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Evaluation of Opportunities for Connected Aircraft Data to Identify Pavement Roughness at Airports

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This paper reviews the construction and maintenance guidelines for airfield pavements, as well as the current methods for assessing pavement conditions. A study is performed on an airport's taxiway to determine if acceleration data from airframe mounted accelerometers and on-board avionic systems can be used to provide an estimate of pavement roughness. A comparison of international roughness index (IRI), three-axis accelerometer data, and normal acceleration data from the G1000 unit is presented based on a field study performed at the Purdue University Airport (KLAF). The paper concludes that there is a potential for crowdsourced data obtained from an aircraft's on-board system such as the G1000 to act as an additional tool for airport managers to monitor surface conditions between routine and detailed inspections.

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Airports are an essential component of the nation's transportation system and regularly compete for federal, state and local funding. The United States Department of Transportation (USDOT) is asking all transportation systems to embrace quantitative asset management techniques (Federal Aviation Administration, 2017; U.S. Department of Transportation, 2017). Performance measures can range from usage reports, traditional asset rating systems, to emerging "crowd source" data regarding traffic delays, pothole locations, and ride quality.

The cost of collecting asset management data using traditional inspection techniques can be challenging and many transportation modes have begun to examine crowdsourced data to supplement traditional inspection techniques. Doan, Ramakrishan, and Halevy (2011) define crowdsourcing as a process that "enlists a crowd of humans to help solve a problem defined by the system owners" (p. 87). Another definition is "a sourcing model in which organizations use predominantly advanced Internet technologies to harness the efforts of a virtual crowd to perform specific organizational tasks" (Saxton, Oh, & Kishore, 2013, p. 2). In regards to transportation, crowdsourcing has been used to monitor traffic flow, ideal bike routes, and pavement surface conditions (Alessandroni et al., 2014; Belzowski & Ekstrom, 2015; Buttlar & Islam, 2014; Carrera, Guerin, & Thorp, 2013; Dennis, Hong, Wallace, Tansil, & Smith, 2014; Fox, Kumar, Chen, & Bai, 2015; Yi, Chuang, & Nian, 2013).

Many modern general aviation aircraft now have extensive sensors, including airframe accelerometers. This paper examines ground transportation trends and explores the feasibility of using existing airframe accelerometers to collect airfield pavement condition data to supplement the current asset management techniques used at airports. The objective of this exploratory study is to compare pavement condition data collected using conventional survey vehicles with two different airframe-mounted accelerometers.

Background

Fox et. al proposes crowdsourced data from multiple vehicles as an emerging solution to detect potholes on the roadway (Fox et al., 2015). Under sampled, heterogeneous and distorted signals from embedded sensors in vehicles were used to develop a system that detects potholes. Empirical experiments showed that the system was capable of detecting 88.9% of the potholes on a 38 km stretch. Another system utilized smartphones as probes in cars for mobile sensing to detect and assess anomalies on the roadways (Alessandroni et al., 2014; Yi et al, 2013).

A study conducted by the Michigan Department of Transportation and the Center for Automotive Research examined crowdsourced data from connected vehicles to monitor and assess pavement conditions (Dennis et al., 2014). The study proposes that data from embedded sensors and smartphones in a vehicle will become more prevalent for pavement monitoring in the upcoming years. The research also suggests a possible 3- to 5-year timeline for interconnected vehicle and infrastructure systems to assess pavement conditions including the acute distress events such as potholes. Surface distress such as rutting, cracking and crowd-sourced

International Roughness Index (IRI) that require advanced sensors for data collection can be collected in the next 10 or more years (Dennis et al., 2014).

A minimal level of service must be maintained for transportation pavements, and this level of service can vary across modes of transportation. Airports have particularly rigorous construction and surface monitoring requirements to ensure safe operation of aircraft. Airfield pavement roughness standards are in large part driven by concern for aircraft loss of directional control (Federal Aviation Administration, 2004). Another concern is fatigue on aircraft components (increase stress and wear) and other factors which may impair the safe operation of the aircraft (cockpit vibrations, excessive g-forces)(Federal Aviation Administration, 2009).

In contrast to road vehicle suspension systems, the primary purpose of an airplane suspension system is to absorb energy expended during landing. Airplane suspension systems have less capacity to dampen the impact of pavement surface irregularities (Federal Aviation Administration, 2015c). A study performed in 2015 regarding the feasibility of aviation rumble strips (Bullock et al., 2015) found there was considerable variation in airframe acceleration among different types of aircraft during taxiing. This paper reports on the potential to obtain pavement condition data associated with ground movements on taxiways and runways from automated aircraft data loggers such as the G1000 or low-cost airframe accelerometers. This is consistent with a broader aviation trend to move toward a *connected aircraft* environment that goes beyond traditional transponders, Aircraft Communications Addressing and Reporting System (ACARS) messages and the internet (Ros, 2016). Connected aircraft have implications not only in terms of sensors, but also the ability to collect, store, and use the data, including datalinks and systems to archive the data.

