DESIGN PROGRAM BASED PCN EVALUATION OF AIRCRAFT PAVEMENTS

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ABSTRACT

The PCN evaluation and reporting procedure has been detailed in FAA Advisory Circular No 150/5335-5B. The procedure essentially covers estimation of PCN for the pavement thickness, considering the aircraft traffic in terms of the fleet mix operating from the facility. The actual correlation of the ACN-PCN is based on COMFAA version 3.0. The COMFAA programme derives its pavement thickness estimation from the charts provided in FAA Advisory Circular No 150/5320-6D, which for flexible pavement designs are based on the CBR – ESWL method and for rigid pavements are based on the Westergaard's theory and are included in ICAO, Aerodrome Design Manual Part 3 – Pavements. With advances in computing technology, new pavement design methodologies have also evolved viz; Mechanistic-Empirical designs based on Layered Elastic theory for Flexible pavements and Finite Element analysis for Rigid pavements. FAA, vide its Advisory Circular No 150/5320-6E has provided the guidelines for use of this methodology for design of aircraft pavements. The design methods being able to model and analyse the pavement structures in a better way, they provide for a more efficient pavement thickness design. The design thicknesses computed by the FAARFIELD software for both rigid and flexible aircraft pavements is thus based on an advanced pavement analysis methodology compared to that computed by the COMFAA software. The PCN reporting based on COMFAA is therefore not matched in design principle and thus to the design thicknesses computed by FAARFIELD or any other software adopting mechanistic-empirical methods. The paper presents an alternative approach based on first principles for evaluating and reporting the design PCN value aligned the specific design principle / methodology adopted by the software used for pavement design. For the purpose of this paper, FAARFIELD software is adopted for analysis and reporting of the Design PCN value.

INTRODUCTION

For achieving the design life of aircraft pavements, the bearing strength of pavements need to be taken into account whilst planning aircraft operations. Therefore ICAO makes it mandatory for all airports to publish the Pavement Classification Number for all pavement facilities at the airport in the Aeronautical Information Publication (AIP).

The ICAO ACN-PCN system is used by airport operators as a pavement management tool, whereby aircraft that operate at Aircraft Classification Numbers (ACN) lesser than the Pavement Classification Number (PCN) for a particular pavement can do so without causing undue damage to the pavement, with no weight restriction for unrestricted number of passes. The ICAO Aerodrome Design Manual Part 3, Clause 1.1.2.1 [2]. states that "The ACN-PCN method is meant only for publication of pavement strength data in the AIP. It is not intended as a pavement design or pavement evaluation procedure, nor does it restrict the methodology used to design or evaluate a pavement structure." The ICAO, ACN-PCN method permits all states to use any design/evaluation method. Consequently the bearing strength of the aircraft pavements in terms of PCN is reported on the basis of the load rating of the aircraft in terms of ACN.

The FAA provides guidance for using the standardised ICAO method of reporting the PCNs vide Advisory Circular AC 150/5335-5B [4], Standardized Method of Reporting Airport Pavement Strength – PCN. The COMFAA software developed by FAA provides the tool for PCN evaluation. The Advisory Circular also states that "The ACN-PCN system is only intended as a method of reporting relative pavement strength so airport operators can evaluate acceptable operations of airplanes".

The philosophy expressed in the ACN-PCN method is thus intended to allow the airport operator, the liberty to select any method of pavement evaluation. However, though not specifically mentioned in the ACN-PCN method, this philosophy also translates into a liberty of selecting the value of PCN for publication. More often, the decision as to what value to select is a balance between commercial considerations and the actual strength of the pavement. An airport operator may choose to increase the PCN without strengthening a pavement, in order to attract larger aircraft and thereby gaining increased revenue. The airport operator would make this decision consciously knowing that the overloading operations of larger aircraft would reduce the life of the pavement, and would result in the need for early maintenance.

Given the above thought process, it is likely that the actual PCN value is not published in the AIP. All the same, at the design stage, the pavement designer is required to recommend the expected PCN value for the design pavement section. There is therefore a need to estimate the PCN value with a standard evaluation method. However, since the pavement designer has the liberty to use any design methodology, it is a corollary that the PCN evaluation of the design section is established on the basis of the same design theory and methodology. The FAARFIELD software provided by FAA utilises mechanistic-empirical formulations for design of rigid and flexible aircraft pavements.

The authors have identified that the PCN evaluation methodology based on COMFAA does not correlate with the design principles forming basis of the design software FAARFIELD. The differences and their wider implications have been highlighted in this paper.

Irrespective of the pavement design methodology adopted, the PCN value should be evaluated on the basis of first principles ie. its basic definition, which is, the equivalent of that for ACN of an aircraft (defined further in the paper). It is only then that the designer would establish with some certainty that the pavements would achieve the intended design life ie. if the operator chooses to publish the same PCN value as estimated by the designer.

This paper proposes an alternative approach to PCN evaluation based on first principles, which seeks to put the pavement design and evaluation process at par with each other. For purpose of this paper the FAARFIELD software is utilised for the proposed methodology of PCN evaluation.

PCN EVALUATION METHODS.

The PCN evaluation procedure allows for reporting of PCN on the basis of a technical evaluation or by experience based on aircraft previously using the pavement. When a new pavement is designed, a technical evaluation is usually undertaken. The PCN values are thus expressed in the following format [2];

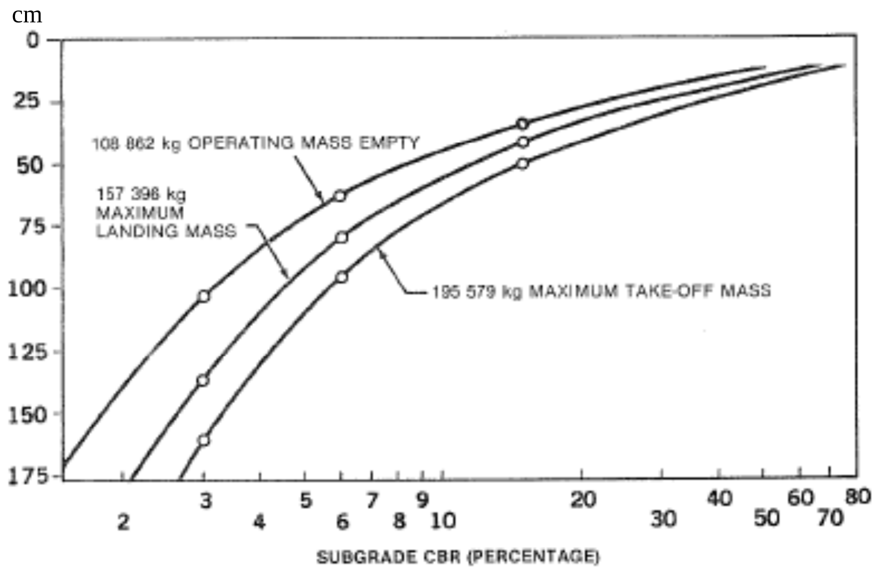
50/R/C/W/T Or 50/F/C/W/U

Where the numerical value is the PCN for R(Rigid) or F (Flexible) pavement designed or constructed on Subgrade category (A, B, C or D) . The tire pressure allowed is expressed in High, Medium, Low and Very Low categories (W, X, Y and Z). The evaluation method follows as either ; Technical (T) or Using experience (U).

