt in the seat of his or her pants and filed a complaint report citing an approximate location of the bump. Airport personnel would then try to identify the rough area using standard rod and level survey and relatively short straight edges. A repair would be designed and constructed which usually reduced or alleviated the problem, or more precisely that pilot's complaint. Such an approach to assess roughness was subjective and passive since it only addressed the roughness after it was a problem. It also proved disruptive because pavement closures in addition to planned maintenance or rehabilitation were required to perform the unscheduled repairs.

In the 1970's the Port Authority began using a more objective and scientific approach to identifying pavement roughness - Vibration Analysis using the Power Spectral Density function (PSD). A Power Spectral Density function of the pavement roughness was used as the input to a transfer function, which modeled aircraft natural frequency and the damping effect of the tires and shock absorbers. The output was the aircraft response at the center of gravity, measured in g-force. This method could be used to identify pavement roughness before pilots complain, but it had two significant drawbacks. The first was it required a survey of pavement elevations every two feet along each wheel path, to determine the PSD function of the pavement roughness. The second was the transfer function accounting for the damping effect of the aircraft was simplified and assumed that the struts are linear forces. It also did not include operation variables such as wind, and air density.

Since the rod and level survey required for PSD was expensive, and required extended runway closures, in the end it was used only on runways to identify areas in need of repair following pilot complaints. Starting approximately 1990 PSD was replaced with Aircraft Simulation based runway assessment.

RUNWAY ASSESSMENT

Profile Measurement

The first step in assessing an airport pavement for roughness is measuring the elevation profile. The profile should reflect what the aircraft encounters. Since aircraft can have longitudinal landing gear spacings approaching 100 feet and speeds beyond 150 knots, long wavelength roughness (300 feet or more) can cause significant aircraft response. In addition, most runways with commercial jet traffic are grooved to improve water runoff characteristics. The grooves should not be reflected in the profile because they have no effect on the aircraft. The tire will bridge the grooves. Consequently, the Port Authority uses a device called the Auto Rod and Level (AR&L) to measure runway profiles. It measures a profile that is true with respect to mean sea level therefore capturing all wavelengths and changes in grade. In addition, the AR&L elevation sensor is in contact with the pavement and therefore bridges the grooves similar to an aircraft tire.

Typically a Port Authority runway roughness assessment will include three lines of survey measured from the painted threshold mark on one end to the painted threshold mark on the opposite end. These include the centerline and 10-15 feet left and right of center. The crown on both ends of the runway is measured as well. An elevation reading is taken every foot and stored on a laptop computer. The profile is plotted on the fly to give the operator feedback. In addition, comments are inserted into the data stream for situational awareness, event markers, etc. For example, the centerline of an intersecting runway or taxiway or a visible roughness event such as a raised slab will be inserted into the data stream.

Most profile data collection is conducted at night from midnight to dawn to minimize the impact on air traffic. In most cases a 10,000-foot runway will be completed in one night. The profile plotted in Figure 1 is a typical example of an AR&L measured profile data set. This particular section of pavement identifies a bump that was causing DC-8 pilot complaints during takeoff. It was not a Port Authority runway.