Literature Review

The Federal Aviation Administration (FAA) has released many Advisory Circulars (AC) outlining standards for the construction, monitoring, maintenance and inspection of airfield pavements (Federal Aviation Administration, 2004, 2009, 2014a, 2014b, 2015a). The National Plan of Integrated Airport Systems (NPIAS) identifies nearly 3,400 existing and proposed airports that are significant to national air transportation (Federal Aviation Administration, 2015b). Airports identified by the NPIAS are eligible to receive Federal funding under the Airport Improvement Program (AIP). The AIP provides grants to public agencies for the planning and development of public-use airports as long as they follow FAA guidelines throughout the entire pavement lifecycle (Federal Aviation Administration, 2016a).

Pavement Management Program (PMP)

A pavement’s lifecycle begins with construction. FAA construction standards help protect this investment by ensuring pavements last as long as possible with the least amount of maintenance. These standards are outlined in the FAA’s Standards for Specifying Construction at Airports (AC 150/5370-10G). The AC identifies materials and methods for the construction on airports, and consists of a wide range of topics; general provisions, earthwork, flexible base courses, rigid base courses, flexible surface courses, rigid pavement, fencing, drainage, turf, and lighting installation (Federal Aviation Administration, 2014a).

Pavements need to be managed, not just maintained. One of the requirements of AIP grants is for airports to develop and sustain an effective airport pavement maintenance-management program. A PMP provides a "consistent, objective, and systematic procedure for establishing facility policies, setting priorities and schedules, allocating resources, and budgeting for pavement maintenance and rehabilitation" (Federal Aviation Administration, 2014b, p. 2).

A PMP is a set of defined procedures for collecting, analyzing, maintaining, and reporting pavement data. It assists airports in finding optimum strategies for maintaining pavements in a safe serviceable condition over a given period, reducing the life cycle cost. It can also provide specific action points required to maintain a pavement network at an acceptable level of service while minimizing the cost of maintenance and rehabilitation (M&R). "A PMP not only evaluates the present condition of a pavement, but also predicts its future condition through the use of pavement condition indicators" (Federal Aviation Administration, 2014b, p. 2). Figure 1 shows a typical pavement condition life cycle. To minimize lifecycle cost, it is important to implement maintenance and rehabilitation activities before substantial deterioration begins. The FAA also encourages all airports to develop maintenance programs to preserve their facilities even if they are not required to do so. Since smaller general aviation airports have very tight budgets, crowdsourced pavement data has the potential to provide a very basic and cost effective condition assessment.

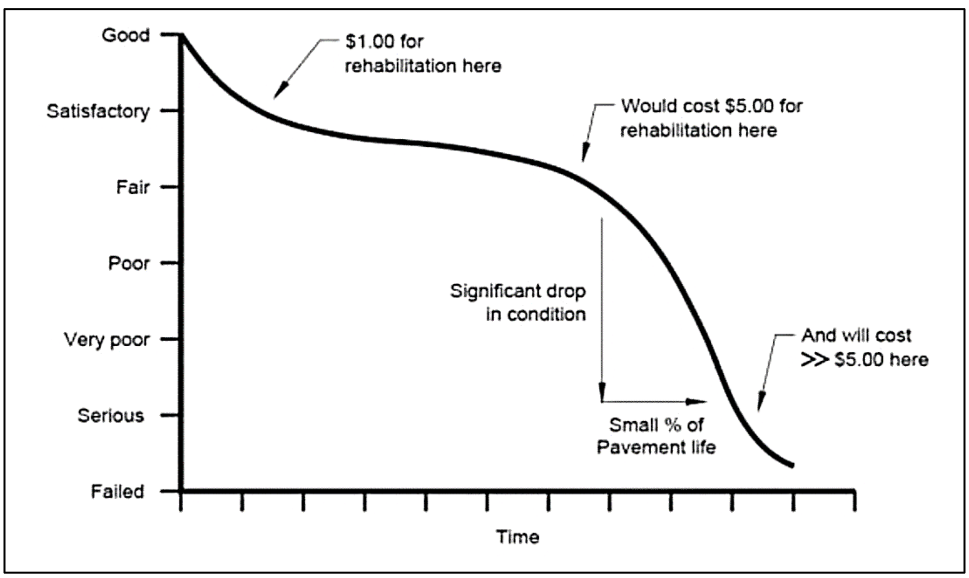


Figure 1. Pavement condition life cycle (Federal Aviation Administration, 2014b).