ICAO, ACN Method. Broadly the ICAO – ACN method is based on the reference thicknesses required for aircraft for a particular load as given by the manufacturer and vice-versa. The computation of the reference thickness for flexible pavements is from the CBR equation which utilises the equivalent single wheel load obtained by the Boussinesq’s theory of a single elastic half space and for Rigid pavements based on Westergaard’s theory [2]. While the reference stress is defined for Rigid pavements as 2.75 MPa, the limiting strain value is not defined for Flexible pavements.

For rigid pavements, the reference thickness for a particular weight of aircraft is determined from the chart based on Westergaard's theory considering a standard tire pressure of 1.25 MPa and a standard concrete stress of 2.75 MPa (Working Stress as per Portland Cement Association). For flexible pavements, the reference thickness is based on the US Corps of Engineers – CBR design method. Both are then correlated by charts to the ACN provided by the manufacturer for 10,000 coverages of the particular aircraft.

Chart provided by ICAO for the computation of reference thickness and ACN for flexible pavement for a DC 10-10 aircraft is given below.



Reference: ICAO, Aerodrome Design Manual, Part 3, Pavements, 1983
Figure 1. DC10-10 Flexible Pavement Requirements for 10,000 Coverages.

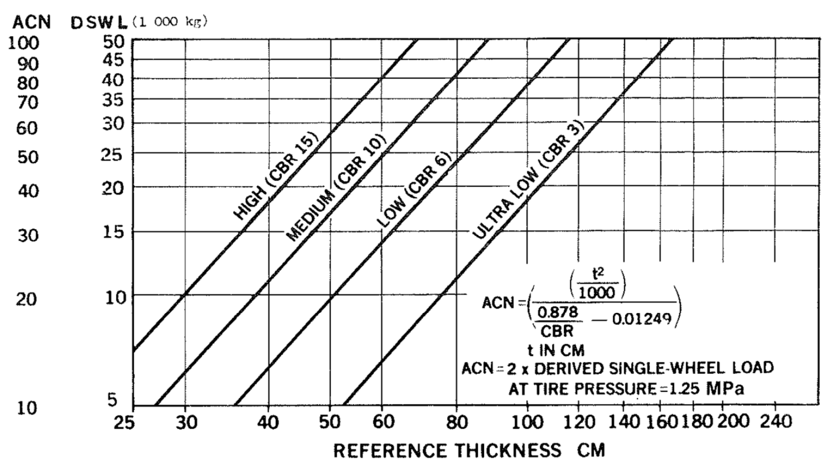
Flexible pavement ACN is determined by obtaining the DSWL from the chart developed on basis of the following equation [2]

$$t = \sqrt{\frac{DSWL}{C_1\, CBR} - \frac{DSWL}{C_2\, P_S}}$$

Where, t = reference thickness in cm

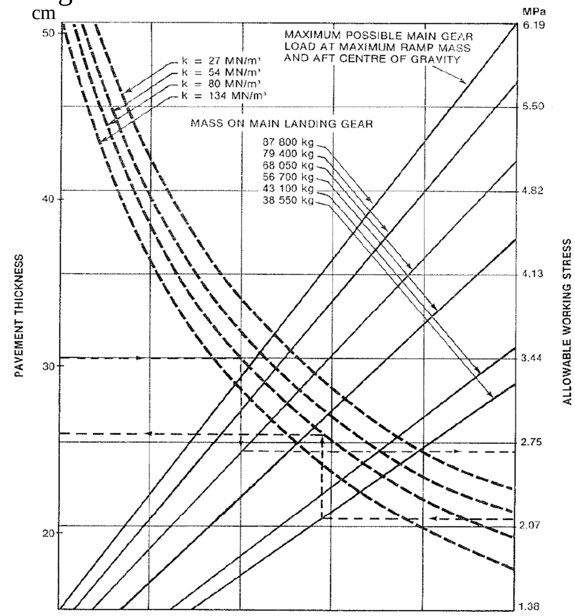
DSWL = Derived Single Wheel load with tire pressure P_s = 1.25 MPa

Constants C1 = 0.5695 C_2 = 32.035



Reference: ICAO, Aerodrome Design Manual, Part 3, Pavements, 1983
Figure 2. ACN Flexible Pavement Conversion Chart

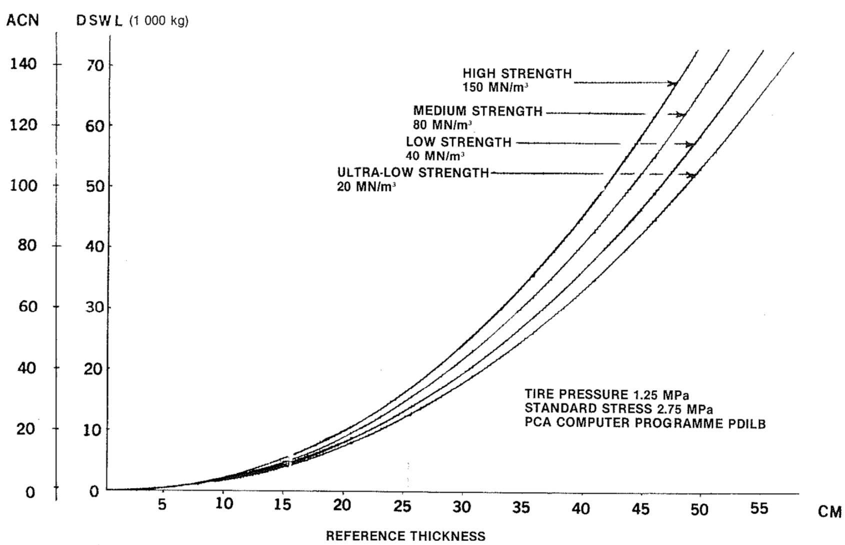
Chart provided by ICAO for the computation of reference thickness and ACN for rigid pavement for a B727 aircraft is given below.



