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QUANTIFYING THE RISK OF PAVEMENT RELATED FOREIGN OBJECT DAMAGE

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Abstract: Traditional airfield pavement management has its roots with the US Army Construction Engineering Research Laboratories work beginning in the early 1970's that effort being the basis for M.Y. Shahin's 1994 treatise on the subject and subsequent development of the MicroPAVER pavement management software. The MicroPAVER methodology does not use quantified measures of user costs as part of its project selection process. Other asset management techniques are economics based whereby projects are selected based on their economic benefits to users such as the World Bank developed Highway Development and Management (HDM) transport economics based analysis or the US Army Corps of Engineering's "Risk and Reliability Engineering for Major Rehabilitation Studies" risk quantification technique. The authors have developed a technique whereby the MicroPAVER methodology is used as the airfield pavement capital project identification tool which is then augmented by a quantification of the risk associated with failing to undertake the project. In this case, the risk is identified as the product of the probability that a distressed pavement surface will cause Foreign Object Debris Damage (FOD) to aircraft and the cost to air carriers of dealing with this damage. The probability is established based on the number and type of aircraft movements on the project pavement, the size of the surface and the current and predicted FOD index. The probability is calculated under the two alternative courses of action; fund and undertake the pavement rehabilitation project or not. This comparative analysis is conducted for all pavement projects generated by the MicroPAVER process and used to justify capital funding and prioritize the projects. This paper first discusses the inputs required and the MicroPAVER project selection process. It goes on to describe and apply the risk quantification and project prioritization and selection procedure based on a real life example as implemented at Saskatoon International Airport.

Keywords: Airport Airfield Pavement Management FOD Risk

1 INTRODUCTION

In 2016, the Saskatoon Airport Authority (SAA) retained a consultant to undertake pavement condition and inventory data collection and to develop an Airport Pavement Management System (APMS) for the runways, taxiways, and aprons at Saskatoon John G. Diefenbaker International Airport (YXE) as shown in Figure 1.

The consultant offered a choice of techniques for managing airfield pavements. The updatable and repeatable geo-referenced pavement surface distress rating system and overall condition rating based on ASTM D5340's Pavement Condition Index (PCI) is common to all approaches. The GIS linked, fully geo-referenced pavement management inventory and condition database (MicroPAVER) is common to all techniques. MicroPAVER endorsed by the Federal Aviation Administration (FAA), is used across North America by airport authorities for managing a pavement network.

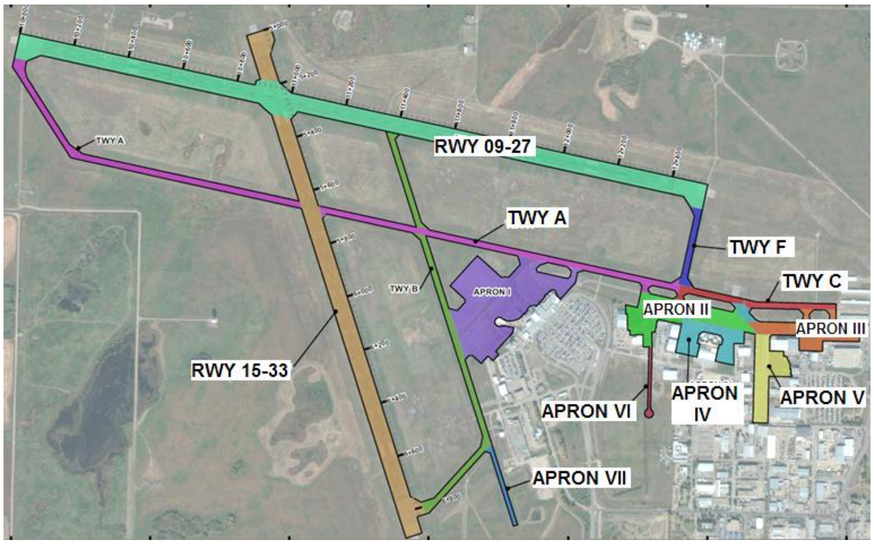

Figure 1: YXE Pavement Network Layout

The approaches differ in how future conditions are predicted and how multi-year rehabilitation/repair programs are developed. The traditional approach involves first developing a set of pavement analysis sections that are homogeneous in terms of structure, age and traffic (airfield movements) and then measuring the current PCI for each. The measured PCI is compared to the current age of the pavement surface and forms the basis of time versus condition performance prediction models, the assumption being that future performance will be similar to historic performance. A set of maintenance and rehabilitation treatments, their costs and the predicted PCI values that would trigger the treatment, are established based on historic best practices. The treatments, triggers and costs are applied to the predictive models resulting in a multi-year forward looking works programme around which the pavement maintenance and renewal budgets are built.

