Toward a new ICAO Aircraft Classification Number (ACN) methodology

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ABSTRACT: The ACN/PCN method rests on the concept of a single-wheel load which has been employed as a means to define the landing gear assembly-pavement interaction without specifying pavement thickness as an ACN parameter. For flexible pavements, airplane landing gear flotation requirements are determined by the California Bearing Ratio (CBR) method for each standard subgrade support category. The CBR method uses a Boussinesq solution for stresses-strains and displacements in a homogeneous, isotropic elastic half-space. To standardize the ACN calculation, the ACN-PCN method specifies that ACN values be determined at a frequency of 10,000 coverages. This is done by equating a fictitious pavement thickness, given by a mathematical model for an aircraft gear assembly, to the pavement thickness for a single wheel at a standard tire pressure of 1.25 MPa (181 psi). Since it is generally well known and accepted that CBR method is outdated and no longer in use for pavement design and analysis purpose, this paper proposes a new approach for equating a pavement thickness which would be required by a given aircraft to the pavement thickness required for a standard single wheel-load, by using the Multi Layers Linear Elastic Analysis (ML^2EA) procedure. For this first attempt, the paper does not intend to give full details on the procedure but offers the basis of a new approach with its numerical implementation and further work to be done for method refinement.

KEY WORDS: Pavement rating system, multi-layer linear elastic system, ACN, PCN, design.

INTRODUCTION

The promulgation of a new or improved method/system must provide better performance and significant benefit to the industry in order to replace the current system. The introduction of the Multi-Layer Linear Elastic Analysis (ML^2EA) based method, combined with the emergence of new materials, new pavement construction methods, and improved maintenance techniques, allows airport owners to optimize their pavement life prediction methods (i.e. more precise pavement thickness design procedures). The primary benefit to the airport owner is lower cost, and improved pavement management with the additional ability to safely accommodate today's complex traffic (i.e. heavier airplanes and higher frequency of operations). The introduction of this new model into the ACN methodology would benefit all ICAO member states. By upgrading the ACN-PCN system to the linear elastic analysis techniques, airport owners would make optimal use of their pavement infrastructure and be able to properly manage aircraft operating weights and frequencies. The ability to evaluate a pavement concession based on overload would also be provided.

1 BACKGROUND

1.1 Current ACN-PCN system

The engineering system used for the control of aircraft loadings on airside surfaces is the ICAO ACN-PCN method. The ACN-PCN (ICAO-Annex-14) is a reporting method for weight-bearing capacity introduced for worldwide civil use in the mid-1980. ICAO requires that the strength of pavements for aircraft with mass greater than 12,500 lb (5,700 kg) be made available by using the ACN-PCN method and reporting all of the following information: Pavement Classification Number, pavement type, subgrade strength category, maximum allowable tire pressure category or maximum allowable tire pressure value and evaluation method used.

1.2 New rational approach

Since at least the last two decades, the layered elastic theory has been intensively used worldwide for pavement design and analysis and is the recommended practice by almost all Civil Aviation Authorities. Consequently, two pavement design systems co-exist in the ACN-PCN method, the CBR design procedure for the derived single wheel load (DSWL) determination and ACN publication on one side, and the ML^2EA system used for airfield pavement design on which PCNs are derived on the other side

As stated in the ICAO Aerodrome Design Manual Part.3 Pavements, the ACN-PCN method is not intended for pavement design or analysis. The current concept of DSWL uses the CBR design procedure for standardized conditions (tire pressure of 1.25MPa and 10 000 coverages), whereas current worldwide practices for pavement design are based on the ML^2EA. The ML^2EA is derived from Burmister's layered theory (Burmister 1943). The new proposed approach consists in modifying the procedure used for ACN calculation by introducing the ML^2EA model into the DSWL determination procedure. This would align current pavement design procedure and the ACN calculation methodology. The benefit is twofold. First, it provides consistency between the ACN-PCN method and the latest advanced pavement design procedures, and secondly, it addresses aircraft complex gear geometry and multi-wheel arrangements. Furthermore, the new ML^2EA method also referred as the mechanistic model as compared to the semi-empirical procedure developed by Boyd and Foster in 1952 would eliminate the need to further address alpha-factors for flexible pavement ACNs (introduced to offset the over-estimated damage produced by multi-wheel arrangement in the initial CBR equation). This would no longer be required since the multi-wheel effects are already considered in the ML^2EA system. In addition the current one-leg approach would be replaced by the entire aircraft main landing gear arrangement as the input parameter for the ACN calculation. As an example, the entire A380 Main Landing Gear (MLG) will be considered whereas calculations on A380 Wing Landing Gear (WLG) and Body Landing Gear (BLG) are currently made separately, the aircraft ACNs being the maximum between them

2 SELECTED COMPUTER PROGRAM

For this study, the ALIZE-lcpc software (www.ifsttar.fr), based on the linear elastic methodology has been selected to initiate the implementation of the proposed procedure for ACN calculation. The software has been adapted to cope with the objective, specifically to automatically determine the new DSWL. Other software could also cope with the purpose, but with some mandatory adaptations.