Early intervention of deterioration is not only important from a cost perspective, but as AC 150/5380-6C, Guidelines and Procedures for Maintenance of Airport Pavements, states, "timely maintenance and repair of pavements is essential in maintaining adequate load-carrying capacity, good ride quality necessary for the safe operation of aircraft, good friction characteristics under all weather conditions, and minimizing the potential for foreign object debris (FOD)" (Federal Aviation Administration, 2015a, p. 1).

Each airport is responsible for establishing a schedule for regular and routine pavement inspections. Routine inspections usually consist of daily visual checks to monitor surface conditions and do not require specific equipment. There are many variables that may adversely affect the pavement, such as heavy vehicle operations or severe weather, which may necessitate additional inspections. Airport personnel should also solicit reports from airport users and conduct daily drive-by inspections. These qualitative inputs are important, but very hard to normalize. Crowdsourced ride data has the potential to augment user reports with objective analytical airfield surface movement ride quality data.

Current Methods to Assess Airfield Pavement Condition

Since 1995, airports have been required to implement a pavement maintenance-management program to receive Federal funding for any construction project. An element of PMP is an annual detailed inspection of pavement conditions. The USDOT and the FAA have approved tests, and some airports have developed innovative ways to measure pavement conditions. Two methods specified by the USDOT are Pavement Condition Index (PCI) and International Roughness Index (IRI), as described below.

ASTM D5340, Standard Methods for Airport Pavement Condition Index, “provides a measure of the present condition of the pavement based on the observed distresses on the surface of the pavement which also indicates the structural integrity and surface operational condition” (American Society for Testing and Materials, 2012, p. 2). The PCI is calculated using visual assessments, rating distress type, quantity, and severity. Figure 2. Standard Pavement Condition Index (PCI) Rating Scale provides a qualitative explanation of PCI scores.

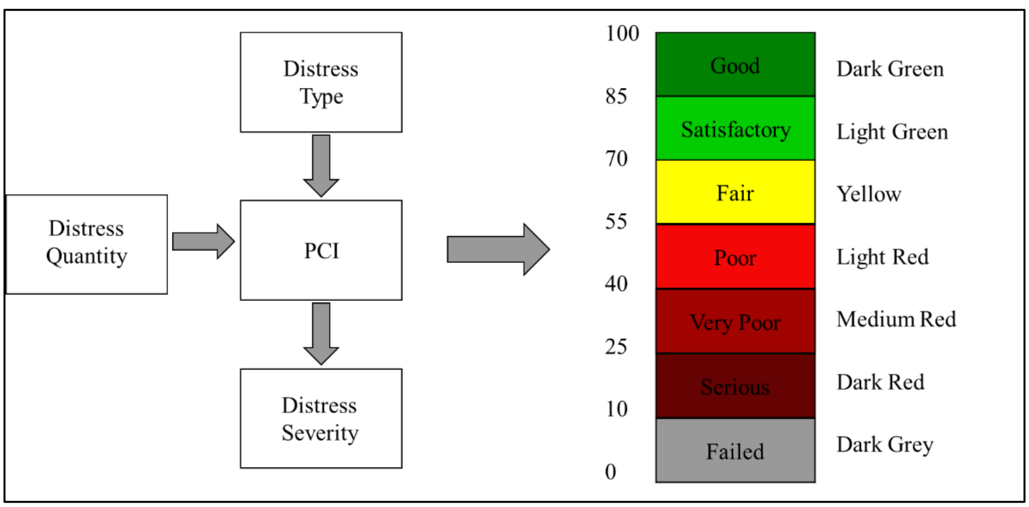


Figure 2. Standard Pavement Condition Index (PCI) rating scale (American Society for Testing and Materials, 2012).

IRI is a profile-based metric established by a study conducted by the World Bank to measure the roughness of the pavement (Sayers, Gillespie, & Paterson, 1986). The IRI defines the characteristic of the road surface along the longitudinal profiles of the travelled wheel track using high speed vans equipped with lasers and accelerometers. The commonly reported units are meters per kilometer (m/km) or millimeters per meter (mm/m), but can also be expressed as inchers per mile (in/mile). A scale of acceptable standards for different surfaces are shown in Figure 3. International Roughness Index (IRI) Scale. These examples of detailed PMP inspections are in addition to routine maintenance inspections that are conducted more frequently to ensure that the taxiways and runways are safe for operations (Federal Aviation Administration, 2014b).