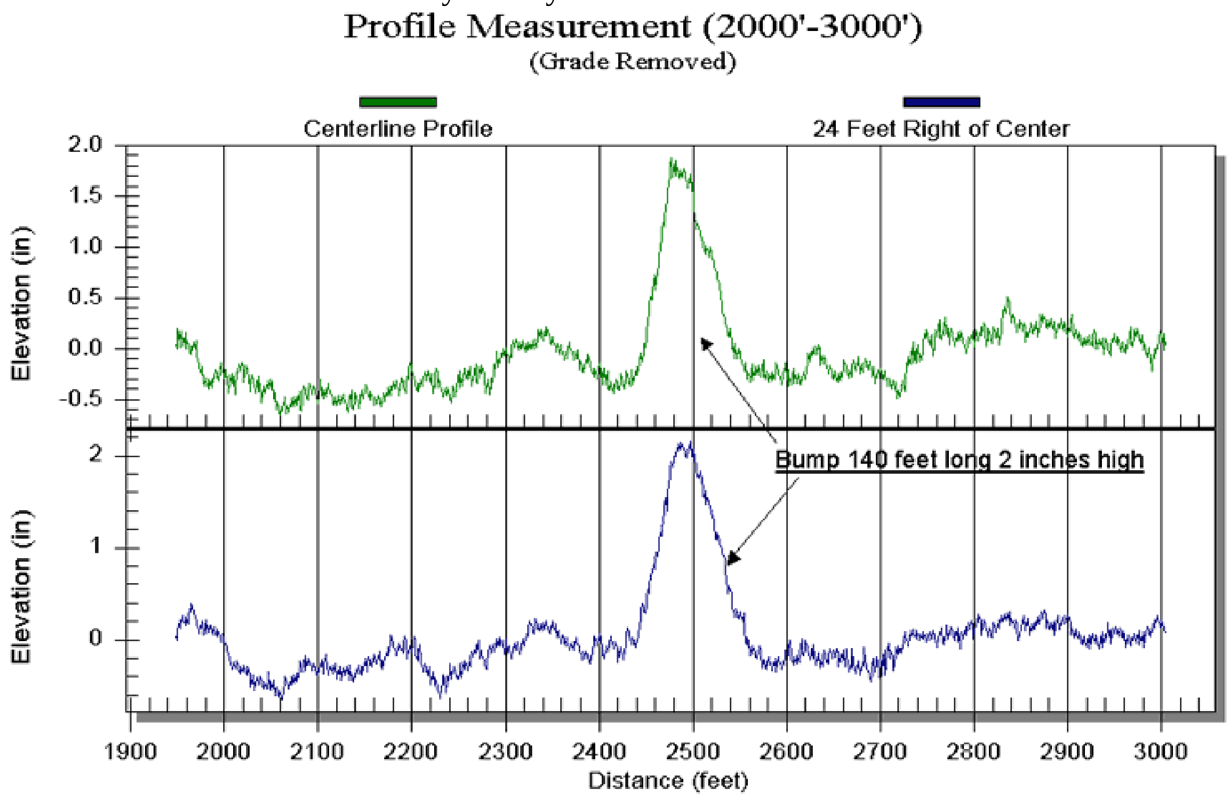

Figure 1. Typical plotted profile clearly showing bump causing DC-8 response.

<u>Aircraft Simulation</u>

We require smooth airport pavements to minimize the dynamic response of the aircraft that use them. Consequently the best measure of merit for smoothness is to determine how aircraft respond to these pavements. Instrumenting an aircraft is one possibility, but that is cost prohibitive. An alternative approach is to simulate how a variety of aircraft would respond to that pavement in question. A software package called APRas is a suite of computer programs that are designed to assess airport pavements using the profile data measured by the AR&L. APRas simulates a variety of aircraft conducting taxi, takeoff, and landing operations. The forcing function in the mathematical model is the runway profile itself. The aircraft simulation algorithms are the result of over 30 years of evolution. They have been validated with measured aircraft test data on multiple occasions and continually improved over the years. Like any computer simulation however, it is just a simulation and cannot be expected to produce an exact correlation. Nonetheless, it has consistently proven to be a successful tool in locating areas in the runway that cause unwanted aircraft response. Figure 2 is the plotted results of a DC-8 taking off on the runway shown in figure 1. The top graph is the vertical acceleration at the pilot's station. The second trace is the vertical acceleration at the aircraft's center of gravity. Both are banded by a +/- .4g reference, which is defined as the "threshold of discomfort" as reported by Goldman and Von Gierke[1]. The third trace is the profile of the runway. The bump that caused the complaints is obvious in this case.