2.1 ALIZE-lcpc overview

ALIZE has been the reference software for roads and motorways pavement design in France for more than thirty years. The French design method is a rational method, based on the computation of the resilient stresses and strains in roadways by the classical multi-layer elastic linear model. The design is carried out by comparing these calculated values in all the layers, to the admissible stresses and/or strains values which are evaluated according to the fatigue characteristics of the materials (bounded materials) or their rutting behavior due to plastic deformation (untreated materials and soils), taking into account the cumulative traffic specified for the pavement. The software has been extended to the design of airfield pavements, leading to a specific version of the ALIZE-lcpc software dedicated to airport structures, namely the ALIZE-Airfield pavement software. This new version of ALIZE software has been developed by the LCPC under a cooperative agreement with the STAC (French civil aviation technical centre).

The structures selected for the study are typical flexible pavement structures composed from subgrade to surface of an untreated subbase layer (UGA), a base asphalt concrete layer (BAC) and the surface asphalt concrete layer (SAC). As per the current procedure for ACN calculation, the subgrade failure mode criterion is retained for all calculation, but the asphalt material fatigue failure mode not. This will require selecting and fixing the BAC and SAC layers when implementing the proposed procedures for ACN calculation.

This mechanistic design method, also referred as “rational design method” involves calculating pavement damage from these critical strains using empirical equations called ‘failure criteria’ or ‘performance relationships’ of the form:

(1) $N = \left[\frac{k}{\varepsilon}\right]^b$ For subgrade and soil failure mode criteria

Where *N* is the predicted life (allowable strain repetitions ε)
k is a material constant.
b is the damage exponent of the material.
ε is the load-induced vertical strain on subgrade top
The empirical parameters *k* and *b* are determined by calibrating the design method against observed performance of test pavements or of pavements in service.

2.2 Cumulative damage factor (CDF) and Wöhler-Miner’s rule hypothesis

The damage produced by one stress application is obtained by rearranging (1)

(2) $\Delta CDF = \frac{1}{N(\varepsilon_{\max})} = \left(\frac{\varepsilon_{max}}{K}\right)^{\beta}$, With β = -1/b

The CDF concept is needed to predict the total damage produced on the pavement for a given material. This treats the level of pavement strain response to aircraft loading as a direct indicator of pavement damage over the complete life of the pavement. The cumulative damage from all of the aircraft contributes to the failure of the pavement according to the strain imposed by the individual aircraft loading. The Damage Factor for the i^{th} loading is defined as the number of repetitions (ni) of a given strain divided by the ‘allowable’ repetitions (Ni) of the strain that would cause failure. The Cumulative Damage Factor is obtained by summing the damage factors over all the loadings in the traffic spectrum using Wöhler-Miner's hypothesis.

The Total Damage Factor (CDF) is defined by:

(3) $CDF = \sum_i n_i \Delta D_i = \sum_i \frac{n_i}{N(\epsilon_{max})} = \sum_i n_i \left(\frac{\varepsilon_{max}}{K}\right)^{\beta}$ Where εmax= εz for granular material

i is summed over the mix traffic. The pavement is presumed to have reached its design life when the cumulative damage reaches 1. If the CDF is less than 1, the pavement has excess capacity and the CDF represents the proportion of pavement life consumed by the design traffic. Conversely, if the CDF exceeds 1 then the pavement is deemed to be unacceptable and must be modified in the next trial so that the deficiency is overcome.

2.3 Continuous integration of Miner-Wöhler law and individual damage computation

The equation (3) is not fully adapted when addressing several complex loadings (e.g. multi-wheel assembly) which produce in the pavement structure complex cumulative strains (multi-peaks loading with incomplete back to zero between them, due to the longitudinal interaction between axles). For such loadings, the equation (3) cannot be applied properly. The use of the continuous Wöhler-Miner'rule as an integral law allows to generalize the formalism accordingly, and to compute the damage growth produced by one stress application.