Reference: ICAO, Aerodrome Design Manual, Part 3, Pavements, 1983

Figure 3. B727 Rigid Pavement Requirements for 10,000 Coverages.

Rigid pavement ACN for the reference thickness determined above is then obtained by correlating from program/ chart developed by the Portland Cement Association (PCA). The stress computations are based on Westergaard's theory in this program.



Reference: ICAO, Aerodrome Design Manual, Part 3, Pavements, 1983

Figure 4. ACN Rigid Pavement Conversion Chart

ACN values obtained from these correlation charts for Rigid and Flexible pavements are therefore reported as PCN for the reference thickness. The PCN for an evaluation thickness is calculated and reported on basis of the allowable aircraft weight in relation to the PCN at the reference thickness.

FAA – PCN Evaluation and Reporting Method. The FAA procedure for PCN analysis is given in FAA Advisory Circular No 150/5335-5B [4]. The procedure given in the Advisory Circular is based on the COMFAA program developed by the FAA. The procedure essentially covers estimation of PCN for the design pavement thickness, considering the entire aircraft traffic in terms of the fleet mix operating from the facility. The actual computation of the ACN-PCN is based on COMFAA version 3.0.

COMFAA METHOD

For flexible pavements, the COMFAA methodology [4] can be summarised as:

1. Determine and input the traffic volume in terms of annual departures for each aircraft and CBR of the subgrade soil.
2. COMFAA program calculates pavement thickness for a 20 year life. The calculation of reference thickness is based on the CBR – ESWL method [4] developed by the US Corps of Engineers, as incorporated in FAA Advisory Circular No 150/5320-6D [1].
3. Using the COMFAA support spreadsheet the evaluation thickness is converted in terms of standard equivalent pavement structure used in COMFAA; 127mm of P401 (Asphalt Concrete) on 203mm of P209 (Crushed aggregate) on available thickness of P154 (subbase)
4. Using the annual departures, pass to traffic cycle (P/TC) ratio, the converted evaluation pavement thickness and the CBR of subgrade, the program computes total equivalent coverages for 20years, taking each aircraft in turn as the critical aircraft.
5. Further, the program computes the corresponding design thicknesses at MTOW for the equivalent number of coverages of each aircraft.
6. Considering the converted evaluation thickness now, the program computes the maximum allowable weight of the aircraft for same number of equivalent coverages.
7. The ACN of each aircraft at its computed maximum allowable gross weight and appropriate ICAO standard CBR, is computed for 10,000 coverages and reported as the numerical PCN value.
8. The PCN for the pavement is reported as the highest numerical PCN value computed in the above steps for the particular subgrade category.

For rigid pavements, the COMFAA methodology can be summarised as:

1. Determine and input the traffic volume in terms of annual departures for each aircraft and the modulus of subgrade reaction (k) of the subgrade soil.
2. Using the COMFAA support spreadsheet compute the k value directly beneath the PCC layer based on the evaluation pavement structure and the k value of the subgrade.
3. Using the annual departures, pass to traffic cycle (P/TC) ratio, evaluate the PCC slab thickness and the k value directly beneath the PCC layer. The program computes total equivalent coverages for a 20 year life, taking each aircraft in turn as the critical aircraft. (the calculated thickness is based on the PCA method or FAA Method and Westergaard's edge loading analysis, choice being with the user).
4. Further steps for evaluating the PCN value are same as for the Flexible pavement, except that the subgrade category is reported on basis of the k value.

ADVANCES IN PAVEMENT DESIGN METHODOLOGY.

With advances in computing technology, new pavement design methodologies have evolved. Typically, designs are now based on Mechanistic-Empirical formulations for which use layered elastic theory for flexible pavements and finite element analysis for rigid pavements. FAA, vide its Advisory Circular No 150/5320-6E [3], has provided the guidelines for use of these methods for design of aircraft pavements and the methodologies are summarised below.

Flexible Pavement Designs: The Mechanistic – Empirical design method of flexible aircraft pavements is based on layered elastic analysis theory, incorporating empirical results based on field and testing facility National Airport Pavement Testing Facility (NAPTF) observations. The layered elastic analysis performs analysis of stresses and strains in the flexible pavement structure which comprises multiple layers of different material. The materials of each of the pavement layers such as asphalt concrete, bituminous macadam, crushed aggregate bases course, granular subbase course and subgrades are characterised by their Elastic Modulus and Poisson's ratio. For the analysis, the thickness of each material layer is considered in the structure. Loading of aircraft with multiple wheel gear assembly is applied and stresses and strains are computed for all critical locations under the complete gear assembly. In general, fatigue of the asphalt layers is not considered critical for airport pavements, the number of load repetitions being low and therefore the critical location invariably is the subgrade top where the vertical strain based on the materials, assumes importance for deformation analysis. The computation of stresses and strains using layered elastic theory is based on the expanded solutions of the Boussineq's equations and worked upon further by a number of researchers with the latest being the formulations by Ahlvin and Ulery [7]. The computed stress and strain values based on these equations are further used in the failure models incorporated in various design methods, which may be calibrated based on field test results.

The elastic layered theory incorporated in the FAARFIELD software is used for computation of the vertical subgrade strains for loading of each aircraft in the fleet mix. These values primarily form the basis of the failure model which has been calibrated to the NAPTF results for a number of aircraft gear configurations in combination with a variety of materials [8]. Thereby, the mechanistic-empirical approach of design of flexible pavements is recognised as a more accurate one, in which even the non-linear behaviour of the granular materials is accounted for through realistic field behaviour. The FAARFIELD software, like all other layered elastic analysis based design methods, restricts the vertical subgrade deformation, by limiting the value of the vertical strain caused by each aircraft main gear loading at the top of the supporting subgrade, so that the manifested shear uplift on the surface is limited to 25.4mm (1in). The allowable load repetitions for this strain is computed based on the - failure criteria equation as given in FAARFIELD help manual [9]

Cumulative deformation is computed due to the strain values caused by each aircraft load repetition and compared in a ratio to the total allowable deformation. The cumulative deformation termed as Cumulative Damage Factor (CDF) is limited to a value of 1 for the pavement design and it also takes into account the percentage coverage which actually causes damage for each pass of the aircraft.

