technology platform for transport, infrastructure and public space

The PCN Runway Strenght Rating and Load Control System

State-of-the-art study 2003/2004

CROW-report 04-09

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Acronyms and Abbreviations

AC	Advisory Circular
ACN	Aircraft Classification Number
ACNsg	Aircraft Classification Number study group of ICAO
APPOC	Airfield Pavement Points Of Contact
APSDS	Airport Pavement Structural Design System
ASWG	Airfield Services Working Group of NATO
CAA	Civil Aviation Authority
CBR	California Bearing Ratio
CROW	Information and Technology Center for Transport and Knowledge
cm	Centimeter
DCP	Dynamic Cone Penetrometer
DSWL	Derives Single Wheel Load
ESWL	Equivalent Single Wheel Load
FAA	Federal Aviation Administration
FWD	Falling Weight Deflectometer
GPR	Ground-Penetrating radar
ICAO	International Civil Aviation Organization
in	Inch
k	Modulus of Subgrade Reaction
kg	Kilogram
kp	Kilopound
lb	Pound
LEA	Linear Elastic Analysis
LEDFAA	Layered Elastic Design - FAA
MN/m^3	Mega Newton per Cubic Meter
MTOW	Maximum Take-off weight
MPa	Mega Pascal
MWHGL	Multi Wheel Heavy Gear Load
NATO	North Atlantic Treaty Organization
NAPTF	The National Airport Pavement Test Facility
NGA	Next Generation Aircraft
OEW	Operating Empty Weight
PAVERS	Pavement Evaluation and Reporting Strength
PCA	Portland Cement Association
PCASE	Pavement-Transportation Computer Assisted Structural Engineering
PCN	Pavement Classification Number
pci	Pounds per Cubic Inch
psi	Pounds per Square Inch
STANAG	Standard NATO Agreement

Summary

United Nations member states are required to evaluate and publish the strength of airport pavements using ICAOs ACN-PCN system. The method concentrates on classifying the relative damage of aircraft. ICAO foresees that each pavement authority will define a Pavement Classification Number (PCN) by whatever means is considered suitable to indicate the support level of a particular pavement such that all aircraft with a published ACN equal to or less than the reported PCN can use that pavement safely, without load bearing failure or undue damage to the structure.

The system does not dictate a specific design method for PCN assignment. For states or individual civilian airport authorities, technical PCN values are often determined as an extension of existing national pavement design and evaluation technologies. As a consequence, technical PCNs can vary depending on the evaluation method used. However, ICAO does relate PCN to the pavement life and the annual volume of traffic, implying a pavement to have a variable PCN as a function of the desired structural pavement life. Therefore the PCN functions a managerial pavement tool, its selection not only dependant on the technical value, but is largely dependant on the business decision. This does not a license an airport to assign any desired PCN to a pavement. ICAO does give guidance on how to access a pavement PCN and there must be a relation between assigned PCN, the traffic mix that uses the pavement, and structural pavement life. Should a higher PCN be assigned to a pavement, the structural life will be shortened as a consequence.
For NATO purposes, the ACN-PCN system is used to compare bases, manage pavements and plan missions. The PCN is assigned based on a number of passes of a critical aircraft, which can vary per NATO nation. As NATO nations provide additional information to the PCN code with respect to the evaluation aircraft and number of passes used, a common denominator is found in the U.S. PCN evaluation method. NATO nations consider this a transient method while progressing to Layered Elastic Analysis

As pavement design and evaluation technology evolves using Layered Elastic Analysis and calibrated failure criteria derived from material testing and full-scale pavement tests become available, pavement prediction performance, design and technical PCN improve. Nevertheless it should be borne in mind that, although layered elastic based procedures exist, a considerable amount of engineering judgment is still required. In order to harmonize and arrive at reproducible and realistic PCNs, an uniform set of pavement transfer functions (performance models) and material characterization (properties) are required. Since these are highly dependant on the local materials used, this must be addressed on a national level.

As a consequence to the fact that ICAO does not prescribe or dictate a specific method for the PCN assignment, the derived PCN calculation result is likely to vary to a great extend. As a continuation of this study, harmonization of the degrees of freedom in the analytical methods to be used is thought necessary. Harmonization is needed for standardization of the pavement models, the calculation steps, the assessment or selection of material characteristics (transfer functions), the structural pavement life, the design criterion in relation to the true pavement damage, reliability concept as well as traffic and wander. Since sophisticated design tools already exist, it is recommended to concentrate on harmonization rather than further developing software which is already available in the public domain or as propriety software. This guidance can be used in the Netherlands by airport pavement engineers or regulatory be prescribed by national Civil Aviation Authorities to arrive at realistic pavement designs and comparable PCNs.