For a given variable ε the differential expression of the Miner-Wöler equation is:

(4) $\Delta D(y, z_k) = \frac{\beta}{K^{\beta}} \int_{-\infty}^{+\infty} \varepsilon(x, y, z_k) >^{\beta-1} < \frac{d\varepsilon}{dx}(x, y, z_k) > dx,$

Where k is the number of the evaluated peak for each profile. ε (x,y,z_k) is the longitudinal profile of the variable ε, computed along the straight line (y,z_k) and <F> the positive part of the equation F. This integral, is analytically calculated for each profile (y,z_k) by identifying the max. (ε_{peak} (y,z_k)) and min ($\varepsilon_{troughs}$ (y,z_k)) of the function . Indeed, it can be shown that the previous integral can be written with the following expression:

(5) $\Delta D(y, z_k) = \frac{1}{K^{\beta}} \left[\sum_{peak-first}^{peak-last} \epsilon_{peak}^{\beta}(y, z_k) - \sum_{trough-first}^{trough-last} \epsilon_{peak}^{\beta}(y, z_k)\right]$

Note, the multi-peaks loading effect handled though the Miner's continuous integral presented above, is also considered by the CBR design method, by mean of the Pass-to-Coverage ratio (longitudinal gear factor), according to a completely different computation (details are available in the FAA-*Advisory Circular N° 150/5335-5B)*

As an example, figure 1 shows the damaging contribution of a signal composed of successive peaks and troughs produced by one pass of a 6-wheel bogie (A380 Body landing gear). Note a bogie is a multi-wheel assembly with a number of wheels equal to or greater than four.

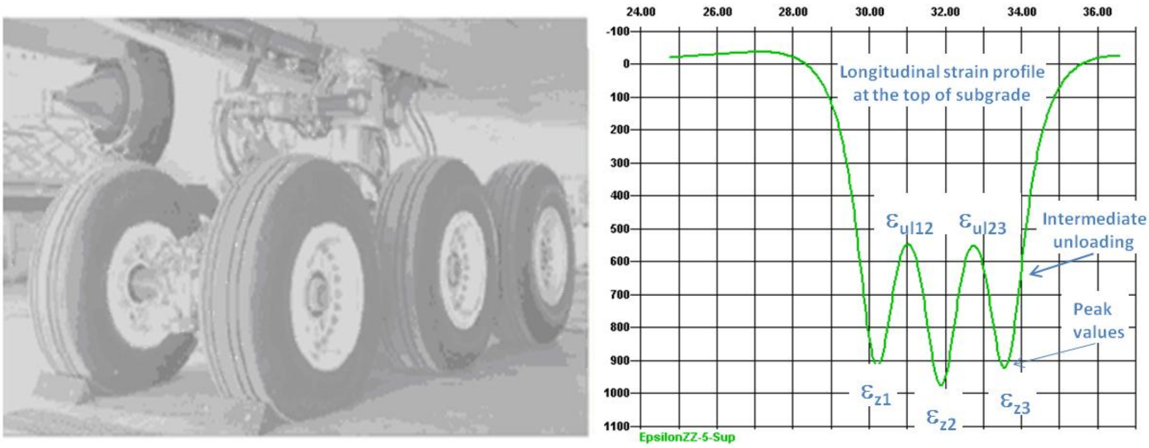

Figure 1: Vertical strain on top of subgrade of a 6-wheel bogie configuration

The below formula gives the longitudinal damage contribution for one stress application of the 6-wheel bogie loading

$$\Delta D_{tridem} = \frac{1}{K^{\beta}} \left(\varepsilon_{z1}^{\beta} - \varepsilon_{ul12}^{\beta} + \varepsilon_{z2}^{\beta} - \varepsilon_{ul23}^{\beta} + \varepsilon_{z3}^{\beta}\right)$$

This calculation allows, for each aircraft and for each vertical plan zk, to build the elementary transversal damaging profile which is described by all values ΔD(yj, zk) with 1< j<total number of longitudinal profile.

3 PROCEDURE IMPLEMENTATION

3.1 Definition

The basis of the procedure remains identical to the current applied method, namely: equating the required pavement thickness (according to the subgrade failure mode criteria) for an aircraft landing gear to the pavement thickness of a single wheel load at standard tire pressure inflation of 1.5MPa (more representative of the current aircraft fleet). This procedure allows the determination of the DSWL without further reference to thickness. Equating the required thickness between DSWL and the actual aircraft implies the same stress is applied to the pavement, as prescribed in the ICAO Aerodrome Design Manual part.3, §1.1.3.2.d. The procedure involves the determination of a number of passes for which the required pavement thickness is computed and the standard tire pressure of the DSWL.