As is most often the case there is a back-log of projects that currently meet the PCI trigger values resulting initially, in a large set of projects available to be done immediately. Direct implementation of all of these projects is not feasible both financially and operationally. This necessitates a prioritization process whereby some projects are deferred to meet fiscal and operational constraints.

The authors conducted a literature review of internet accessible Federal Aviation Advisory Circulars, Transport Canada Advisory Circulars, International Civil Aviation Organization Circulars, Airport Cooperative Research Program Reports, Transportation Research Board Reports as well as general internet searches to investigate the use of a pavement generated FOD index directly as a basis for priortizing airfield pavement projects, the search yielded a single example where FOD is a basis for ranking projects[i], Although that 2016 presentation described rating risk in categories of high, medium and low, it did not go so far as to provide a methodology quantify the relative and future risk between competing high risk pavement projects.

This paper describes a methodology whereby the SAA decided to first carryout the works program development using on the traditional approach described above, augmented by a risk based prioritization approach recently developed by the consultant. With this approach, the pavement performance prediction modeling, and the development of a multi-year pavement repair plan is based on the monetized value to the airfield users of the risk of Foreign Object Debris (FOD) related damages. This pavement repair plan uses economic justification based on the financial value of risk associated with FOD from pavement surface distresses. This paper conveys the methodology employed by this analysis technique.

2 PAVEMENT NETWORK DEFINITION AND INVENTORY DATA

In determining the airside pavement boundaries and network wide project limit definitions, the consultant worked with the SAA to obtain historic construction records and maps to establish a baseline network definition map, which illustrates the breakdown of pavement network into branches, sections, and sample units that correspond with the inventory in the GIS and database software. These records and associated pavement structural layer thicknesses were verified using Ground Penetrating Radar (GPR) which in turn was validated with borehole data. The result is a reliable database of construction and surfacing history based inventory to be used as the basis for modeling pavement performance. Figure 2 shows visually an example of the resultant GIS polygons related to the underlying database through Identification (section ID) numbers.

Figure 2: Pavement Management Analysis Section Polygons

The process resulted in a total of 54 different analysis sections for pavement condition data collection and performance modeling purposes. These sections will define future individual projects limits.

3 PAVEMENT DATA COLLECTION PLATFORM

The consultant conducted, near full coverage, automated pavement condition data collection activities on the airfield pavements (runways / taxiways / aprons) using three data collection platform vehicles. The first data collection platform was for Pavement surface distresses using a laser crack measuring system (LCMS), laser based pavement profile device to measure roughness and terrestrial LiDAR. The second platform was the heavy falling weight deflectometer (HWD) which measures pavement strength. Finally, a vehicle mounted Ground Penetrating Radar (GPR) determined pavement structural thickness. The roughness was not measured on aprons.

The LiDAR data is used to define the surface drainage conditions as well as to define the pavement distortions as required, in conjunction with the crack measurements, to calculate the ASTM D5340 PCI. The profile data is used to calculate a Boeing Bump Index (BBI) to determine whether there is risk of airframe damage due to roughness during take-off and landing. The Deflection data is combined with the structural thicknesses to arrive at a measure of the adequacy of the pavement relative to the aircraft that use a given pavement section.

4 PAVEMENT SURFACE CONDITION (PCI AND FOD)

The PCI is a standard index expressing the condition of the pavement surface as a function of the severity and extent of the visible surface distresses. The PCI is a numerical rating that ranges from 0 to 100 with 0 being the worst possible condition and 100 being the best. The PCI is determined using the methodology documented in the American Society for Testing and Materials standard ASTM-D5340. Continuous monitoring of the PCI is used to establish the rate of pavement deterioration, which permits early identification of major rehabilitation needs.