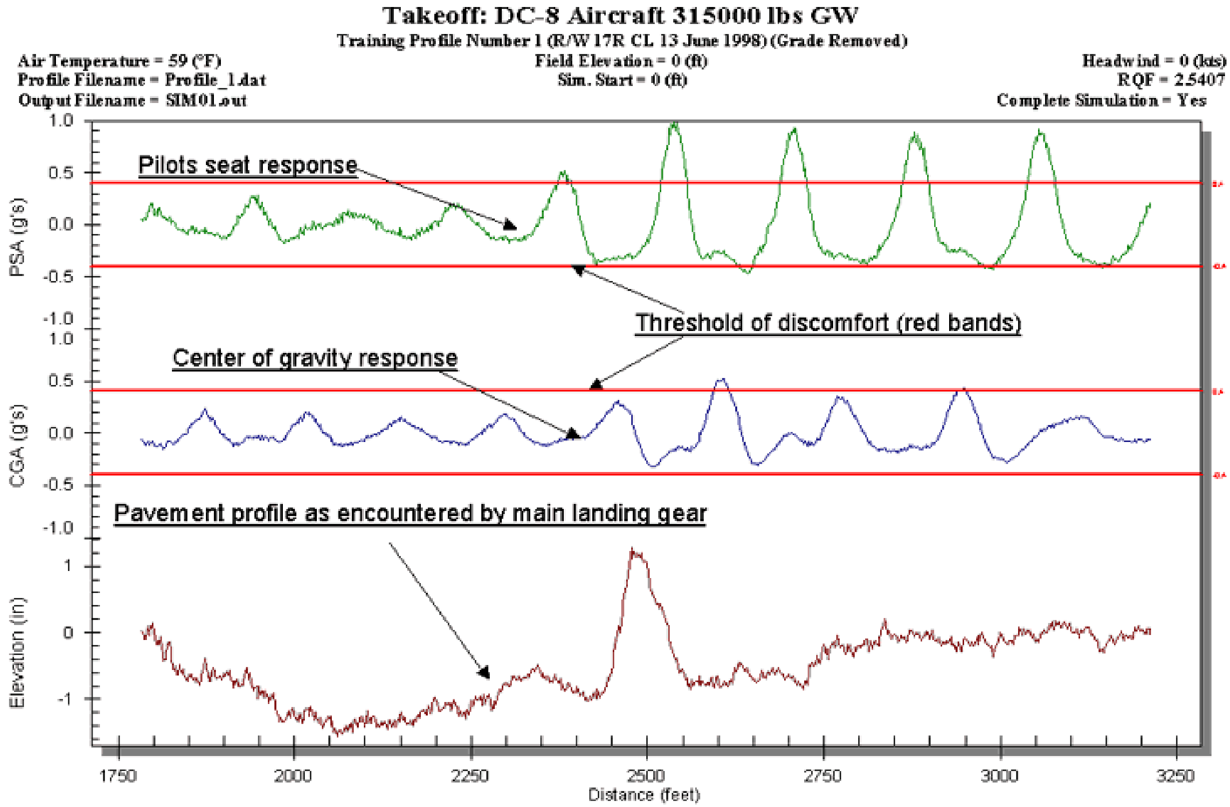

Figure 2. Simulated aircraft response confirming pilot reported roughness in a DC-8 cargo jet.

When assessing our runways for roughness, several aircraft are used in the simulations. Usually, a wide body like the Boeing 747-400 and a smaller aircraft like the Boeing 737 or MD-80 series aircraft. The distance between the main and nose landing gears can have a significant impact on the aircraft's response. By simulating these two categories of aircraft, namely long wheelbase vs. short wheelbase, most areas of roughness can be detected. Takeoff and landing operations are simulated. In addition, field elevation, headwind component, and temperature are included in the simulations. Wind and air density will affect the takeoff and landing distances and therefore change the encounter speed of a bump/dip at some particular location on the runway.

Resonance is another factor to consider when assessing roughness. If a bump or series of bumps is encountered by the aircraft at a speed that "tunes" the bump to the natural frequencies of the aircraft, relatively small amplitude bumps can cause significant aircraft dynamic response. For example, if the natural pitch frequency of a commercial jet is 1 cycle per second and a bump 100 feet long is encountered at 100 feet per second, then resonance occurs. Since an aircraft could be taking off or landing from either end of the runway or an abort could occur at any runway location, any speed of encounter is possible at almost any location on the runway. In order to consider this factor in the roughness analysis, the simulation program called VSweep (Velocity Sweep) is used. VSweep divides the pavement into sections (usually 500 feet in length), simulates an aircraft traversing that section at all velocities, and presents the results as a Ride Quality Index (RQI). RQI is computed by summing the rms of the pilot's station and aircraft center of gravity peak vertical accelerations for each pavement section. Experience has shown that an RQI of 4.0 or higher can generate pilot complaints on runways.

Straight Edge Simulation

Straightedge analysis is another technique used in Port Authority runway roughness assessment. FAA Advisory Circular AC 150/5370-10A, which contains smoothness specifications for new pavements, uses 16-foot (for asphalt) straightedge criteria for shorter wavelength roughness and a specification for grade for long wavelength roughness. The Advisory Circular specifies that the limits of ¼ inch for the 16-foot straight edge and ½ inch for grade control cannot be exceeded more that 15% of the time per lot. Deviation from a straightedge is an intuitive way of visualizing roughness events. Using the profile data collected with the AR&L, a straight edge of any length can be simulated. Figure 3 is the plotted results of a simulated 16-foot straight edge. Areas that exceed ¼ inch are apparent. Figure 4 is the plotted results of a 100-foot straight edge, which has proven to be effective at identifying longer wavelength roughness events that affect aircraft response. It also is a reflection of the adherence to grade control.