3.2 Impact on PCNs

The FAA Advisory Circular AC 150/5335-5B dated 26th August-2011 provides a guidance for using the standardized International Civil Aviation Organization (ICAO) method known as the ACN/PCN method to report airport runway, taxiway, and apron pavement strength. The procedure is based on the aircraft ACNs composing the past, current and forecasted traffic of the pavement under consideration (for the desired pavement design life). Therefore, both items (new ACN calculation procedure and PCN determination/publication) should be brought together in order to address the consequences which would occur for an already established PCN and any change in the ACN. In the case of an ACN change, the airport owner / authority will have to decide either whether to determine a new PCN according to the new ACN's, or to wait for the next major pavement rehabilitation for publishing a new PCN value.

If the new ACN's derived from the proposed procedure provide similar results as compared to the current procedure, what is the relevance of developing an entirely new method, except for the sake of engineering precision?
If, on the contrary, the new ACN's are significantly different from those currently obtained, then common sense would suggest republishing all PCN's, which would be determined from the ACN's of aircraft included in the reference traffic. If not done, the new ACN's could result in the refusal or acceptance of a large number of aircraft, thereby either putting the pavement at risk or leading to underutilization of the pavement. An interim solution could be the determination of a weighting coefficient, applied to the newly obtained DSWL in order to cope with "already published" PCN's.

3.3 Inputs parameters

3.3.1 Tested aircraft

The computation has been done for aircraft representative of the main (short-medium-long range) aircraft family from the single-aisle aircraft (short/medium range, A320, 737) to the heavy aircraft such as the A380 (Table-1). It must be however highlighted that any new ACN procedure would remain valid for all aircraft with a Maximum Taxi (Ramp) Weight (MTW) greater than 5700 kg.

Table-1: List of tested Aircraft

Aircraft	**MTW (t)**
A320-100 (Single-aisle)	68.4
737-400 (Single-aisle)	68.3
A321-100 (Single-aisle)	85,4
737-900 (Single-aisle)	79.2
A330-200 (Long-range)	233.9
767-400ER (Long-range)	204.6
777-300ER (Long-range)	352.4
A380-800 (New-Large Aircraft)	562
A380 Body Landing Gear (BLG)	348.5
A380 Wing Landing Gear (WLG)	241.7
787-9 (New generation)	251.8
A350-900 (New generation)	268.9

3.3.2 Pavement structures

For this first attempt, three sets of surface asphalt concrete (SAC) and base asphalt concrete (BAC) thicknesses are selected and the four subgrade strength categories retained in the current ACN procedure, namely CBR3 (ultra-low), 6 (low), 10 (medium) and 15 (high); only the thickness of the untreated graded aggregate (UGA) subbase layer is adjusted by iterative computation to arrive at a CDF of 1 considering the subgrade failure mode criteria (12 cases are then assessed per aircraft). The Young-modulus E has been chosen to cope with the one used in the US software FAARFIELD for P-401/P-403 material (which would roughly correspond to the French equivalent material at a temperature of 30°C and frequency 10Hz). Figure 2 illustrates the three selected structures used for the numerical implementation

Poisson's ratio is 0.35 for all material. All layers are assumed always fully bonded. The pavement design life is 10 years, with a total number of passes of 36500 over the period (i.e.10 aircraft passes per day over the design period).
Subgrade modulus values for flexible pavement design can be determined in numerous ways. The procedure applicable for this purpose is to use the above mentioned CBR values and substitute in the relationship: E = 10 x CBR (E in MPa) ~ 1500 x CBR (E in PSI). Ultimately, the new method will only consider a range of representatives' subgrade modulus as an entry parameter which will substitute the current CBR.
This method provides designs compatible with the earlier flexible design procedure based on subgrade CBR. The damage exponent of the soil is set at b= 4.505, the material constant is k=16 000
The subbase material (UGA) E-modulus depends on the subgrade characteristics and the subbase layer is subdivided into sub-layers never exceeding 25cm.
The sub-layers moduli are determined with the following procedure (procedure details are provided in the French technical guidance titled: "*Méthode rationnelle de dimensionnement des chausses aéronautiques souples*":

UGA, Emax=600MPa, Poisson's ratio=0.35

$$E_i = \min(3 \times E_{i-1}, E_{max})\ , Last\ UGA\ thickness\ = t(UGA) - (i-1) \times 0.25$$