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Samenvatting

ICAO, onderdeel van de Verenigde Naties, heeft de lidstaten en –organisaties opgedragen de draagkracht van vliegveldverhardingen te evalueren en publiceren op basis van het ACN-PCN classificatiesysteem. De methodiek spitst zich toe op het classificeren van vliegtuigbelastingen op een relatieve schaal.

De methode voor de vaststelling van de PCN mag door de vliegveldbeheerder worden bepaald. Het systeem dicteert geen specifieke methode. Vaak wordt de nationaal gebruikelijke verhardingsontwerp- en evaluatiemethode toegepast om een technische PCN te berekenen. Dit houdt in dat de technische PCN kan afhangen van de toegepaste rekenmethode. Echter, ICAO geeft wel een aantal randvoorwaarden voor de rekentechnische bepaling van de PCN. Zo moet er een relatie zijn tussen PCN, het vliegverkeer dat van de verharding gebruik maakt en de structurele levensduur van de verharding. Met andere woorden: de PCN kan afhankelijk zijn van de gewenste onderhoudslevensduur. Toewijzen van een hogere PCN dan de technische betekent in de praktijk een kortere levensduur en omgekeerd.
NATO hanteert de ACN-PCN methode om de draagkracht van de verschillende vliegvelden te vergelijken, de verhardingen te beheren en om missies te coördineren. De PCN wordt per land op een verschillende wijze bepaald. Bijvoorbeeld op basis van een aantal toelaatbare lastherhalingen van een bepaald vliegtuig. Om toch een intern vergelijkbaar getal te krijgen, verstrekken de NATO lidstaten naast de PCN code, ook het evaluatievliegtuig en het aantal lastherhalingen waarop de PCN is gebaseerd. Met de Amerikaanse PCN-methodiek kunnen de NATO-PCNs dan worden vergeleken. Dit is een tijdelijke aanpak. Verwacht wordt dat NATO over zal stappen naar een lineair elastische aanpak.

Nu de rekentechnieken mede op basis van de verbeterde gedragsmodellen afkomstig van proefvakken op praktijkschaal steeds beter worden, en daarmee de voorspellingskracht toeneemt, kan een PCN ook nauwkeuriger worden bepaald. Niettemin moet worden gerealiseerd, dat bij het ontwerpen en evalueren van verhardingen een beroep wordt gedaan op de vaardigheid van de verhardingsontwerper. Om beter vergelijkbare en realistische PCNs te krijgen is het nodig om de materiaaleigenschappen en het gedrag onder herhaalde belasting te harmoniseren. Dit is in hoge mate afhankelijk van de beschikbare materialen en onderzoeksmethoden en moet daarom per land worden bepaald.

Inherent aan het gegeven, dat ICAO enkel randvoorwaarden geeft en geen specifieke PCN-methode voorschrijft, kunnen PCN-berekeningen verschillende rekenresultaten opleveren. Als vervolgfase van de voorliggende studie wordt voorgesteld om te komen tot harmonisatie van vrijheidsgraden in de PCN-berekening zoals de te gebruiken rekenmethoden, rekenstappen, randvoorwaarden, standaardisatie van invoer en materiaal- en vermoeiingseigenschappen alsmede het verkeer (laterale spreiding ed.) en de levensduur van de verharding in relatie tot de PCN en de ontstane schade. Harmonisatie van de berekeningswijze wordt belangrijker geacht dan het verder ontwikkelen van in de markt beschikbare software. De voorgenoemde uitgangspunten kunnen behalve voor de vaststelling van de technische PCN, ook voor het ontwerpen van vliegveldverhardingen worden gebruikt. Ook kan deze set van ontwerprandvoorwaarden door de nationale luchtvaartautoriteit als de Inspectie Verkeer en Waterstaat, Cluster Criteria Luchthavens, Unit Infrastructuur worden voorschreven bij een verhardingsontwerp en als voorwaarde voor de bepaling van een PCN in Nederland.

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1 Introduction

The Aircraft Classification Number / Pavement Classification Number (ACN/PCN) system has been adopted by ICAO as the standard for the international reporting of airfield pavement bearing strengths. The ACN, a relative number expressing the relative damage caused by an aircraft can be calculated using a prescribed ICAO method. By contrast with ACN, PCN assignment is not fixed by a prescribed technical method. The method of PCN evaluation is left up to the airport.