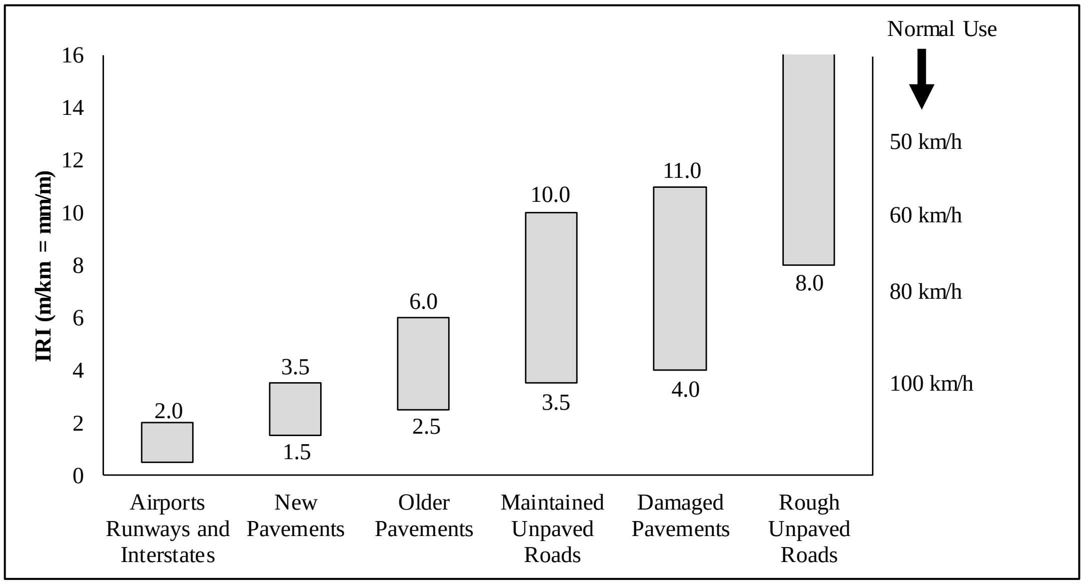


Figure 3. International Roughness Index (IRI) scale (Sayers et al., 1986).

FAA also has measurements they use to assess pavement conditions. The Boeing Bump is the FAA accepted methodology for evaluating airport runway longitudinal profiles for single event bumps; the Boeing Bump requires a minimum survey interval of 0.82 feet for evaluation (Figure 4. Boeing bump index)(Federal Aviation Administration, 2016b). Surface profiles are also captured by the FAA using a vehicle mounted with three sensors: vehicle elevation, vehicle-to pavement distance, and traveled distance (Federal Aviation Administration, 2015c).