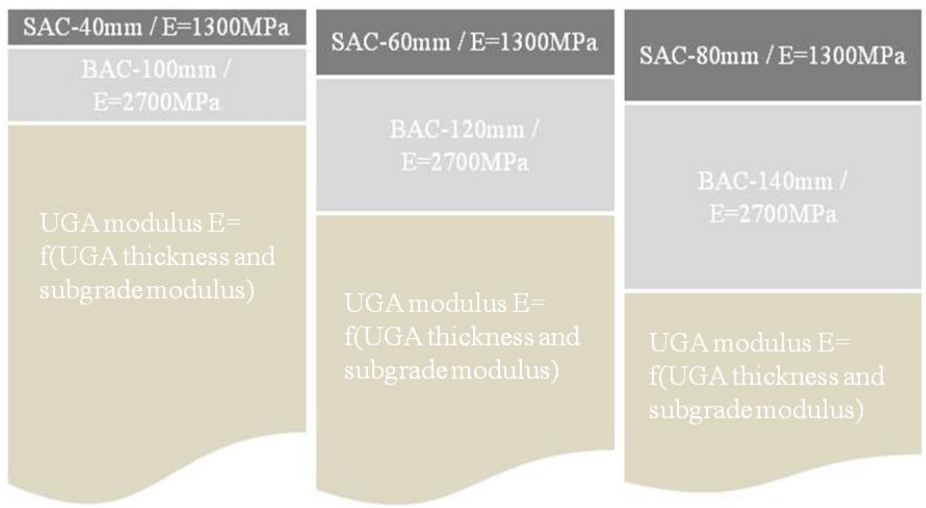

Figure 2: Tested flexible pavement structures

3.4 Numerical results

This Figure 3, 4, 5 and 6 show the current and new ACNs of the listed aircraft derived from the various tested parameters i.e. the thickness of bituminous material (SAC and BAC), the subgrade strength, and the subgrade failure mode criteria. Note, the current ACNs are those computed and published by the aircraft manufacturer according to the ICAO computer programs provided in the ICAO-Aerodrome Design Manual Part.3-Pavements-second edition 1983 (Doc 9157-AN/901-Part 3)

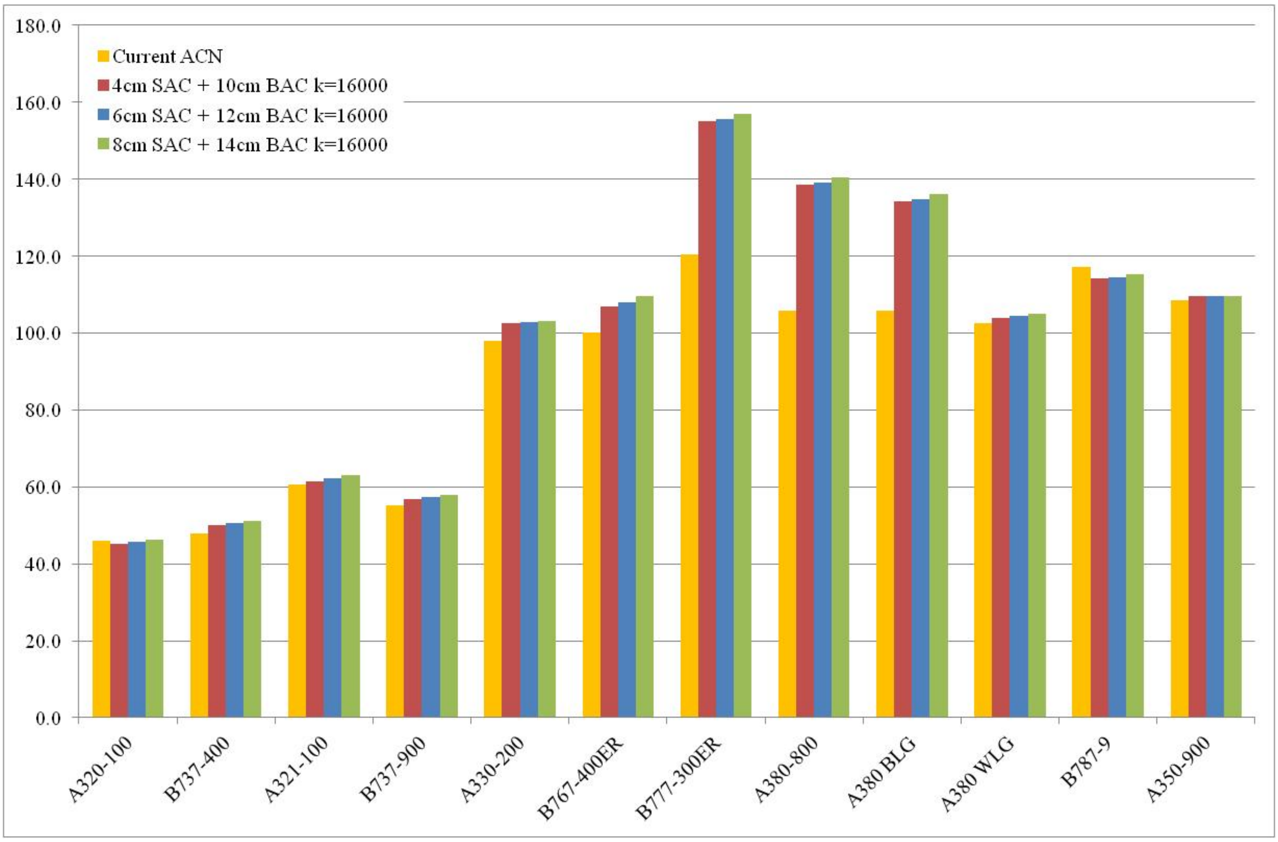

Figure 3: New ACNs for CBR 3 (E=30 MPa)