At the instigation of CROW's Coordinating Committee on Airfield pavements, a study into PCN assignment has been undertaken. The objective of the study is twofold. First to clarify on ICAO's ACN/PCN reporting system for civil airports, and present the status on ACN/PCN. The second objective is to investigate PCN assessment methods currently utilized by member states. The investigation must lead to a number of recommendations which can ultimately result in a standard method for PCN assessment for usage within the Netherlands and/or NATO practice.

As NATO is also moving towards the ACN/PCN methodology, a questionnaire has been prepared to gain insight in the methods used in the PCN assessment on military airfields. This questionnaire has been prepared by the NATO Airfield Pavement Working Group in conjunction with CROW. Based on a study on current methods and the results of the questionnaire, recommendations for the assessment of a PCN can be made.

It must be noted that full-scale research projects are being undertaken in the United State and France which may contribute to the development of an alternate ACN-PCN procedure based on advanced design procedures. As the results of the research projects a/o. new pavement design and PCN assignment software, will not become available before 2006, the results of the study undertaken by CROW can form the basis for a guideline for a standard on PCN assessment. The guidance can also be used by NATO nations or regulatory be prescribed by a nations Civil Aviation Authority to arrive at realistic and comparable PCNs.

The Information and Technology Centre for Transport and Infrastructure CROW contracted KOAC•NPC Dutch Road Research Laboratories to conduct a state-of-the-art study as of 2003/2004 about The PCN Runway Strength Rating and Load Control System.

2 The ACN-PCN Method

2.1 Introduction

The ACN-PCN system of rating airport pavements is designated by the International Civil Aviation Organization (ICAO) as the only approved method for reporting strength. The ACN-PCN method came into use in 1981. Although there is a great amount of material published on how to compute an ACN (Ref. 1 and 2), ICAO has not specified regulatory guidance as how an airport authority is to arrive at a PCN, but has left it up to the authority as to how to perform this task. This is a result of member states reluctance to agree on an international standardized method of pavement evaluation, but rather to rely on their own internally developed procedures. Acceptance of the ACN-PCN method itself resulted only from the omission of a uniform evaluation standard in that many states felt that their method was superior, and a change to another method would be costly in terms of study, research, development, field training, staff familiarity, and all other attendant concerns. As a consequence, there is a great amount of uncertainty among ICAO states that do not have well established evaluation methodology as to exactly how to arrive at a PCN and still be within the boundaries of whatever ICAO guidelines might exist. Additionally, without published ICAO standard recommendations on this subject, the determination of PCN has most certainly been anywhere from inconsistent to erroneous. The purpose of this chapter is to explain the rating process and its principles.

2.2 The ACN-PCN method

The engineering system used for the control of aircraft loadings on airside surfaces is the ACN-PCN method. The International Civil Aviation Organization (ICAO) (DOC 9157-AN/901 and Amendment number 35 to Annex 14, Ref. 1) devised the ACN/PCN method as an effective, simple, and readily comprehensible means for reporting aircraft weight-bearing capacity of airfields. The ACN-PCN is a reporting method for weight-bearing capacity introduced for world wide civil use in the mid-1980's. ICAO requires that the strength of pavements for aircraft with mass greater than 12,500 lb (5,700 kg) be made available using ACN-PCN method by reporting all of the following information (Ref. 1):

- Pavement Classification Number
- Pavement type
- Subgrade strength category
- Maximum allowable tire pressure category or maximum allowable tire pressure value
- Evaluation method

The ACN-PCN system is simple to use. Each aircraft is assigned a number that expresses the structural effect on a pavement for a specified pavement type and a standard subgrade category. Each airport operating authority reports site pavement strengths using the same numbering system. The pavement is capable of accommodating unrestricted operations provided the aircraft load number is less than or equal to the pavement strength number. Maximum tire pressure limitations may also be applied to some pavements which may further restrict certain aircraft operations. The ACN is based on the static application on aircraft loads to the pavement surface making them somewhat conservative in nature. Member States to ICAO are required to evaluate and publish the strength of airport systems using the ACN/PCN system. The national CAA publishes weight bearing limits in terms of ACN/PCN in a Flight Information Publication for civil and international use. The intent is to provide planning information for individual flights or multi-flight missions which avoid either overloading of pavement facilities or refused landing permission. The ACN and PCN are defined as follows:

1. ACN is a number that expresses the relative structural effect of an aircraft on different pavement types for specified standard subgrade strengths in terms of a standard single-wheel load.