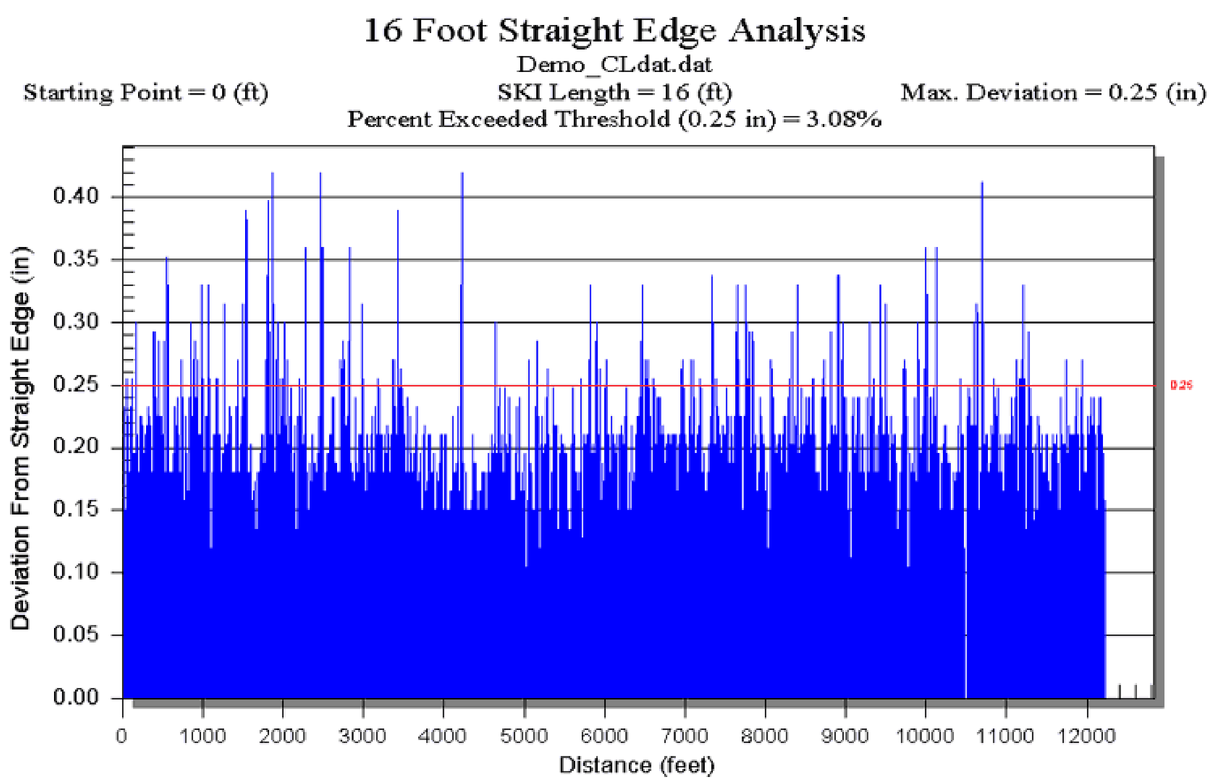

Figure 3. Plotted results of a typical 16-foot straight edge assessment used in APRas 3.0