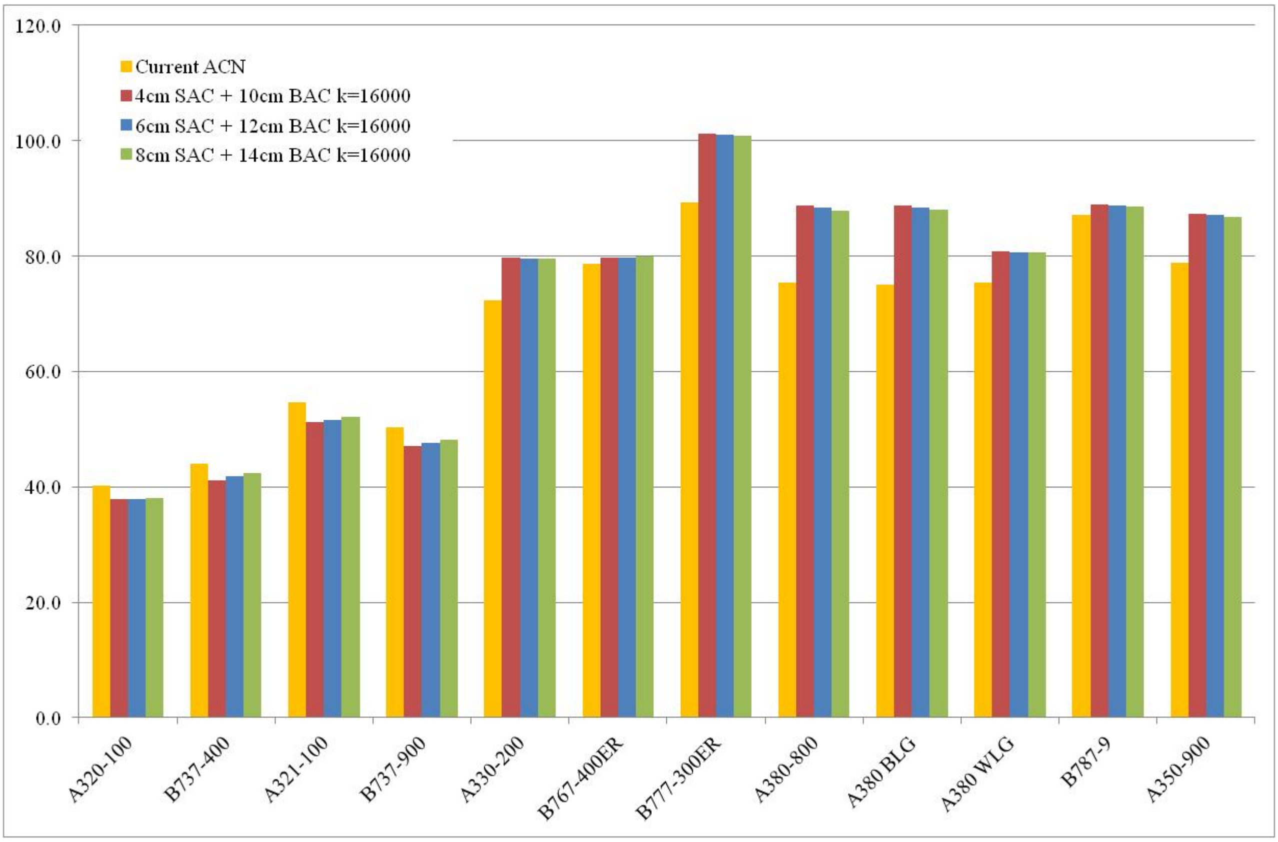

Figure 4: New ACNs for CBR 6 (E = 60 MPa)