The potential for presence of foreign object debris is evaluated using the FOD index. The generation of FOD is closely associated with safety hazards and risk for the airport users. An aircraft is susceptible to damage from pavement debris on the airfield[ii]. The FOD index is determined in a similar manner to that of the PCI; however, only those distresses and distress severity levels that have the potential to generate FOD are considered. The FOD index is on an inverse 0 to 100 scale with a higher value representing a greater potential for FOD. The detailed distress types and severity levels for FOD potential are described in the ASTM Standard.

The PCI and FOD index for all sections were calculated by MicroPAVER following ASTM-D5340. Overall, pavements at YXE had an area-weighted PCI of 66 and an FOD index of 15 in 2016.

5 ANALYSIS METHODOLOGY

It is more cost effective to preserve pavements by renewing or rehabilitating the surface while they are still in relatively good condition than it is to allow pavements to deteriorate to the point that the surface needs to be removed and replaced, or reconstructed. A surface replacement can cost more than five times as much as a surface renewal[i], but allowing the surface to deteriorate from fair to poor condition provides only small additional pavement life. Figure 3 illustrates the savings that can be realized by addressing pavement conditions at the most cost-effective time. This is the premise behind MicroPaver's PCI based prioritization method. The methodology models the PCI going forward and determines the point at which the pavement will transition from good to fair condition and from fair to poor condition. It then selects projects based on these thresholds.

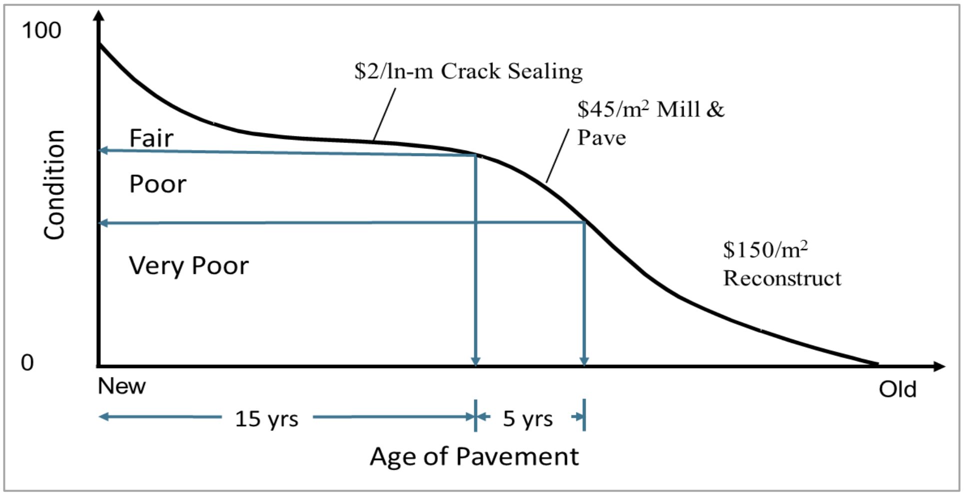

Figure 3: Minimizing Life Cycle Costs

The simple PCI based approach is limited in that it considers only the direct agency costs for pavement preservation and rehabilitation activities. It does not consider the number of users of each pavement section nor the risk to airfield users. At YXE, Runway 09-27 and associated taxiways receive considerably more use than Runway 15-33. Therefore, all other conditions being equal, there would be more risk of damage to aircraft (FODd) on Runway 09-27 than Runway 15-33. If operational considerations require one runway to be open at all times, then Runway 09-27 should be repaired first because it has the higher risk.

At YXE, the risk based user costs are largely related to FOD_d. In some cases, however, roughness can also affect users. A direct application of PCI methodology also does not consider airfield operations when prioritizing projects.

A four part methodology is used for this study. First the BBI is checked to verify that the runways are not unacceptably rough. A second step calculates a monetary FOD_d risk for each pavement section of the facility and a risk ranking. The PCI based selection is used to generate an initial prioritization of projects and their costs. Outside of MicroPAVER, the monetized user costs (risk) are combined into a benefit/cost ratio, which measures the reduction in risk (the savings in user costs) attributable to the pavement improvement against the direct YXE agency cost of the pavement improvement. A final step applies a knowledge of airfield operations to the process and discussion with the SAA to confirm, for example, that the projects are scheduled so the airport can continue major flight operations.