2. PCN is a number that expresses the relative load-carrying capacity of a pavement in terms of a standard single-wheel load.

3. The system is structured so that a pavement with a particular PCN value can support, without weight restrictions, an aircraft that has an ACN value equal to or less than the pavement's PCN value.

4. ACN values will normally be provided by the aircraft manufacturers. The ACN has been developed for two types of pavements, flexible and rigid, and for four levels of subgrade strength.

5. The PCN value is for reporting pavement strength only. The PCN value expresses the results of pavement evaluation in relative terms and cannot be used for pavement design or as a substitute for evaluation.

2.3 Aircraft Classification Number

Under the ACN-PCN system, each aircraft has assigned an ACN that indicates design thickness requirements for the aircraft on a more expanded scale that ranges from an ACN of 5 for light aircraft to an ACN of 130 or more for heavy aircraft. ACN values are published for both flexible and rigid pavements and at four (4) subgrade categories that span the range of subgrade and bearing support values normally encountered. The ranges of subgrade strength covered by these categories are shown in Table 1.

Subgrade Category	Pavement Type	Characteristic Subgrade Strength	Range of Subgrade Strengths
A - High	Rigid	150 $MN/m^2/m$	All k values above 120 $MN/m^2/m$
	Flexible	CBR 15%	All CBR values above 13%
B - Medium	Rigid	80 $MN/m^2/m$	60 to 120 $MN/m^2/m$
	Flexible	CBR 10%	CBR 8% to CBR 13%
C - Low	Rigid	40 $MN/m^2/m$	25 to 60 $MN/m^2/m$
	Flexible	CBR 6%	CBR 4% to CBR 8%
D - Ultra Low	Rigid	20 $MN/m^2/m$	All k values below 25 $MN/m^2/m$
	Flexible	CBR 3%	All CBR values below 4%

Table 1 Ranges of standard subgrade strength

The ACN-PCN system is not intended for the design nor for the evaluation of pavements, nor does it dictate the use of a specific method for the design or evaluation of pavements. To archieve this, the system shifts emphasis from the evaluation of the pavement to *the evaluation of aircraft loads*. The concept of a single-wheel load has been employed as a means to define the landing gear assembly-pavement interaction without specifying pavement thickness as an ACN parameter. This is done by equation 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).

ACNs *must* be calculated using *a prescribed technical method*, which is clearly defined. An aircraft's ACN is calculated from its weight, its wheel layout, its tire pressure, and to the ICAO strength category. ACN's are calculated according to the computer listings given in Annex 14 of the International Civil Aviation Organization (ICAO) Airport Pavement Design Manual. The ICAO ACN pavement computer programs of two different previously existing programs. For flexible pavements, the S-77-1 method (Ref. 4) is utilized in which traffic terms of passes is replaced by a constant standard coverage's value. Likewise, rigid pavement ACN is computed by a subset of the PCA pavement computer program(Ref. 5), except the variable term of working stress is replaced by a constant standard value. To obtain a classification number for a multi-wheel undercarriage an ESWL has to be calculated and to do this, a pavement thickness must be defined. The ACN-PCN method defines the thickness, known within the method as "Reference thickness" by designing a realistic pavement on a given subgrade. The reference thickness is obtained by using specific design methods for flexible and rigid pavements.

For flexible pavements use is made of the extended CBR design method for airfields as developed by the United States Army Engineer Waterways Experiment Station (Ref. 4). For multiple wheel gears, the equivalent single wheel load is determined by using theoretical Boussinesq deflection factors. Using these factors the total vertical deflection at the top of the subgrade as caused by the entire landing gear is assessed. A load repetition factor is used to account for number of wheels in the ACN calculation and level of traffic. The CBR equation considers all loads as an equivalent single wheel load (ESWL) and, the pavement life and the number of applied wheel loads are considered by the alpha factor. In order to calculate the fictitious pavement thickness, known within the method as reference thickness, the number of coverage's is set at 10,000. The ACN by definition is two times the equivalent load in 1,000 kg units of a single tire ('Derived Single Wheel Load, DSWL), that would require the same pavement thickness as required for the aircraft. The standard procedure is capable of evaluating aircraft with up to 32 wheels.