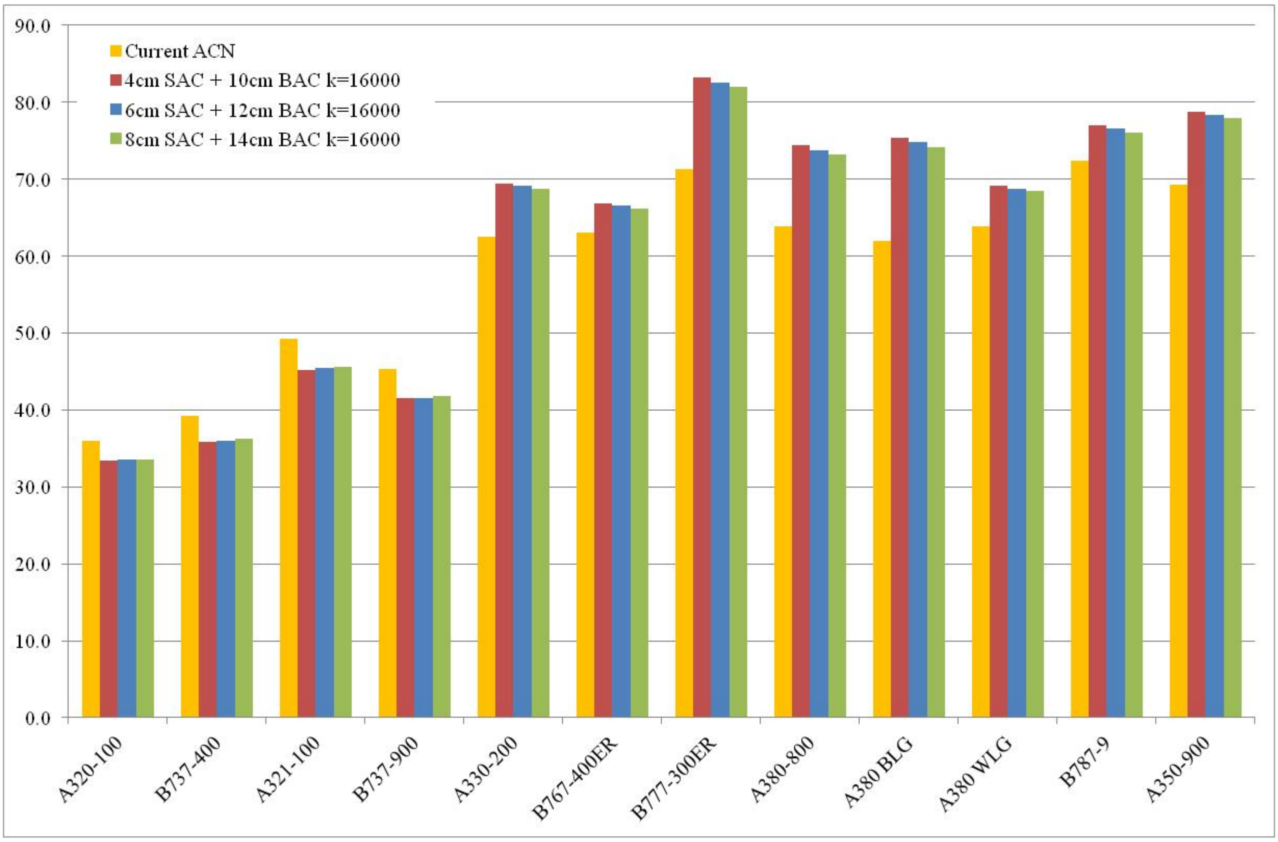

Figure 5: New ACNs for CBR 10 (E = 100 MPa)