The methodology is therefore an advanced approach to design of aircraft pavements compared to the CBR – ESWL method and is generally being adopted as the preferred design method for flexible pavements.

The CBR-ESWL method for flexible pavement designs and the associated nomographs are included in ICAO – ADM Part 3, Pavements [2]. The FAA had provided the design charts / nomographs with aircraft load, repetitions and subgrade CBR as inputs to determine the required thickness. Though the Mechanistic – Empirical design method explained above is adopted by FAARFIELD, the CBR-ESWL method continues to form the basis for pavement thickness computation in COMFAA. The COMFAA programme by FAA gives the design thickness required for a standard configuration of Flexible pavement; 125mm Asphalt on 200mm Crushed Aggregate layer on GSB as required over varying subgrade (CBR) categories.

The CBR-ESWL method is based on equivalent single wheel load computations for equal deflections at varying depth into the pavement structure and matching out with the design pavement thickness required based on given empirical relations for total pavement thickness required over a particular CBR of the subgrade for different load classes / ESWLs. The pavement thickness thus derived does not account for the strength parameters of pavement material layers above the subgrade; except that it stipulates that the material in each layer should have a higher CBR value than the lower layer. Each layer thickness can be progressively designed based on total pavement thickness required above it [6]. The thickness is adjusted for aircraft traffic by using a load repetition factor (α factor) based on number of wheels considered for ESWL calculations and traffic load repetitions. For each aircraft class a standard pass to coverage ratio is prescribed.

A comparison of the design pavement thicknesses based on FAA design charts, COMFAA and FAARFIELD using the below given design parameters is highlighted in Table 2 below.

Design Parameters : Subgrade CBR: 6% ; Design Life: 20 years
Aircraft Fleet Mix: Aircraft fleet mix considered for analysis is as given in Table 1.

Table 1.
Aircraft Fleet Mixes.

Aircraft	MTOW (Tonnes)	Annual Departures		Aircraft	MTOW (Tonnes)	Annual Departures	
		Fleet Mix 1	Fleet Mix 2			Fleet Mix 1	Fleet Mix 2
A320-200 Twin std	77	10951	17,155	B737-900	79	2393	26,171
A321-200 std	89	1157	2,373	B767-400 ER	204	0	694
A300-B4 std	171	0	1,314	B747-400B Combi	397	110	730
A330-300 std	230	5419	1,314	B777-300 Baseline	300	0	1,007
A340-300 std	275	0	511	B777-300 ER	353	221	416
A340-600 std	368	0	250	MD11ER	285	0	219
A380-800	560	365	37	B787-8 (Preliminary)	228	673	0

Table 2.
Comparison of the flexible pavement design thicknesses based on FAA design charts, COMFAA and FAARFIELD.

Flexible Pavement layers	Thickness (mm)					
	Fleet Mix 1			Fleet Mix 2		
	FAA design charts	COMFAA	FAARFIELD	FAA design charts	COMFAA	FAARFIELD
P-401/ P-403 HMA Surface	125	127	125	125	127	125
P-209 Cr Ag	383	203	450.4	408	203	441.7
P-154 UnCr Ag	765	826.9	687.1	826	881.5	766.6
Total	**1273**	**1157**	**1262.5**	**1359**	**1211.5**	**1333.3**

It can be seen that the design thicknesses obtained from the FAA design charts, COMFAA and FAARFIELD software are mostly comparable, though based on different design methodologies. The FAARFIELD software is reported to have been calibrated in order to minimize the deviation from the previous design standard, when the aircraft mix contained only the older airplane types, covered under the earlier procedure.

Rigid Pavement Designs: The Mechanistic – Empirical design method of Rigid aircraft pavements is based on finite element analysis theory , incorporating empirical results based on field test results. The finite element analysis performs analysis of stresses in the rigid pavement structure which comprises mainly Portland cement concrete (PCC) on a stabilised base / subbase and subgrade. The Finite element modelling may differ between various analysis and design software in terms of the element types, sizes , support and boundary conditions. The aircraft main gear loading is directly applied on the concrete slab model with actual wheel spacing. Edge load stress analysis is carried out to an accuracy defined by the model and size of the elements selected and for the computer based analysis.

Finite Element (FE) stress analysis based on NIKE 3D program has been incorporated in the FAARFIELD software. The program models the rigid slab in 8 node brick, incompatible solid elements of thickness same as the slab, resting on extended stepped subbase foundation, with a sliding interface and the subgrade modelled as an infinite element [10]. The FE program is used for computation of the horizontal edge stress values for each of the fleet mix aircraft. These values form the basis of the failure model which is established by incoporating NAPTF results collected for a number of aircraft gear configurations, in combination with varying slab support strength values making it more a performance/failure model based on full-scale traffic tests [5]. Thereby, the mechanistic-empirical approach to the design of rigid pavements is recognised as a more accurate one. The FAARFIELD rigid pavement design software, like all other rigid pavement analysis based design methods, computes the edge load stress caused by each aircraft main gear loading at the bottom of the concrete slab. The edge load stress is reduced by 25% to account for load transfer across joints and akin to interior loading. Allowable repetitions of the aircraft loading are computed based on empirically established fatigue relationship for PCC given in the rigid pavement failure model equation in FAARFIELD help manual [9] and compared as a ratio to the expected repetitions, thus giving the damage factor. The design thickness is established based on a cumulative damage factor (CDF) of 1 for all aircraft load repetitions as per the design fleet. The pavement design also takes into account the percentage coverage which actually causes damage for each pass of the aircraft.

The difference in design methodology from that in ADM Part 3 is that the analysis is based on a more scientific and accurate technique utilising FE analysis made possible by faster computing speeds. The analysis based on Westergaard's equations has limitations for modelling complex wheel gear assemblies and to that extent would be erroneous. For multiple wheel gear assemblies the Westergaard's analysis would result in higher edge load stresses than the values obtained from FE analysis by NIKE 3D [10]. However, the FE model incorporated in FAARFIELD has been calibrated for rigid pavement design, in order to minimize the deviation from the previous design standard.