For rigid pavements the reference thickness is the thickness of the concrete slab which will give a maximum flexural 'working' stress of 2.75 MPa (398 psi) when loaded at it center by one main wheel gear of the aircraft. The stresses in the rigid pavement are calculated using Westergaards formula for a slab on a Winkler (dense liquid) foundation. The actual method is the Picket and Ray solution as embodied in the PCA computer program PDILD (Ref. 5).

ACNs of today's civil aircraft may be found in a number of different sources. One of the most comprehensive and up-to-date is the Airport Directory Section of Jepessen flight books (Ref. 3). Another extensive source is found in the ICAO publication, Part 3, Pavements (Ref. 2).

However, this source is not as current as is Jepessen publication. A third source is the Airplane Characteristics for Airport Planning Manuals, as published by the major aircraft manufacturers. This data is generally the most current, and it is normally presented in graphical form (Refs. 6 and 7). These graphs give the ACN between MTOW and OEW for four (4) standard subgrade strengths and the two (2) pavement types. ACNs of military aircraft can be found in Refs. 8, 9 and 10. However, the military ACN data for civil aircraft is not always consistent with those published by ICAO. Alternatively, ACNs values for aircraft can be calculated using computer software available on the internet (Ref. 11).

2.4 Pavement Classification Number

The PCN number indicates the suitability of a pavement area for unrestricted operations by any aircraft that has an ACN *and* tire pressure not exceeding the limits reported in PCN format of stated pavement type and subgrade strength category. The method of PCN pavement evaluation is left up to the airport, under the approval of the regulating CAA. Some guidance to the selection of an appropriate PCN is provided in Chapter 3, 'Evaluation of pavements' of the Aerodrome design manual (Ref. 2). Although ICAO does not give specified regulatory guidance on how to determine a PCN, it states that the PCN must represent a relation between allowable load i.e. the ACN of the critical i.e. most damaging aircraft and the structural pavement life.

In the most fundamental terms, the determination of a rating in terms of PCN is a process of deciding on the maximum allowable gross weight of a selected critical airplane for a pavement knowing its ACN at that weight, reporting it as PCN. This process can be as simple as knowing the operational gross weight of each aircraft that is currently using the pavement and looking up its ACN (referred to as the *Using* aircraft method). This method can be applied with limited knowledge of the existing aircraft and pavement characteristics. The second method is more complex and referred to as *Technical* evaluation. In order to be successfully implemented, the technical evaluation requires an intimate knowledge of the pavement and its traffic, as well as basic understanding of engineering methods that are utilized in pavement design. An overview of different procedures is presented in Chapter 4.

The ICAO PCN pavement strength reporting system involves publishing a five (5) part strength code in the form of 51 FDWT for flexible pavements or 62 RBWT for rigid concrete pavements. Briefly, the first number is the reported PCN value on a scale of 1 to about 130, with 1 representing a weak pavement and 130 a very strong pavement. The second part of the code is either an "F" for flexible pavement systems or "R" for rigid pavement systems. The third part is a letter code A, B, C, or D indicating the subgrade/bearing strength, with A representing a high supporting strength and D a very low strength. The fourth part indicates the tire pressure limitation in MPa if applicable (0.5 MPa in the example above) - "W" indicates that no tire pressure restriction is in effect. The fifth and final part of the PCN code indicates the evaluation method used to determine the pavement strength - "T" if derived from an engineering study or "U" if based on satisfactory aircraft usage.

PCN	Pavement Type	Subgrade category	Tire pressure	Evaluation method
	R – Rigid F – Flexible	A – High B – Medium C – Low D – Ultra Low	W – No Limit X – to 1,5 MPa (217 psi) Y – to 1,0 MPa (145 psi) X – to 0,5 MPa (73 psi)	T – Technical U - Using Aircraft

Table 2 PCN reporting format

If the pavement is of composite construction, the rating should be the type that most accurately reflects the structural behavior of the pavements –either rigid or flexible. It is permissible to add a note stating that the pavement is composite, but in application only the rating type ("R" or "F") is utilizes in the assessment of the pavement capability. Pavements having gravel, compacted earth or is unpaved, laterite, coral, etc. surfaces are classified as flexible for reporting, and therefore should be rated with a PCN having a pavement code "F".

If desired, PCNs may be published to an accuracy of 1/10th of a whole number; however as discussed in the introduction of this chapter, the wisdom of relying on absolute pavement ratings even to a whole number can be questionable in that such judgment is required in obtaining a rating due to the many variables involved.