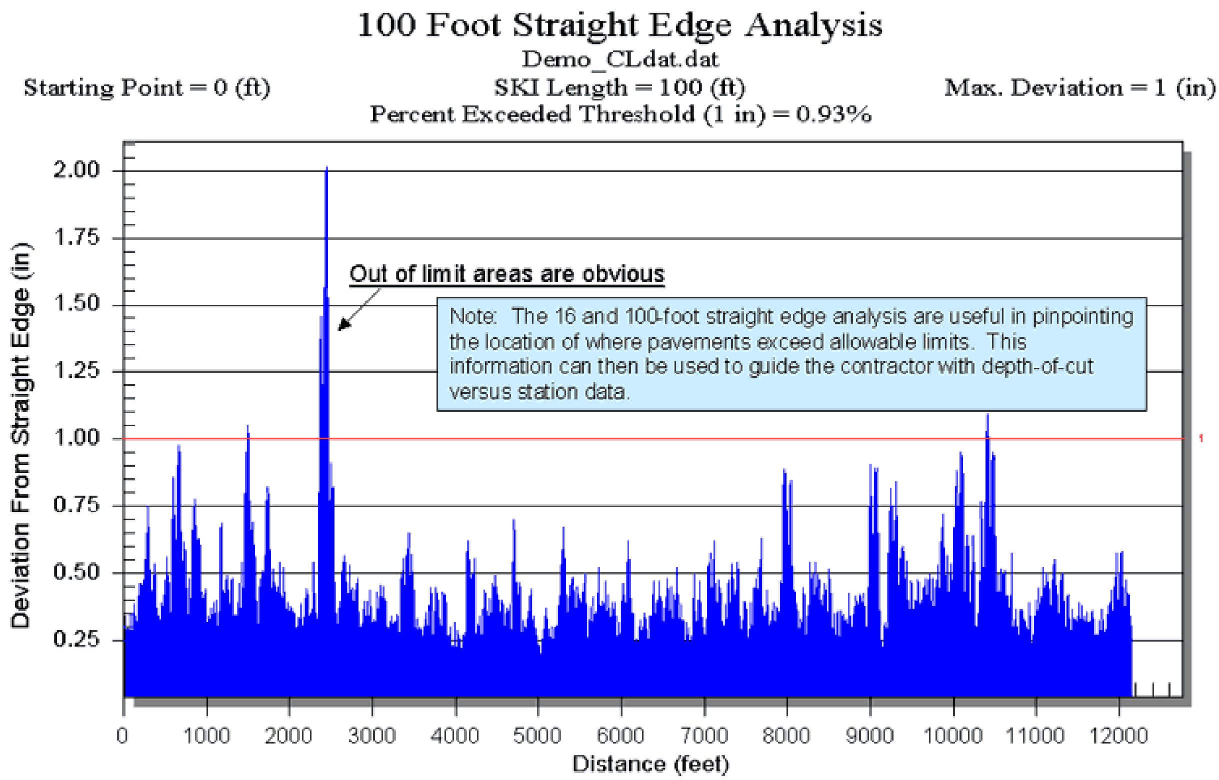

Figure 4. Plotted results of a typical 100-foot straight edge assessment used in APRas 3.0

One other straightedge method used by the Port Authority is called the straight edge sweep (SkiSweep). SkiSweep finds the maximum deviation from all straight edge lengths ranging from 2 to 300 feet in length. Then it compares the runway being analyzed to a known rough runway (one that generated many pilot complaints) and to a known smooth runway (a new, very smooth one). Figure 5 is a typical SkiSweep plot. This straightedge analysis method is used only to compare one runway to another from a wavelength perspective. It does not give an indication of how the runway will affect aircraft dynamic response.

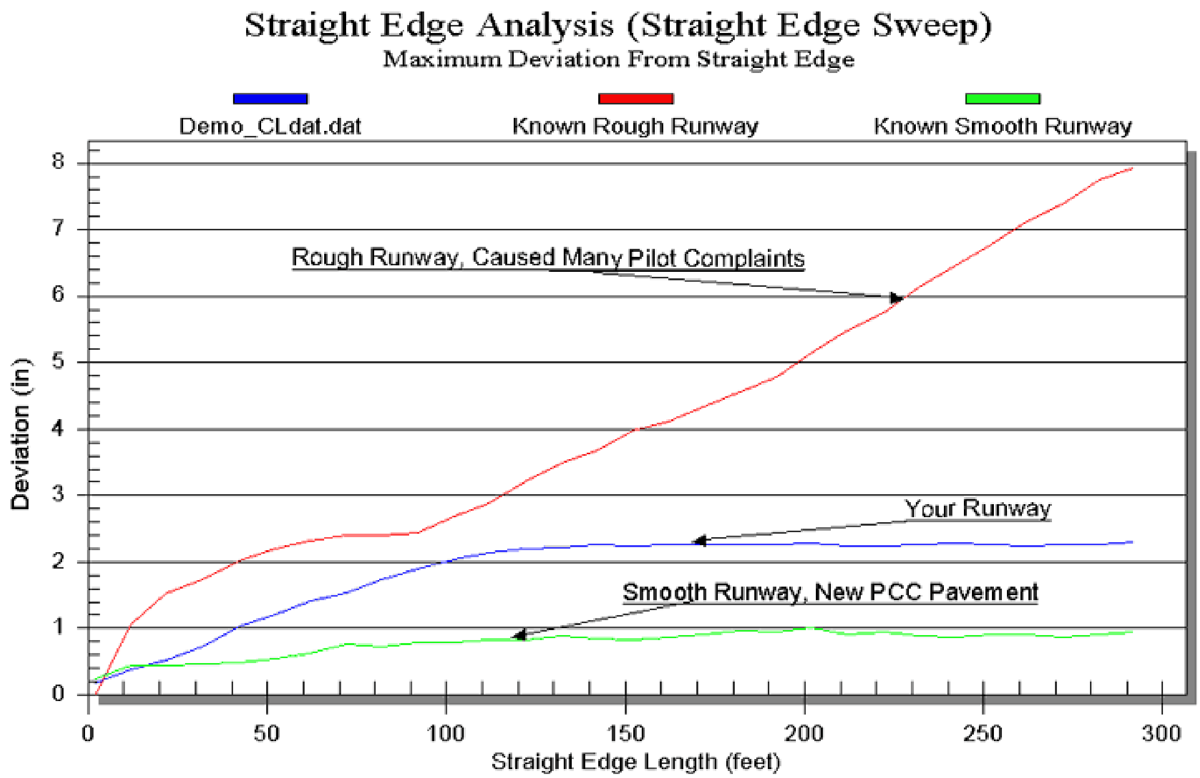

Figure 5. Plotted results of a typical straight sweep simulation showing how the pavement in question compares to a known smooth and a known rough airport pavement.

<u>Pavement Smoothness Index</u>

Pavement Smoothness Index (PSI) is designed to be a pavement management tool that summarizes the detailed smoothness assessment processes and presents the results in single color-coded chart for easy interpretation. It is a compilation of four primary smoothness assessment tools.