Another major difference is in the consideration of subgrade strength for analysis by COMFAA and FAARFIELD. Though the standard rigid pavement design procedure prescribes for determination of the Modulus of Subgrade reaction (k) values through plate load tests conducted in field at the worst moisture condition, pavement designers find it more convenient to use the correlated k values from soil CBR tests, which are simple to conduct in laboratory at saturated soil condition. The k values over subbase are further correlated from empirically established relations. Though the correlation method is an approximation, it is widely accepted. Pavement analysis methodologies incorporate the k value on the basis of PCA relationship for correlating k value from CBR, as included in ICAO ADM Part 3 Figure 3.2 [2], and the same is therefore presumed to be applicable for the ICAO –ACN method. COMFAA analysis for PCN should therefore also be based on the same. Being a FE analysis where the model incorporates the pavement layers characterised by their Elastic Modulus (E) values and poison's ratio, the

FAARFIELD software computes the E value from input k value (as recorded during plate load test) through the relationship between k and the E. $\left[k\ (pci)\ =\ \left(\frac{E}{26}\right)^{0.7788}\right]$

In that sense, the consideration of subgrade strength for analysis between COMFAA and FAARFIELD are different; whilst the COMFAA uses Modulus of Subgrade Reaction for analysis, the FAARFIELD uses Elastic Modulus. However, in case an analysis is to be carried out with an input k value derived from the soil CBR (E in psi =1500 CBR), the above relationship could also be utilised by a designer using FAARFIELD. The considered k values for COMFAA- PCN analysis and FAARFIELD design analysis would then differ.

The COMFAA programme gives the design thickness required for a standard rigid pavement with PCC strength of 4.5 MPa on varying k value, directly beneath the concrete slab.

A sample comparison between the design pavement thicknesses based on FAA design charts, COMFAA using PCA method and FAARFIELD for same input data is given in Table 3 below.

Aircraft Fleet: As given in Table 1 above; Design Life: 20 years
Subgrade k: 25.8 MN/m^3; directly beneath PCC, k: 91 MN/m^3 (COMFAA support spreadsheet)

Table 3.
Comparison of the Rigid pavement design thicknesses based on FAA design charts, COMFAA and FAARFIELD.

Rigid Pavement layers	Thickness (mm)					
	Fleet Mix 1			Fleet Mix 2		
	FAA design charts	COMFAA	FAARFIELD	FAA design charts	COMFAA	FAARFIELD
PCC Surface	421	370.1	425.1	425	379.5	427
P-304 CTB	150	150	150	150	150	150
P-209 Cr Ag	200	200	200	200	200	200
P-154 UnCr Ag	200	200	200	200	200	200

The FAARFIELD designs are comparable with the established earlier design procedures/charts based on Westergaard’s analysis as included in the FAA/ICAO nomographs, but differ significantly to those computed through COMFAA when utilising the PCA based design suite. It is to be noted that for ACN computations, ICAO prescribes the PCA method.

PCN CORRELATION PROBLEMS

The Mechanistic – Empirical design methods, being able to model and analyse the pavement structures in a better way, are expected to provide a more efficient pavement thickness design (without calibration to match with previous design standards). These design methods as explained above have been incorporated in the FAARFIELD design software. The design thicknesses computed by the FAARFIELD software for both rigid and flexible aircraft pavements are thus different (for a number of cases evaluated), from that computed by COMFAA software, though calibrations have been made in FAARFIELD to make the same comparable. Even then, the PCN reporting based on COMFAA is not matched in the principle of pavement structure analysis and therefore to the design thicknesses computed by FAARFIELD or any other software adopting mechanistic-empirical methods. There are other software which use the mechanistic – empirical design methodology but are not calibrated to provide for comparable design thicknesses to earlier standards. Apart from the calibration of pavement analysis model, there are other factors such as layer equivalencies and k value consideration that affect the design thickness computation. The PCN analysis and reporting when using a mechanistic–empirical design approach should therefore logically be based on the principle and methodology adopted for design and for the same design traffic.

Consider the following examples for appreciating the problem in PCN value interpretation by COMFAA whilst designing the pavement structure with FAARFIELD.

Flexible Pavement Analysis

Aircraft Fleet Mix: Aircraft fleet mix considered for analysis is as given in Table 1, fleet mix 2.
Subgrade CBR: 6%; Design Life: 20 years

Table 4.
Design thickness by FAARFIELD

Flexible Pavement layers	Thickness (mm)
P-401/ P-403 HMA Surface	125
P-209 Crushed Aggregate	441.7
P-154 Uncrushed Aggregate	766.6
Total	**1333.3**

The critical aircraft identified is B777-300ER with a CDF contribution of 0.65.

Table 5.
Equivalent design thickness by COMFAA support spreadsheet

Flexible Pavement layers	Thickness (mm)
P-401/ P-403 HMA Surface	127.0
P-209 Crushed Aggregate	203.2
P-154 Uncrushed Aggregate	895.6
Total	**1225.8**

A life check for this thickness by FAARFIELD gives a value = 5.3 years, which is far lower than the required design life of 20 years. Therefore the equivalency allocation in the COMFAA software is not correlated to the design software. A consequential problem arises when the design requirement specifies a PCN value for the pavement. Whilst the pavement designs can be carried out to satisfy the PCN requirement, they may not necessarily provide for the design life for the given design traffic.

The COMFAA – PCN analysis results for the above example are given below.

Table 6.
PCN analysis results for flexible pavement from COMFAA

Aircraft Name	MGTOW (Tonnes)	Thickness for Actual Individual Covs.	ACN at MGTOW	Critical Aircraft Total Equiv. Covs.	Thickness for Total Equiv. Covs.	Maximum Allowable Gross Weight for evaluation thickness (Tonnes)	PCN
							C(6)
A320-200 Twin std	77	909.7	47.6	>5,000,000	1201.18	79.81	49.9
A321-200 std	89	894.1	57.3	>5,000,000	1166.78	97.052	63.7
A300-B4 STD	171	964.95	66.6	>5,000,000	1186.55	179.045	71.3
A330-300 std	230	996.07	71.4	544,516	1157.25	248.13	79.8
A340-300 std	275	927.91	69.5	1,206,453	1166.07	293.76	76.5
A340-600 wing	368	964.54	83.6	21,474	1103.6	422.286	103
A380-800 Basic1 Wing	560	767.69	74.9	122,707	1135.64	618.168	87.4
B737-900 ER	79	958.12	51.2	>5,000,000	1191.68	83.099	54.5
B767-400 ER	204	1014.22	79.7	46,397	1122.3	229.89	95.8
B747-400	397	987.26	74.4	179,612	1143.77	435.527	85.7
B777-300 Baseline	300	1002.03	72.6	>5,000,000	1211.25	304.602	74.4
B777-300 ER	353	1094.7	93.6	11,682	1127.37	392.018	110.8
MD11ER	285	936.43	80.5	31,209	1108.65	323.646	98.6