6 TRADITIONAL MICROPAVER APPROACH

As part of this project, the MicroPAVER software was customized to reflect the specific conditions and needs of the SAA for maintaining the pavements at YXE. Customizing MicroPAVER is essential to developing results that are meaningful and applicable to the specific agency and airport needs.

The baseline PCI analysis has three component inputs:

1. Develop a set of PCI prediction models.
2. Establish a set of rehabilitation and maintenance policies and their costs.
3. Establish the triggering thresholds (Critical PCI).

The following section discusses each of these components.

6.1 Pavement Performance Models

MicroPAVER uses performance models to predict future pavement condition. Based on YXE pavement history (Ages) and current pavement condition (2016 PCI), three PCI models were developed one for “Runway Keel sections”, “other Asphaltic pavements excluding runways keel sections” and “PCC pavements” separately. Figure 4 shows the PCI prediction models for each pavement family at YXE.

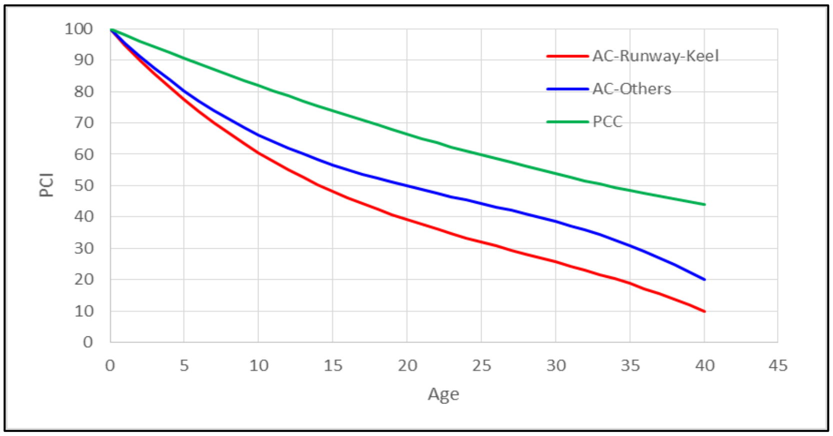

Figure 4 – Pavement Performance Prediction Curves

Runway 15-33 has a current PCI of 40 and its surface is now 19 years old. Runway 09-27 is now 7 years old with a current PCI of 70. Note that on “Runway keel sections”, it takes 7 years for the PCI to drop from poor (55) to very poor (40). At a PCI of 55 it is possible to rehabilitate with a simple mill and inlay, while at a PCI of 40 some surface replacement would be required.

6.2 Rehabilitation and Maintenance Policies and Triggering Thresholds

Rehabilitation costs are determined within MicroPAVER by multiplying the section area by a predetermined unit cost based on a specific PCI. To develop the “unit cost versus PCI” table in MicroPAVER, the SAA used rehabilitation unit costs from previous projects.

In general, reconstruction or full slab replacement is recommended for pavement with a PCI at or below 40, while a mill and fill (with varying amounts of patching repair) or partial slab replacement is recommended if the PCI is between 40 and 70. Rehabilitation is generally not needed for sections with PCIs greater than 70. The critical PCI is the condition level below which the rate of PCI loss begins to increase with time, or the cost of applying localized preventive maintenance increases significantly. The critical PCI also represents the time when major rehabilitation is triggered within MicroPAVER. A critical PCI of 55 was considered for the airside pavements managed by the SAA based on pavement performance curves and construction history. There was a significant increase in the rate of pavement condition deterioration as PCI falls below the critical PCI range.

In general, when a constrained budget analysis is performed, MicroPAVER prioritizes projects in the following order:

1. First priority: Maintenance.
2. Second priority: Rehabilitation above critical PCI, for sections with structural defects.
3. Third priority: Rehabilitation below critical PCI.

There is no prioritization based on user related costs or risk.