- A visual analysis of the pavement profile
- Aircraft simulation including takeoff, landing and velocity sweep (VSweep)
- Straightedge analyses, which normally include a 16-foot straightedge and 100-foot straightedge and SKIsweep.
- Engineering judgment is the final factor in the analysis. This takes into account factors such as aircraft type, airport specifics, threshold locations, etc,

A PSI value is assigned to each 500-foot section of runway. Figure 6 is a typical PSI chart. This particular PSI chart was generated for the runway that caused the DC-8 pilot complaints mentioned above. The values assigned to the PSI number legend are based primarily on the experience of APR Consultants' measurement and analysis of runways all over the world. The calculation of PSI is an automated process that uses weighted factors for all methods of smoothness assessment. For example, if the first 500 feet of pavement is being evaluated, it carries less weight than a section at 3000 feet because of location.

Pavement Smoothness Index "PSI" Chart

Demo Runway PSI Chart

Section	1	2	3	4	5	6	7	8	9	10	11	12	13
Distance Down Runway 13R (ft.)	0 to 500	500 to 1000	1000 to 1500	1500 to 2000	2000 to 2500	2500 to 3000	3000 to 3500	3500 to 4000	4000 to 4500	4500 to 5000	5000 to 5500	5500 to 6000	6000 to 6500
13R													
PSI Number	80	85	77	81	71	65	85	78	82	82	83	85	85

Section	14	15	16	17	18	19	20	21	22	23	24	25
Distance Down Runway 13R (ft.)	6500 to 7000	7000 to 7500	7500 to 8000	8000 to 8500	8500 to 9000	9000 to 9500	9500 to 10000	10000 to 10500	10500 to 11000	11000 to 11500	11500 to 12000	12000 to 12500
13R												
PSI Number	79	85	88	88	88	85	79	73	75	85	85	82

PSI Number Legend

Number	Color Code	Comments	Action Required
90-100		Very smooth	Survey Periodically
80-89		Smooth- no pilot complaints	Survey Periodically
70-79		Smooth with very mild roughness	Survey again in two years.
60-69		Mild roughness	Survey again in one year
50-59		Mild roughness- some pilot complaints	Survey more frequently
40-49		Moderate to significant roughness	Consider repairs
30-39		Significant roughness- continual pilot complaints	Consider repairs
20-29		Significant to severe roughness	Repairs recommended
10-19		Severe roughness	Immediate repairs required
0-9		Severe roughness	Cease aircraft operations until repaired

Figure 6. Typical pavement smoothness index (PSI) chart.

RUNWAY PAVEMENT MONITORING

The Port Authority of New York and New Jersey has adopted a routine program of roughness assessment as part of its pavement condition monitoring efforts. The first step is performing a baseline assessment following runway resurfacing. Additional assessments are made every three to five years to monitor roughness. These assessments are used to track deterioration of runway smoothness. Roughness assessment along with pavement condition index is used to determine when a runway should be rehabilitated. Once runway rehabilitation is scheduled a final roughness assessment is made the year prior to construction. This assessment is used in the design of the runway rehabilitation as described later in this paper.

TAXIWAY ASSESSMENT

<u>Profile Measurement</u>

Taxiway assessment begins with pavement surface measurement using an ASTM 950 Class I inertial profilometer. Three lines are surveyed including centerline and ten feet right and left of centerline. A filtered profile with grade removed divided into 500-foot sections results from the profile measurement. The filtered profile is then evaluated using quarter car simulation or aircraft simulation

International Roughness Index

The International Roughness Index (IRI) is calculated by using the quarter car simulation operating over the filtered profile of the pavement. The resulting IRI is measured in units of inches per mile. This is the same method commonly used on highway pavements. The IRI values for Newark Liberty International Airport (Newark Airport) are shown in Figure 7. The ranges for reporting categories were established by reviewing the data set from the initial survey and setting Category I as the range that includes all pavements smoother than the 80th percentile. Category III was set as the range that includes all pavements rougher than the 20th percentile and Category II includes all pavements, which fall in between these ranges. The range for these categories compares favorably to IRI ranges for various pavement types reported by Sayers and Karamihas [2].