The PCN value evaluated for the equivalent design thickness by COMFAA considering the B777-300 ER as the critical aircraft is 110.8/F/C/W/T. However, in case the PCN was evaluated considering the B777-300 Baseline aircraft , requiring maximum thickness for its equivalent coverages, the PCN would be 74.4/F/C/W/T. This would impose weight restricted operations for B777-300ER aircraft, its ACN at MGTOW being 93.6. However, since the equivalent coverages computed for B777-300 ER are low compared to the total facility traffic (11,682), the design thickness requirement is lower (1,127.37 mm) than that required for other aircraft in the design traffic fleet mix, thereby actually making this aircraft one of the least critical. The same is contradictory to the FAARFIELD analysis which computes the CDF contribution of this aircraft traffic = 0.64. In comparison, the B777-300 Baseline equivalent coverages of the complete design traffic is in excess of 500000 coverages and the CDF contribution of this aircraft for its actual design traffic in FAARFIELD analysis is only 0.18. The PCN computed by COMFAA for the reference thickness is therefore expectedly high = 110.8 for subgrade category C, being higher than that required for equivalent coverages of the critical aircraft B777-300 ER. As per the FAA standard method of PCN reporting [4], the PCN is now required to be reported as 110/F/C/W/T. This would be correct, but for the logic leading to the correct PCN identification.

Rigid Pavement Analysis

Aircraft Fleet Mix: Aircraft fleet mix considered for analysis is as given in Table 1, fleet mix 2.
Subgrade k: 25.8 MN/m^3; directly beneath PCC, k: 91 MN/m^3 (COMFAA support spreadsheet)
Design Life: 20 years

Table 7.
The design thickness by FAARFIELD

Flexible Pavement layers	Thickness (mm)
PCC Surface	427
P-304 CTB	150
P-209 Cr Ag	200
P-154 UnCr Ag	200

The critical aircraft identified is B777-300ER with a CDF contribution of 0.27.

The COMFAA – PCN analysis results are given below, computed by PCA method.

Table 8.
PCN analysis results for Rigid Pavement from COMFAA-PCA Method

Aircraft Name	MGTOW Tonnes	Thickness for Actual Individual Covs.	ACN at MGTOW	Critical Aircraft Total Equiv. Covs.	Thickness for Total Equiv. Covs.	Maximum Allowable Gross Weight for evaluation Thickness(Tonnes)	PCN
							B
A320-200 Twin std	77	329.11	49.6	1,514,182	374.5	97.878	65.9
A321-200 std	89	330.46	59	377,664	379.5	110.331	76.2
A300-B4 STD	171	321.7	60.9	177,680	374.4	208.667	81.1
A330-300 std	230	331.36	60.9	172,007	373.7	284.326	81.2
A340-300 std	275	314.67	59.5	206,922	373.1	340.877	79.5
A340-600 wing	368	336.97	73.6	38,421	378.8	445.445	95.6
A380-800 Basic1 wing	560	282.49	63.1	124,544	373.8	687.013	84.2
B737-900	79	344.56	52.4	1,001,342	376.2	99.502	69
B767-400 ER	204	332.3	69.7	59,463	376.9	246.172	91.3
B747-400	397	321.16	64.4	109,812	374.7	483.236	85.4
B777-300 Baseline	300	328.69	68.9	52,479	371.4	360.878	93.3
B777-300 ER	353	356.81	89.9	6,700	376.9	415.476	117.8
MD11ER	285	314.21	68.7	65,211	376	346.337	90.5

The COMFAA analysis identifies the A321-200 as the critical aircraft based on a maximum thickness requirement for the equivalent coverages of the complete design traffic. It is noted that the CDF contribution of this aircraft for its actual design traffic in FAARFIELD analysis is only 0.04. The COMFAA thickness is computed here based on PCA analysis, being the method recommended for ACN assignment by ICAO.

The PCN value evaluated for the equivalent design thickness by COMFAA considering the A321-200 as the critical aircraft is 76.2/R/B/W/T. It is noted that the maximum ACN in the fleet mix at MGTOW is 89.9 for subgrade category B, that of a B777-300ER. Then if the PCN is reported based on the critical aircraft identified on basis of the pavement thickness requirement, it would restrict the operations of B777-300ER aircraft from the facility. Therefore the COMFAA programme now evaluates the PCN considering B777-300 ER as the critical aircraft. However since the equivalent coverages computed are low (6700), the design thickness requirement of 376.9mm is lower than that required for A321-200. The PCN computed by COMFAA for this reference thickness is obviously high (117.8) for subgrade category B. As per the FAA standard method of PCN reporting the PCN is now required to be reported as 117.8/R/B/W/T.

Further analysis based on FAA edge stress method is given below.

Table 9.
PCN analysis results for Rigid Pavement from COMFAA-FAA Method

Aircraft Name	**MGTOW Tonnes**	**Thickness for Actual Individual Covs.**	**ACN at MGTOW**	**Critical Aircraft Total Equiv. Covs.**	**Thickness for Total Equiv. Covs.**	**Maximum Allowable Gross Weight for evaluation Thickness(Tonnes)**	**PCN**
							B
A320-200 Twin std	77	399.92	49.6	460,708	436.17	74.027	47.3
A321-200 std	89	385.77	59	110,960	436.92	85.14	56
A300-B4 STD	171	329.81	60.9	949,865	435.83	165.646	58.3
A330-300 std	230	351.77	60.9	613,014	436.03	220.704	57.7
A340-300 std	275	327.54	59.5	729,050	435.95	263.997	56.4
A340-600 wing	368	351.68	73.6	124,005	436.85	352.719	69.6
A380-800 Basic1 wing	560	294.35	63.1	714,070	435.96	538.838	59.9
B737-900	79	423.83	53.4	245,481	436.49	75.7	50.8
B767-400 ER	204	342.55	69.7	245,401	436.49	197.414	66.5
B747-400	397	326.44	64.4	639,776	436.01	383.776	61.3
B777-300 Baseline	300	303.2	68.9	3,056,010	435.33	290.999	65.6
B777-300 ER	353	329.15	89.9	367,942	436.28	340.364	84.7
MD11ER	285	325.37	68.7	321,180	436.35	274.84	65.3

In case the PCN analysis is carried out for B737-900 identified as the critical aircraft based on thickness requirement for individual aircraft coverages, the PCN is 50.8/R/B/W/T. This would now impose weight restrictions on almost all aircraft in the fleet. However, as per the latest COMFAA procedure the PCN of the facility is required to be reported as 84.7/R/B/W/T [4].