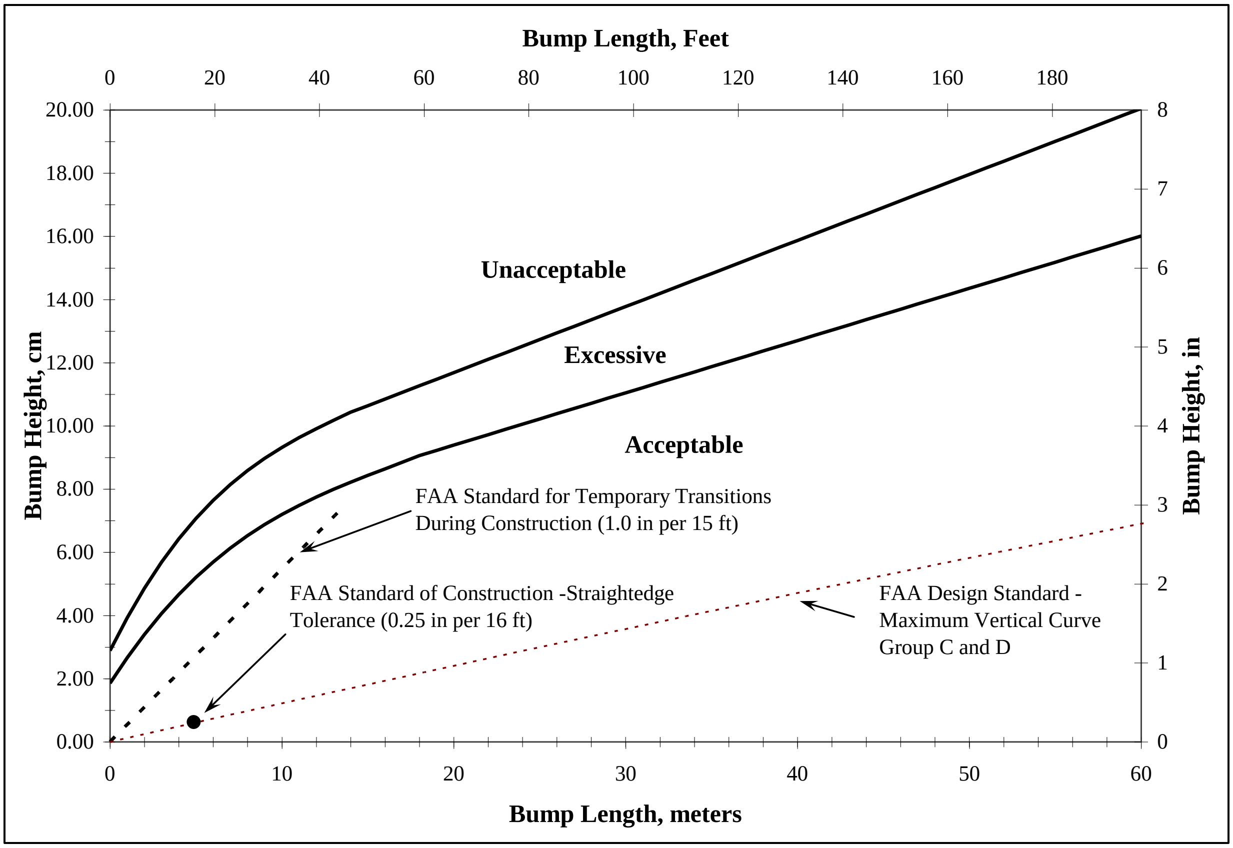


Figure 4. Boeing bump index (Federal Aviation Administration, 2009).

Other airports are taking an innovative approach to monitoring airport pavements. Shanghai Airport Pavement Management System uses geographic information system and global positioning system technologies to identify distress by type, quantity, and location. Software takes this information and computes a real-time PCI rating, aiding airport authorities in determining the most effective maintenance and rehabilitation activities (Chen, Yuan, & Li, 2012). Oakland International Airport uses laser crack measurement system (LCMS), a high speed data collection equipment that can take downward-facing images of the pavement and collect 3D imagery (Keegan, Katherine; Jung, 2014).

Purpose

The objective of this study is to compare IRI data collected using conventional survey vehicles with two different airframe mounted accelerometers, a custom three-axis accelerometer mounted on a Cessna 172 seat rail frame and one-axis factory installed Cirrus SR 20 accelerometer that is factory configured to log data in the G1000 avionics package.