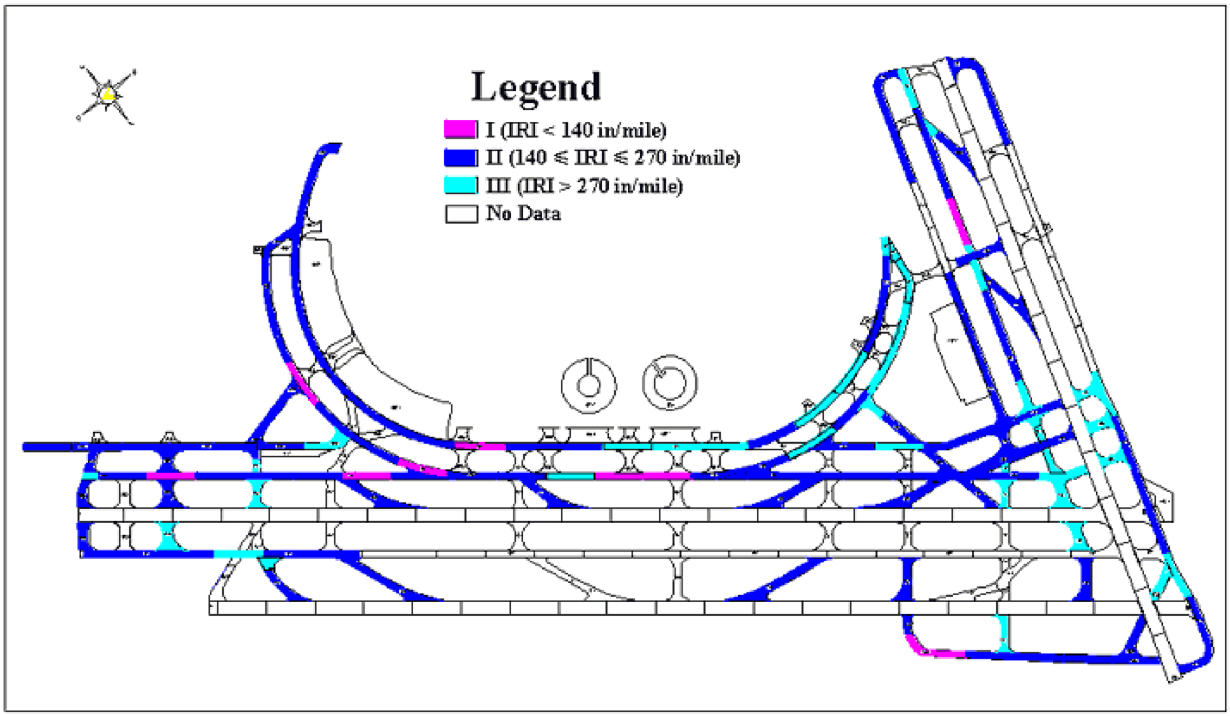

Figure 7. 2003 IRI Values at Newark Airport

Aircraft Simulation

Aircraft simulation of taxiways is conducted using the filtered profile data collected from the inertial profilometer mentioned above. The profile data is modified and put in a format that is required by the software package APRas. Taxiways are assessed the same way as runways except the aircraft simulation process is limited to taxi speeds only. The Port Authority has used a 30 knot constant speed aircraft simulation to assess taxiway roughness.

TAXIWAY PAVEMENT MONITORING PROGRAM

Since 2001, all taxiway profiles excluding short cross-connecting taxiways are measured using profilometers each year. Profiles are measured in conjunction with PCI inspections. Initially, taxiway smoothness is assessed using IRI. If an area of concern is identified, a further assessment may be made using aircraft simulation. The Port Authority has not yet established trigger values for pavement rehabilitation of taxiways using IRI or aircraft simulation. Taxiway roughness assessment along with PCI and Structural Remaining Life are used to determine when rehabilitation is required.

The data collected over the past three years does indicate that IRI and PCI are not always directly related. Figure 8 shows a comparison of PCI and IRI for an area of John F. Kennedy International Airport (Kennedy Airport). It shows that areas within one PCI range can have IRI readings ranging from category I (smoothest) to III (roughest).