This would still impose weight restricted operations for B777-300ER (ACN at MGTOW = 89.9). The design thickness by FAARFIELD however caters for the design traffic of this aircraft.

The flaw here is that the PCN value is based on an analysis method which is dissonant with the actual pavement design method adopted. It would be proper that a PCN value, reflecting the pavement structural behaviour as modelled by the designer under the design traffic is reported, so as to facilitate the airport operator a better control on the operating aircraft traffic, in order to achieve the design life of the pavement.

ALTERNATIVE DESIGN PROGRAM BASED PCN EVALUATION & REPORTING

The PCN analysis and reporting must essentially be based on the definition of ACN which in effect implies that one must adopt first principles of the analysis.

Definition of ACN –- The ACN of a pavement structure is numerically defined as two times the derived single wheel load with a tire pressure of 1.25 MPa, where the derived single wheel load is expressed in thousands of kilograms.

The ACN thus obtained is to be reported as PCN for the evaluation pavement thickness.

It would therefore be prudent to retrace the pavement design to determine the Equivalent Single Wheel Load (ESWL) which dictates the critical design parameter for the pavement structural design, same as per the design methodology and software utilised.

Following the above principle, the PCN evaluation methodology in respect of the designed pavement structure computed utilising FAARFIELD could alternatively be undertaken based on the following guidelines :-

Flexible Pavements

1. Re-run the pavement design file on FAARFILED and download the output files.
2. Study the Output analysis file and identify the maximum vertical subgrade strain that is caused by the critical design aircraft, which is usually the one with maximum CDF contribution. However, vertical subgrade strain caused by all other aircraft should also be checked for the maximum value and identification of the critical aircraft.
3. Run the pavement life check with the FAARFIELD software for single wheels with tire pressure = 1.25 MPa, with incremental gear loads.
4. Form the downloaded output file determine the single wheel load which causes the same vertical subgrade strain as that by the critical design aircraft in the actual pavement design analysis report output.
5. Compute the ACN as 2 * the single wheel load in tonnes, as determined.
6. Adopt the PCN numerical value equal to the ACN so computed.

Rigid Pavements

1. Re-run the pavement design file on FAARFILED and download the output files.
2. Study the output analysis file and identify the maximum tensile edge load stress at the bottom of the slab that is caused by the critical design aircraft which is usually the one with maximum CDF contribution. However, the edge load stress caused by all other aircraft should also be checked for the maximum value and identification of the critical aircraft.
3. Run the pavement life check with FAARFIELD software again for the pavement structure for a design load of single wheels with a tire pressure of 1.25 MPa, with incremental gear loads.
4. From the downloaded output file, determine the single wheel load which causes the same horizontal stress as that caused by the critical aircraft and was utilised for the pavement design.
5. Compute the ACN as 2 * the single wheel load in tonnes, as determined.
6. Adopt the PCN numerical value equal to the ACN so computed.

PCN EVALUATION EXAMPLES

Flexible Pavement

Aircraft Fleet Mix: Aircraft fleet mix considered for analysis is as given in Table 1, fleet mix 2.
Subgrade CBR: 6%; Design Life: 20 year
Evaluation Thickness: As given in Table 2, fleet mix 2 computed by FAARFIELD
The maximum vertical strain on subgrade is -0.00119836 for B777-300ER.
The single wheel load corresponding to the same vertical subgrade strain is 63000kg.
Therefore, the ACN of B777-300ER for the above given parameters = 2*63000/1000 = 126
The PCN should be reported as 126/F/C/W/T.

The PCN evaluation for flexible pavements in the proposed method takes into account the material properties of the flexible pavement layers, being integral to the mechanistic design procedure. The vertical subgrade strain as computed for the pavement structure designed by FAARFIELD is notably lower than that computed for the COMFAA generated pavement thickness. The PCN value thus computed on basis of the maximum allowable load is higher than that computed by COMFAA; 110/F/C/W/T.

Rigid Pavement

Aircraft Fleet Mix: Aircraft fleet mix considered for analysis is as given in Table 1, fleet mix 2.
Subgrade k: 25.8 MN/m^3; directly beneath PCC, k: 91 MN/m^3 (COMFAA support spreadsheet)
Evaluation PCC Thickness: 427 mm ; Design Life: 20 years
The maximum horizontal stress at bottom of concrete layer is 360.6377 psi (2.487MPa) for B777-300ER.
The single wheel load corresponding to similar horizontal stress at bottom of concrete layer is 425000kg.
Therefore, the ACN of B777-300ER for the above given parameters = 2*425000/1000 = 85
The PCN should be reported as 85/R/B/W/T.

The PCN evaluation for rigid pavements in the proposed method takes into account the design flexural strength of concrete. In comparison, the COMFAA method is based on PCA prescribed working stress of 2.75 MPa. It is argued that the PCN as evaluated by the proposed method would still be valid for comparison with the current ACNs, if revalidated for design stress of 4.5 MPa. The ACN assignment by COMFAA is based on the reference thickness computed for the common value of working stress i.e. 2.75 MPa. In the proposed PCN evaluation method, the design and evaluation thickness is also based on a common flexural strength value of 4.5MPa. It is therefore presumed that the ACNs will remain comparable and may require slight modification to take into account the actual design flexural strength of concrete.

This is corroborated by the results given below, using FAARFIELD software for PCN evaluation using PCC strength of 4.5 MPa, 4.25 MPa, 4 MPa and 3.5 MPa (FAARFIELD allows computation for minimum Flexural strength of 3.45 MPa and hence the check could not be carried out for 2.75 MPa). The difference in PCN values thus computed, though minor, has a trend of linear increase towards lower PCC strength. Considering the same trend, the PCN for PCC working stress of 2.75 MPa is extrapolated = 90 /R/B/W/T which is matched with the published ACN for the critical aircraft in the design fleet mix (B777-300ER).