Method

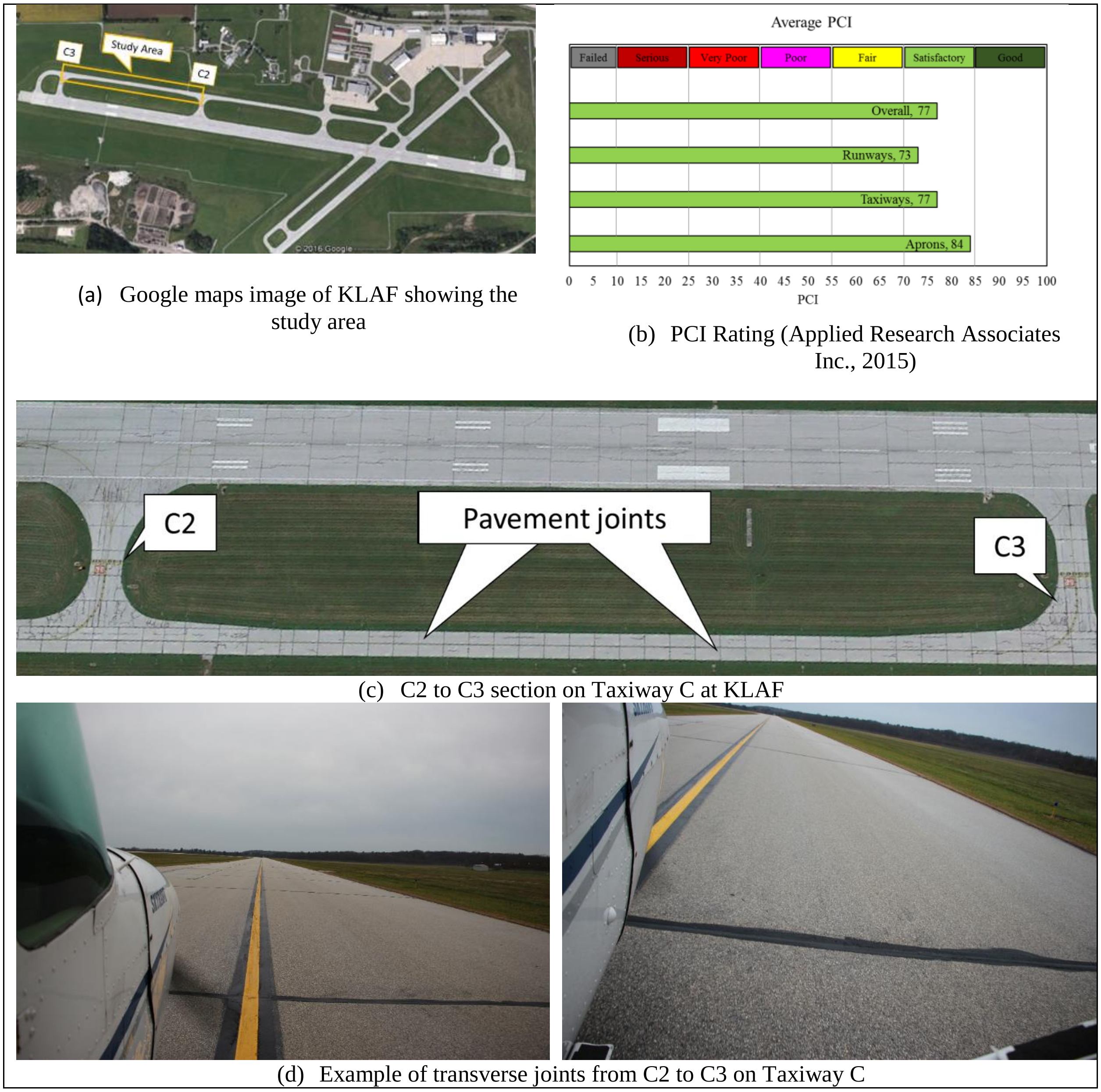
IRI data was collected using inertial profiler equipment. An Ames Engineering 8300 Survey Pro High Speed Profiler utilizing RoLine 3k line lasers, permanently mounted on a Ford panel van collected data while traveling at 20 miles per hour (Figure 5. IRI Inertial Profiler Van). Airframe acceleration data was collected from two different aircraft in two different ways. High frequency acceleration data was collected using a three-axis accelerometer mounted to a Cessna 172 seat rail with an FAA-approved cargo tie-down and a mounting bracket (Figure 6. Mount Configuration For 3-Axis Acelerometer On C172.). Acceleration data was collected while the aircraft was traveling at approximately 15 knots. Lower frequency, one-axis accelerometer data was collected from a factory installed Cirrus SR 20 accelerometer configured to log data in the G1000 avionics package. In addition to acceleration, the G1000 logs several dozen parameters such as lateral g-forces, latitude, longitude and pressure altitude (Garmin, n.d.). Acceleration data was also collected at an approximate speed of 15 knots.

Figure 5. IRI inertial profiler van.

(a) Cargo rail tie down
(b) Bracket to attach the accelerometers to the cargo rail tie down
(c) Rail mount – front view
(d) Rail mount – side view
(e) Seat Rail Mounting

Figure 6. Mount configuration for 3-axis acelerometer on C172.

Data was collected at Purdue University (KLAF) along Taxiway C from C2 to C3, adjacent to Runway 10/28. The mean PCI for all taxiways at KLAF was 77 (Figure 7b). This taxiway section was chosen because it had regularly spaced transverse pavement joints, as shown in Figure 7c/d).



(a) Google maps image of KLAF showing the study area

(b) PCI Rating (Applied Research Associates Inc., 2015)

(c) C2 to C3 section on Taxiway C at KLAF

(d) Example of transverse joints from C2 to C3 on Taxiway C

Figure 7. Surface conditions at KLAF on Taxiway C.