7 USER COSTS BASED ON FOD$_D$ RISK

The effect of Foreign Object Debris (FOD) on maintenance costs can be significant (Transport Canada 2016)[iii]. For example, the cost to repair a FOD-damaged jet engine can easily exceed $1 million or 20% of the cost of a new engine. FOD can also incur extensive indirect costs, including:

1. Flight delays and cancellations, leading to a loss of customers.
2. Schedule disruptions caused by the need to reposition airplanes and crews.
3. Potential liability because of injury.
4. Additional work for airline management and staff.

According to Boeing (Boeing online)[iv], FOD-related direct damage to aircraft exceeds $4 billion annually worldwide. According to the Airports Council International (ACI online)[v] in 2015 there were 68 million aircraft movements worldwide. This means that on average FODd costs airfield users $59 per movement. According to Statistics Canada (2015)[vi], YXE receives about 94,000 annual movements. If this cost is applied to YXE’s 94,000 annual movements, FOD$_d$ costs YXE users $5.5 million/year.

Pavement surface distress generated FOD is a significant contributor to the total amount of FOD produced through airfield operations. U.S. DOT FAA Advisory Circular[vii] reported that 60% of all FOD detected in one year by an automated FOD detection system was metal, and 18% was rubber. In addition, 60% of all FOD was “dark” material, which presumably includes all of the rubber, some of the metal, and much of the rest of the FOD. Much of the rubber might be attributed to pavement joint and crack sealing on medium to high severity cracking or joint spalling. Similarly, much of the remaining non-metal and non-rubber debris might well be attributed to loose “dark” pavement fragments caused by deteriorating pavement surfaces. Although no conclusive studies have been done to indicate how much FOD$_d$ can be directly attributed to pavement surface distresses, anecdotal evidence based on discussions with air carrier maintenance personnel indicate that most of the damage is in the engine run-up areas entering or leaving taxiways and runways. In these areas, the debris is more likely to be pavement related.

Until more reliable information can be determined, and for the purposes of assigning risk in this study, it is assumed that 20% of actual engine damage is pavement surface distress generated. These assumptions lead to the conclusion that there could be more than $1 million of pavement surface distress related FOD_d/year at YXE. The challenge is to apportion this risk to each of the 54 distinct pavement sections identified at YXE.

7.1 Aircraft Movements

According to Statistics Canada[viii], YXE's annual movements are comprised of 20% jet engine aircraft, 30% turbo prop aircraft and 50% piston engines (assuming that the majority of the local civilian movements are piston engines). In order to apply a FOD_d risk based approach, it is necessary to assign both a relative volume of traffic movements and proportion by engine type to each facility. The movements are not broken down by facility in the Statistics Canada reporting and these break downs are not readily available from YXE records.

The number of aircraft movements was first assigned based on Saskatoon's wind rose[ix], supplemented by engineering judgement. The wind rose for Saskatoon implies that aircraft would use Runway 09-27 approximately 75% of the time, as shown in Figure 5.