Table 10.
PCN Comparison with respect to allowable concrete stress

Allowable concrete stress	PCC Thickness	Max. tensile stress at bottom of concrete layer (psi)	Corresponding single wheel load (DSWL) ×1000kg	ACN 2×DSWL	PCN
5.00	391.7	394.4439	41.5	83.00	83/R/B/W/T
4.50	427	360.6377	42.4	84.70	85/R/B/W/T
4.25	446.2	341.2557	42.7	85.43	85/R/B/W/T
4.00	466.6	322.0099	43.1	86.17	86/R/B/W/T
3.75	489	302.3351	43.4	86.83	87/R/B/W/T
3.50	513.4	282.6278	43.8	87.65	88/R/B/W/T
2.75 (Extrapolated)	573.05	226.8613	44.98	89.97	90/R/B/W/T

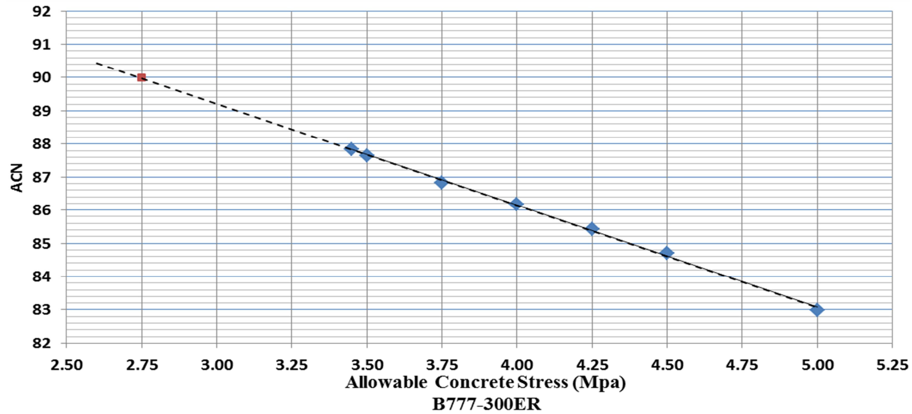


Figure 5. ACNs for allowable concrete stress

The PCN values so obtained by the proposed methodology are higher than the ACNs of the aircraft in the fleet mix (or as a minimum, equivalent to that of the critical aircraft). It would therefore be the airport operator's prerogative to choose the PCN either as evaluated or the maximum ACN in the fleet. The airport operator may take guidance on restricting aircraft traffic as per the design fleet mix. The PCN as published based on the above analysis would also allow for unrestricted passes of aircraft with equal or lower ACNs. This interpretation is based on the fact that the reference thickness for ACN assignment is derived from the charts based on 10,000 coverages (Refer figures 1 & 3) and the charts would also be recalibrated if lower number of coverages were to be considered, leaving the ACNs unchanged. Thereby, even if the coverages of a particular ACN aircraft in the fleet mix were lower than 10,000 coverages, the PCN published would still allow unrestricted passes of the aircraft. The tabulated results below for ACN evaluation of B777-300ER establish the same. The ACNs are computed for 4.5 MPa and correlated for 2.75 MPa as allowable PCC Flexural stress .

Table 11.
ACN value comparison for varying coverages.

B777-300ER						ACN For Allowable Flexural Stress	
P/C ratio	Coverages	Departures	For 4.5 MPa				
			Thick (mm)	HOR Stress (psi)	Single wheel load (T)	4.5 MPa	2.75 MPa
3.86	10000	2591	400	439.8821	44.0569	88	93
	7500	1943	392.2	450.5774	43.8499	88	93
	5000	1295	381.8	466.6439	43.6527	88	93

CONCLUSION

The PCN evaluation and reporting procedure has been detailed in FAA Advisory Circular No 150/5335-5B [4]. The procedure essentially covers estimation of PCN for the design pavement thickness, considering the aircraft traffic in terms of the fleet mix operating from the facility. The actual correlation of the ACN-PCN is based on COMFAA version 3.0. The COMFAA programme derives its pavement thickness estimation from the charts provided in FAA Advisory Circular No 150/5320-6D [1] which are based on the Westergaard's equations for rigid pavements and CBR – ESWL method for flexible pavements given in ICAO, Aerodrome Design Manual Part 3 – Pavements.

With advances in computing technology, new pavement design methodologies have also evolved viz; Mechanistic-Empirical designs based on layered elastic theory for flexible pavements and finite element analysis for rigid pavements. The FAA vide its Advisory Circular No 150/5320-6E has provided the guidelines for use of this methodology for design of aircraft pavements [3]. The design methods being able to model and analyse the pavement structures more accurately, provide for a more efficient pavement thickness design. FAA has provided the FAARFIELD software along with the Advisory Circular. The design thicknesses computed by the FAARFIELD software for both rigid and flexible aircraft pavements are different, from those computed by COMFAA software, though comparable, owing to calibration of the FAARFIELD software. The PCN reporting based on COMFAA is therefore not matched to the design principle and therefore thicknesses computed by FAARFIELD or any other software adopting mechanistic-empirical methods. Although calibrations have been made in FAARFIELD to have a comparable thickness, in essence the design principle and methodology are at variance between the COMFAA and FAARFIELD software. The paper has highlighted the un-intended implications of following different pavement analysis theories for design and evaluation.

The paper presents an alternative approach based on first principles for evaluating and reporting the design PCN value, using the specific methodology utilised in the design software. For the purpose of this paper, FAARFIELD software was used for analysis and reporting of the design PCN value.

The proposed PCN evaluation being aligned with the pavement design principles incorporated in the FAARFIELD software, it computes the PCN based on identification of equivalent single wheel loads that cause the same critical stress and strain in the rigid and flexible pavements structures, respectively and which formed the basis of their designs. Although ACNs as established presently based on the PCA method with 2.75 MPa as the concrete working stress used in determining the reference thickness would remain mostly the same, a re-establishment of ACNs for more commonly used PCC Flexural strength of 4.5 MPa should be considered. The coverages for ACN value establishment can remain as 10,000 as lower number of coverages of a particular aircraft in the design fleet mix is not expected to affect the PCN value to the extent of putting any of the aircraft in the design fleet mix in the overloading category, though the PCN would be reported, based on analysis for actual design traffic.

The proposed methodology which effectively integrates the pavement design and evaluation basis is expected to predict the ACN-PCN values that can be more effectively and realistically be used for control of aircraft operations, thus ensuring that the pavement survives its design life. It is therefore recommended that the industry actively evaluates the proposed methodology for PCN evaluation and reporting, with the goal of adopting this as the new standard.

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