Findings & Discussion

Comparison of Aircraft Accelerometer and IRI Data

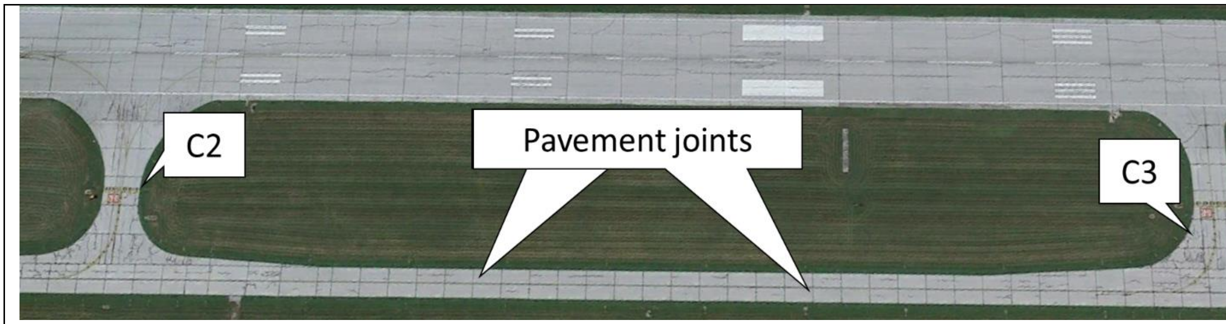
Findings are presented in Figure 8.

- Figure 8a shows photo of the studied taxiway, with three different techniques for measuring ride quality.
- Figure 8b shows a plot of the IRI obtained from a traditional truck mounted sensor (Figure 5) that has been carefully calibrated to calculate IRI.
- Figure 8c shows acceleration plots obtained from a Cessna 172 seat rail mounted 3-axis accelerometer (Figure 6) that is sampling at approximately 400Hz. Anet represents the resultant magnitude of all the three forces (A_x, A_y and A_z).
- Figure 8d shows one axis acceleration plots obtained from a factory installed SR 20 airframe accelerometer that are logged at 1 Hz in the G1000 avionics.
- Figure 8e shows areas that may warrant additional inspection, based on the amplitude of the acceleration in the G1000 data and the net acceleration from the 3-axis accelerometer).

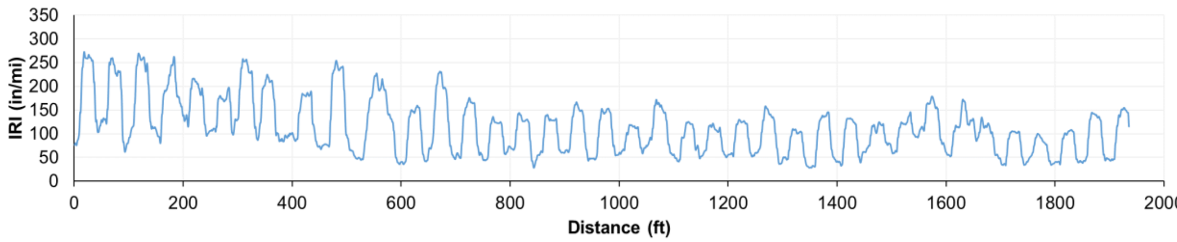
Even though the Cirrus and Cessna have quite different suspension characteristics, it can be seen that the pavement joints and irregularities highlighted in Figure 8. Comparison Of Acceleration And IRI Data For KLAF Taxiway C2 To C3. a are captured and represented by the peaks in each of the three graphs. The Cirrus data has some second-order oscillation in the data, perhaps because a Cirrus has a spring strut on the front wheel.

Previous studies have shown that accelerometer data can be used to estimate approximate IRI values. Linear predictive coding was used by a study to develop an estimate of IRI from accelerometer data collected by smartphones in vehicles (Alessandroni et al., 2014). This method predicts a particular value in the analog signal using a linear combination of the past values. The accelerometer data is passed through prediction filters and mathematical models to derive an estimated IRI value. A roughness index for every point was established based on the crowdsourced data collected from different users and this was used to identify rough areas of the pavement. Another study developed the pavement profile by double integrating the acceleration data (Buttlar & Islam, 2014). This profile was then analyzed using the ProVAL software to estimate the IRI. The study found that the IRI values estimated from acceleration data were similar to the data from inertial profilers.

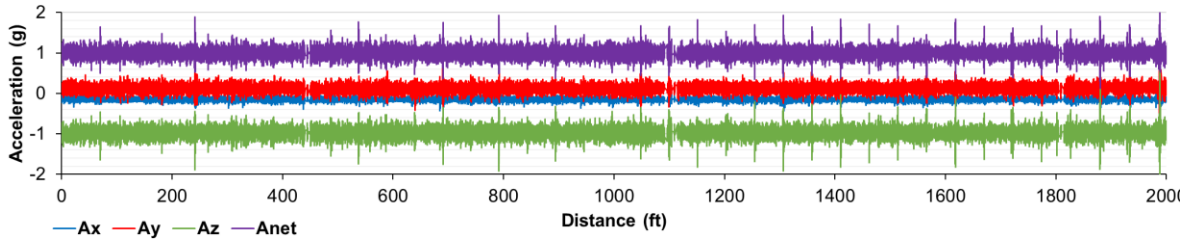
The successful estimation of IRI on roadways from vehicle acceleration data as documented in previous research lays a foundation for similar applications in aviation. In the aviation environment, the data collected from the on-board avionics systems can be used to develop a geo-coded database of the pavement roughness of taxiways, ramps, and runways. Airport managers can use this geo-coded data to identify areas of potential pavement distress that may require inspection and/or maintenance. Crowdsourced geo-coded data can be used as a supplemental tool in an airport PMP.