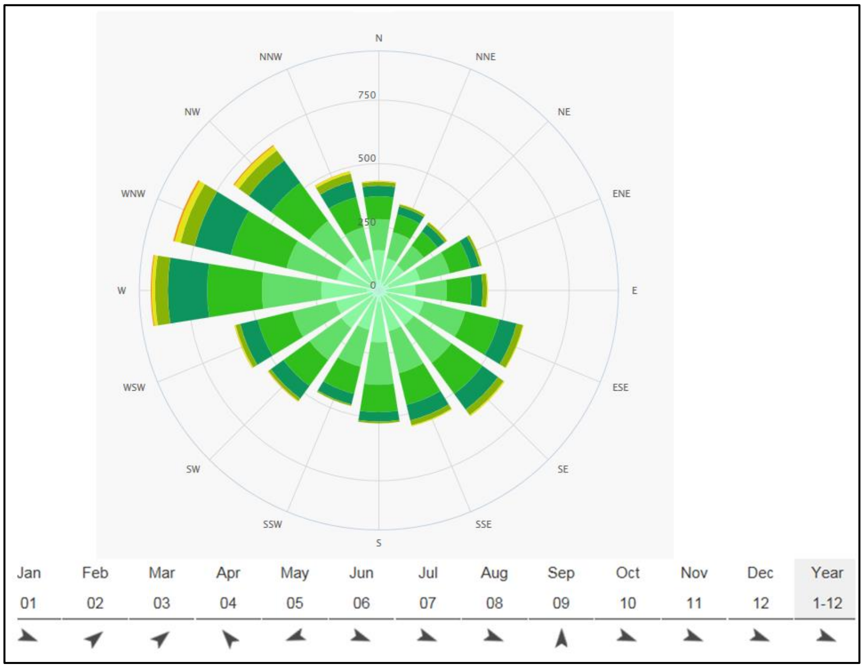

Figure 5: Wind Rose for Saskatoon

Therefore, Runway 09-27 has a total of 70,500 movements per year (75% of all movements = 0.75 x 94,000). The rest of all movements use Runway 15-33 (94,000 – 70,500 = 23,500). Taxi A and Taxi F serve Runway 09–27 once per movement (one take-off and one landing). Apron 1 serves the commercial airlines, while other aprons serve private or local movements. Statistics Canada reports itinerant movements in terms of Levels I-III/Foreign (commercial carriers with more than $2 million dollars in annual revenue), and Level IV-VI (commercial carriers with less than $2 million dollars in annual revenue). The reports also break down itinerant movements by engine type. The detailed movement assignment for each airfield section along with the rationale for assignment was developed.

7.2 FOD Index Prediction Model

A model to predict FOD differs from the PCI model in that FOD increases over time while PCI decreases over time. In addition, the pavement surface distresses that generate FOD as defined by ASTM-D5340 are a subset of all distresses used to calculate PCI. Therefore the FOD predictive model is not simply the inverse of the PCI model.

The distresses which contribute to FOD increase over time, leading to more debris over time and, therefore, a greater potential for damage over time. The MicroPAVER software can calculate a PCI index as well as a FOD index. However, although it allows for the development and use of predictive models for PCI within the software, it does not make provision for this modeling process with respect to the FOD index. The consultants have therefore developed FOD predictive models for YXE that can be used outside of the software to estimate the rising risk of FOD$_d$ over time (Figure 6). A regression analysis is used to develop the curves such that they fit the historical data adequately.

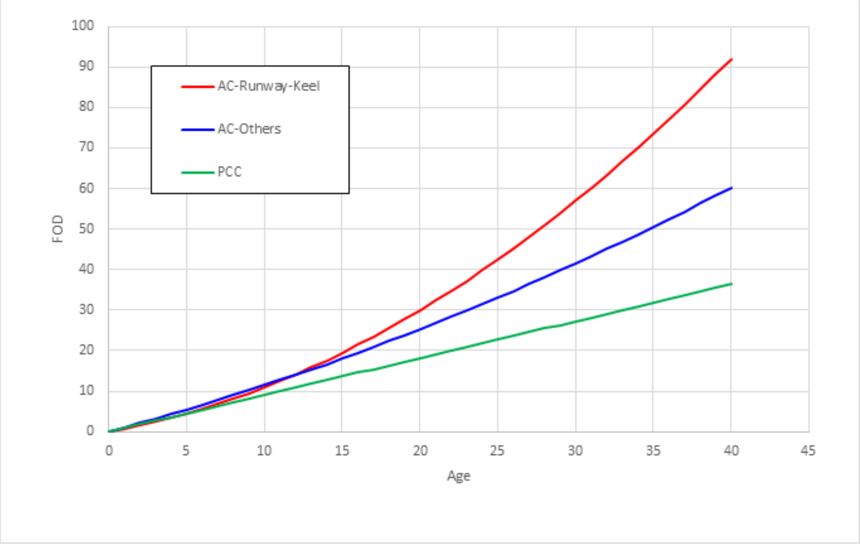

Figure 6: FOD Prediction Models

Because the initial FOD index value as measured in 2016 is different for each pavement section, a different FOD probability profile exists for each pavement section.

7.3 FOD$_d$ Risk Determination

The generally agreed definition of risk is the product of the probability of an event occurring multiplied by the cost of the consequences of the event: Risk = Probability Consequences[ii]. The consequences of a FOD$_d$ event to a jet engine according to Boeing[x] are assumed to be $1,000,000, or a repair cost of 20% of the replacement cost. The analysis assumes repair costs of $100,000 for a turbo prop engine and $10,000 for a piston engine, for the purpose of the risk assessment.