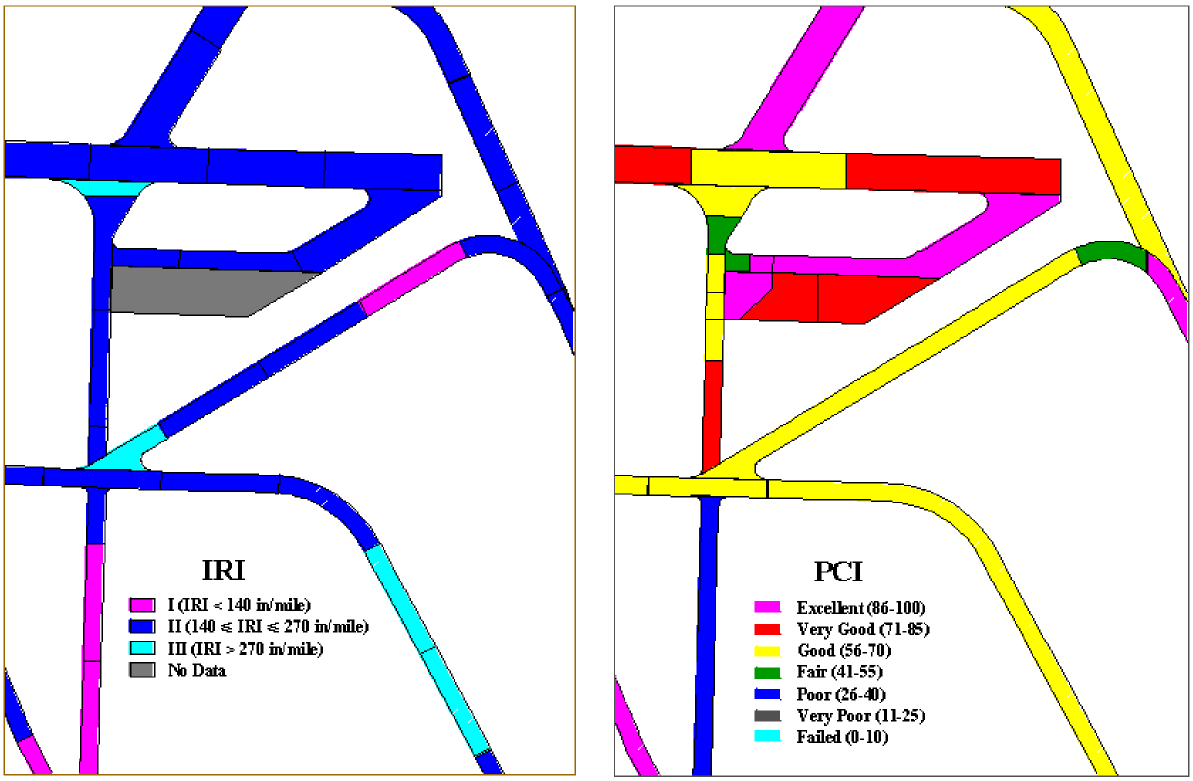

Figure 8. IRI vs. PCI at Kennedy Airport

ROUGHNESS ASSESSMENT IN REHABILITATION DESIGN

The data collected and analysis performed during roughness assessment can be used for design purposes. Two recent examples are the designs of the rehabilitations of Runways 4R-22L at Newark Airport and Runway 13L-31R at Kennedy Airport. At Newark Airport the assessment of Runway 4R-22L identified an area of moderate roughness at the location of a box culvert passing under the runway. The normal twenty-five foot by twenty-five foot grade survey used for overlay design did not identify the dips located adjacent to the box culvert. Additional grades were surveyed which more clearly showed the rough area and the information was included in the bid package. At Kennedy Airport the assessment of Runway 13L-31R identified an area of moderate roughness over a 1000 foot section of the runway. The rehabilitation design was modified to include milling the rough area prior to overlaying the runway.

Another way roughness assessment can be used in design is to verify design grades. Runway intersection design requires balancing the need for smooth pavement and providing proper drainage. The Port Authority uses aircraft simulation to test design grades for runway intersections.

RESEARCH NEEDS AND NEXT STEPS

There is a need to establish an FAA standard for determining “how rough is too rough.” It should not be the responsibility of the pilots to inform the airport owners when the runway or taxiway is too rough. By the time pilots complain, damage is already being done to the aircraft. In addition, the creation of an ASTM standard for objectively measuring and assessing aeronautical pavements is required. The Pavement Smoothness Index (PSI) concept discussed above may be a launching platform in the establishment of a national standard for assessing roughness.

A new definition for what is a smooth newly constructed airfield pavement is also required. Accepting newly constructed pavement based on straightedge and grades every 25 feet is antiquated. Today’s aircraft, with their less forgiving landing gear, require smoother pavements. True profile measurement and aircraft simulation can be used in quality assurance if a definition of a smooth pavement in terms of G-force can be adopted by the industry.

It is anticipated that use of devices such as the AR&L that measure true profile with respect to mean sea level, can be useful in evaluating smoothness at all stages of design, construction and rehabilitation. During design much more grade information could be collected and provided to contractors for bidding purposes. During construction measuring the profile on top of the compacted crushed aggregate allows corrective action before final layers are placed. With measurement each construction stage would be progressively easier to achieve the desired smoothness. In addition, measuring the true profile after the construction is complete and before aircraft operations begin, provides the owner and the contractor with a profile that can be used for acceptance of the pavement from a smoothness perspective. Even more important it becomes a baseline for comparison to future surveys. It will allow an airport to track changes due to traffic and time. Tracking “roughness growth” will become a tool for scheduling and prioritizing pavement maintenance.

CONCLUSIONS

The Port Authority of NY and NJ has performed roughness assessment on airfield pavements for over ten years. Roughness assessment using aircraft simulation has enabled the Port Authority to be proactive in addressing airfield roughness before pilots complain. Roughness assessment also identifies pavement distress, which may not be identified during PCI inspection. During design, roughness assessment results can be used to determine the rehabilitation approach and aircraft simulation may be used to verify design grades at runway intersections. Roughness assessment has proven to be a useful tool for managing airfield pavements.

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