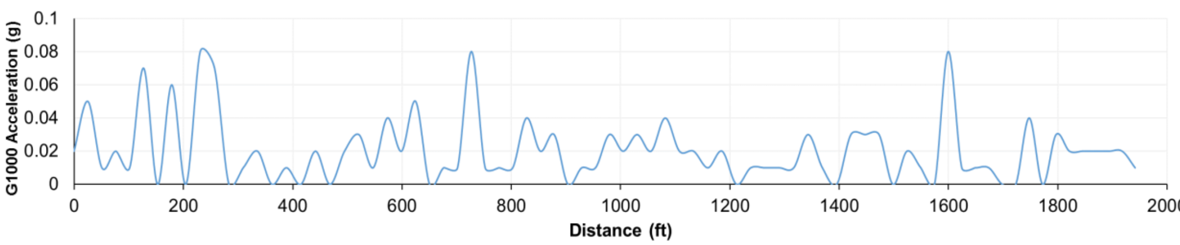
(a) C2 to C3 section on Taxiway C at KLAF



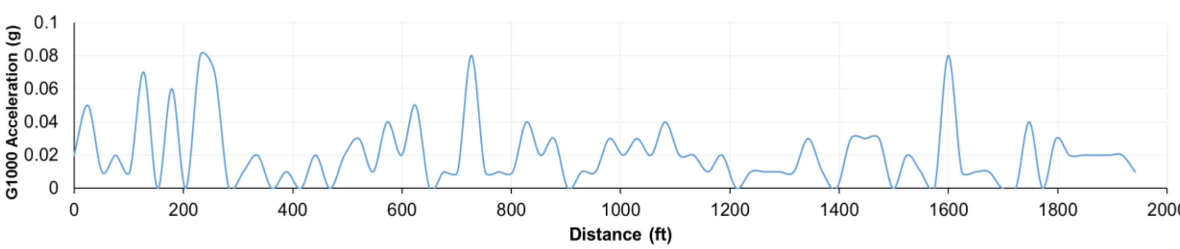
(b) IRI from inertial profiler



(c) Accelerometer data from USB accelerometer



(d) Normal acceleration data from G1000



(e) Areas that may warrant further inspection based on acceleration data

Figure 8. Comparison of acceleration and IRI data for KLAF Taxiway C2 to C3.

Conclusions

This study presents the potential use of acceleration data from airframe mounted accelerometers and on-board avionic systems to provide an estimate of pavement roughness as a low-cost tool to support of an airfield pavement management program. IRI data was obtained from an inertial profiler van, three-axis 400 Hz accelerometer data was obtained using a Cessna 152 and one-axis, 1 Hz acceleration data was obtained from a factory installed accelerometer from a G1000 on a Cirrus SR20. Both aircraft recorded data while traveling at approximately 15 knots and the instrumented van was traveling at 20 miles per hour, the minimum recommended speed for IRI data collection.

The results suggest airframe mounted accelerometers can be used to collect crowdsourced pavement condition, expanding the applicability of previous research that demonstrates the validity of using acceleration data to estimate IRI on roadways. In practice, one-axis accelerometer data, such as that collected from the G1000 might be sufficient, but it would be desirable to record data at a sampling frequency higher than the 1 Hz used in this study. A 100 Hz recording frequency would be ideal, but 10 Hz would likely be sufficient. Analysis comparing accelerometer data at a variety of frequencies with existing assessment methods would be beneficial, including correlation with the Boeing Bump Index, ProVAL software, and PCI.

Recommendations

Further research is recommended to assess the best methods for data collection, including the sampling frequency, the best methods to effectively and efficiently obtain data from aircraft accelerometers and store it, and the best methods to integrate the data from the wide range of aircraft in the GA fleet into a PMP. Future research can also be expanded to explore if accelerometer data can be used to assess the coefficient of friction. This research introduces the concept of utilizing existing technologies currently deployed as a low cost way to monitor airfield surface conditions without having to procure specialized equipment.

Acknowledgements

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