As previously discussed, the assumed annual risk of all pavement surface distress related FOD$_d$ events at YXE is $1 million. Apportioning this risk based on the FOD probability profile, the number and type of each engine movement on each pavement section, weighted by the section’s area, yields a risk value in dollars for each pavement section.

8 MAINTENANCE AND REHABILITATION RECOMMENDATIONS

An unconstrained budget scenario was analyzed to identify the rehabilitation needs and associated costs over the next 10 years to keep all sections at a serviceable condition level (above the critical PCI). Under this scenario, pavements are scheduled for rehabilitation in the first year in which they are predicted to fall below the critical PCI, which generally identifies more work than could feasibly be completed within the constraints that most airport agencies operate. Because this plan identifies when the condition of each pavement section is predicted to reach the established critical PCI – defining the point when a pavement section becomes a candidate for rehabilitation – it is recommended that this analysis serve as the basis for selecting future rehabilitation projects.

This process selected $18.33 million dollars of projects that could be undertaken immediately in 2017. It includes all of Runway 15-33 ($11.2 million), the shoulder sections of Runway 09-27 ($2 million) and some sections of Apron II and Apron III. This unconstrained scenario does not take into account fiscal and operational constraints or the risk benefit cost ratios related to FOD and aircraft movements. Operationally and financially, it would be unrealistic to perform this much work in 2017, so the projects would need to be prioritized.

The ten-year Micro PAVER Results (PCI Analysis) under the unconstrained budget scenario were prioritized by calculating a risk benefit cost ratio. In order to determine financial/economic based priorities, the benefits in terms of the monetary value of the risk reduction over 20 years is divided by the project's capital cost to arrive at benefit/cost ratio for each project. This is then used to prioritize the list of projects.

Table 1: Projects Ranked by Risk Reduction/Cost Ratio

Name	Section ID	FOD	Rehab Year (Unlimited Budget)	Capital Cost	NPV Risk Reduction	B/C*	Benefit (Risk Reduction)
RWY 15-33 (Intersection)	5	22	2017	$1,460,000	$2,692,000	1.844	$135,000
RWY 15-33	10	28	2017	$6,296,000	$4,581,000	0.728	$228,000
RWY 15-33	11	27	2017	$174,000	$125,000	0.718	$6,000
RWY 15-33	9	37	2017	$691,000	$486,000	0.703	$24,000
RWY 15-33	10A	28	2017	$2,562,000	$1,366,000	0.533	$68,000
RWY 09-27	3	3	2022	$201,000	$63,000	0.313	$3,000
TWY F	23	7	2023	$582,000	$181,000	0.311	$10,000
RWY 09-27	4	2	2022	$507,000	$157,000	0.310	$5,000
RWY 09-27	2	3	2023	$1,100,000	$336,000	0.305	$16,000
RWY 09-27	6	3	2022	$3,212,000	$966,000	0.301	$46,000
APRON I	26B	19	2018	$174,000	$52,000	0.299	$3,000

The Net Present Value (NPV) Risk Reduction represents 20 years of growing risk for each section assuming no renewal is performed over the next 20 years.

When sorted and prioritized by B/C ratio, the intersection between the two runways receives the highest priority followed by the remainder of the ACP sections of Runway 15-33. This prioritization has the additional benefit of allowing YXE an opportunity to select the most urgent projects in terms of reducing all costs (direct agency costs as well as airfield user costs). The shoulder sections of Runway 09-27 can be justifiably delayed due to the low risk. However, it has still grouped the majority of the projects into the first year. Operational considerations are then applied using operational experience and engineering judgement.

9 CONCLUSIONS

The risk analysis is a simply calculated and readily applicable additional piece of additional information that can be used to assist asset managers with project prioritization.

The methodology described here is not intended to accurately quantify the actual risks associated with deteriorated airfield pavements but rather to develop an order of magnitude risk of one pavement section relative to another at the same airfield. That being said, airfield pavements, like many other civil infrastructure assets can be assigned a monetized value for risk. This in turn can be used to rationally justify capital project selection decisions.

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