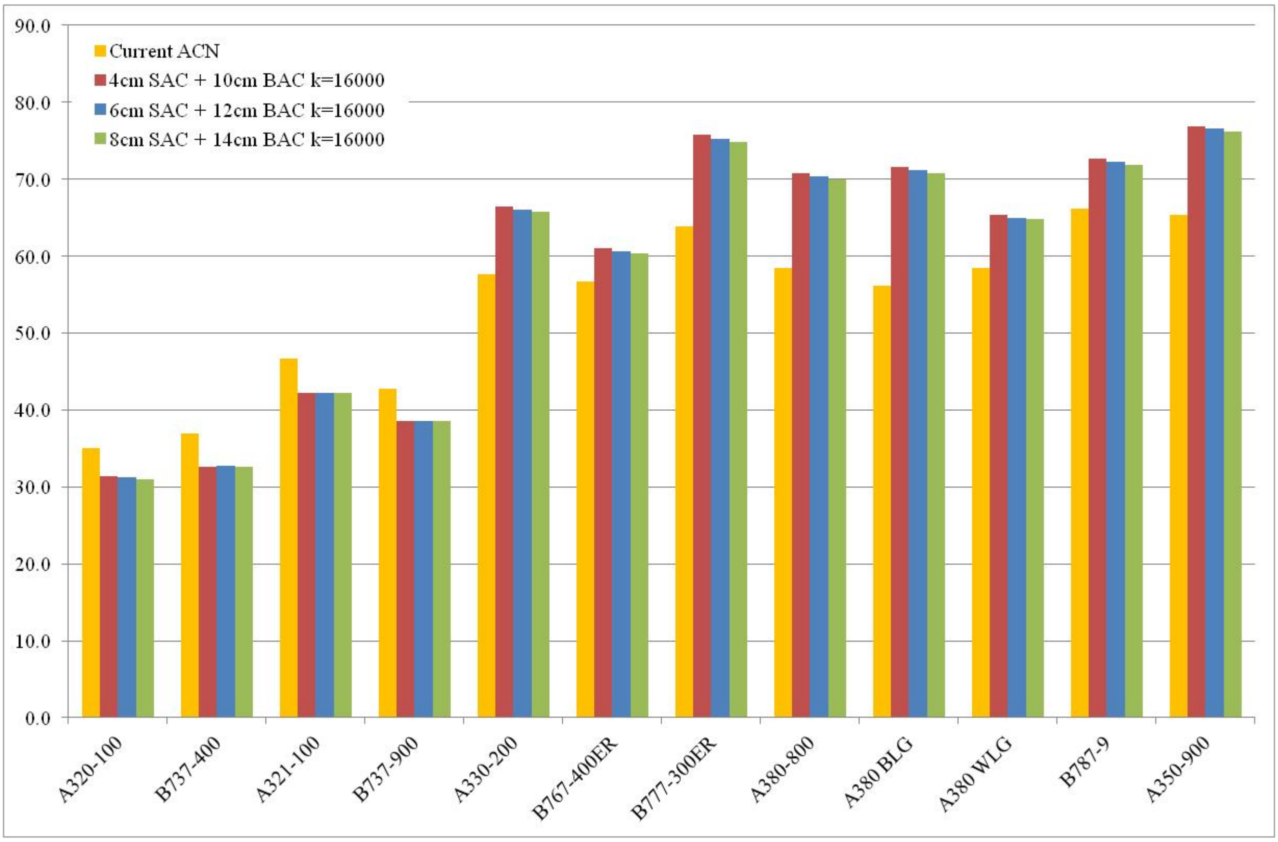

Figure 6: New ACNs for CBR 15 (E = 150 MPa)

3.5 Interpretation

It can be observed first that the different set of surface and base layers give very similar results regardless of the aircraft and the subgrade strength. This is due to the variations of asphalt concrete layers which are compensated by the UGA layer, giving similar equivalent pavement thicknesses and DSWLs when computations are based on the subgrade failure mode criteria.
The values observed on single aisle (SA) aircraft (equipped with dual-wheels on MLGs, i.e. A320 and 737 aircraft families) would suggest that the current CBR procedure over-estimates DSWLs (thus ACNs) for high subgrade strength and is either appropriate or under-estimates DSWLs for low subgrade strengths. Conversely, this trend is inverted for long-range aircraft (equipped with 4-wheel bogies on MLG) on high subgrade strength (values on low subgrade strength are close to the one derived from the current CBR procedure). The ACNs of aircraft equipped with a 6-wheel bogie on MLG (777-300ER, A380-800BLG) are significantly higher with the new proposed procedure for both high and low subgrade strength. This discrepancy between proposed and current method is, without any doubt the result of an exaggerated 6-wheel alpha-factor decrease in 2007, when ICAO decided to revise all alpha-factors for landing gear equipped with 4-wheel or more. The interaction between landing gears are illustrated with the A380 MLG compared to its wing or body gears treated independently. The comparisons between the 787-9 and the A350-900 illustrate pretty well the combined effect of individual wheel-loads, which prevails on high subgrade strength and the gear geometry effect, which prevails on low subgrade strength.

4 CONCLUSIONS AND FUTURE WORKS

It must be noted first that the ACN values obtained by using the ML²EA system, are different from the current DSWL (and ACNs) and that, the change behaves differently following the considered aircraft family and the subgrade strength. These differences between the current and the proposed method militate in favour of the use of the rational approach. Indeed, the ML²EA system addresses more accurately all aircraft parameters which have a direct influence on the pavement thickness adjustment calculation, namely, the gear geometry and general arrangement, the individual wheel-load, the tire pressure and also the lateral wandering.

This first attempt which has been presented to the 7th ICAO Pavement Subgroup meeting in Sept.2012 gave encouraging results but will need to be further investigated by considering a lateral wandering on either both the tested aircraft and the DSWL or only on the tested aircraft, the horizontal strain failure criteria at the bottom of the base layer. Last focus will have to be done on various comparison with other computer programs, ML²EA based (e.g. FAARFIELD from the US-FAA or other programs). Other material damage laws (mainly for soils/subgrades) could be included in the study to evaluate their impact on the obtained ACNs.

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