2.5 ICAO overload guidance

Aircraft with an ACN greater than the PCN reported for a pavement may still be allowed to use the pavement subject to the approval of the airport authority. However, the airport authority should fully understand the implications of allowing overload operations in terms of accelerated structural deterioration and the reduction in pavement service life which may occur.
According to clause 18.1 "Overload operations" of ICAO Annex 14, occasional movements by aircraft on flexible pavements with ACN values no more than 10 percent above the reported PCN should not adversely affect the pavement. For rigid pavement types, the ACN should not exceed the reported PCN by 5 percent. Overloads beyond these limits should be based on the results of a detailed engineering study that compares the individual aircraft load to the structural capability of the pavement. When overloads are allowed, the pavement should be inspected regularly by the airport authority to ensure that unacceptable structural damage is not taking place.

2.6 Pavement strength review and update

The bearing strength of a pavement should be reviewed and re-determined when the structural composition and/or properties of the pavement change as a result of new or restorative construction (such as an overlay/reconstruction) or when significant change in the structural condition of the pavement occurs. According *to Canadian practice*, as a minimum the bearing strength of a pavement should be reviewed, re-affirmed or re-determined as appropriate at least once every ten (10) years. As part of the review process, consideration should be given to re-testing the strength of all or selected pavements at the airport. If the review results indicate that pavement strength values have changed, the airport authority should make the appropriate revisions to the PCN codes reported in the AIP manual.

3 Recent and future developments

Since CROWs Coordinating Committee on Airfield pavements considers to play an active role in the development of an national airport pavement design method including the development of software, it is important to have knowledge on the latest developments regarding the ICAO rating system and related developments. This information is mandatory to formulate a strategy in conjunction with the project plan. This chapter discusses some technical flaws and drawbacks of the current ACN-PCN system, the on-going full-scale pavement testing and the development of new FAA pavement design tools, that can lead to a revision of the ACN-PCN system.

3.1 The ACN rating system under discussion

Aircraft designers, airliners and airport authorities feel that the present ACN procedure hampers the design of efficient airplanes, leading to downloading the operational mass and not using the aircraft and pavement to a maximum extend. In the early nineties Boeing stated that future aircraft such as B777 due in mid 1995, have ACNs that are significantly higher than that of critical aircraft such as B747-400 or MD12X. Considerably higher ACNs indicate problems with respect to the compatibility and acceptance since most International Airports have PCNs that equal the ACN of those critical aircraft. Under ICAOs rating system, B777 could therefore only operate with restricted operating masses. This problem especially affects flexible pavements, having a low or an ultra low subgrade strength. This message alerted ICAO and an international ACN study group (ACNsg) was formed in 1992.

The problem with the current flexible ACN analysis is that it seems to overstate the overlapping stress between widely spaced wheels. Little benefit is given for the extra wheels of heavy modern landing gear designs. In the opinion of the members of the ACNsg, the present ACN procedure is outdated and should be revised completely using multi-layer elastic theory and should be verified by field tests.
After having studied several options (a/o. Refs. 18, 19), ACNsg recommended in 1995 that *an interim alpha factor* of 0.72 at 10,000 coverages is to be used for calculating ACN for 6-wheeled landing gears. Pavement longevity and the number of applied wheel loads are considered via this alpha factor. A reduced alpha-value or load repetition factor results in the ICAO ACN procedure in a smaller reference thickness at 10,000 coverage's. The alpha factor was changed from 0.788 to 0.720. As a result the ACN for B777 at subgrade category D, i.e. CBR 3%, drops from 131 to 106. The ACN of the B747-400 remains unchanged at 101. As a provisional measure and pending justification by full-scale pavement testing, the ACN values for six (6) wheel aircraft configuration including the Boeing B777 airplane, by default are computed using this modified interim alpha factor. The procedure for four (4) wheel aircraft configuration remains unchanged. The ICAO ACNsg has mainly concentrated on flexible ACN. However, an inconsistency can be reported in calculating rigid PCN too. The standard cutoff for rigid pavement is three (3) times the radius of relative stiffness. This gives inconsistent results with large complex gear configurations such as the C-17 (high strength ACN higher than low-strength ACN). An option is therefore provided to change the cutoff. This sometimes leads to numerical problems and the numerical procedure may not converge.

A review of the current procedures for pavement design and evaluation undertaken by ICAO in 1997 indicated the inherent limitations of the procedures currently used for the design of aerodrome pavements for some types of new larger airplanes equipped with six or more wheels per strut (e.g. Boeing 777 and A380-800). A review of the other design methods available indicated the need to identify more mature and globally accepted procedures. In this context, full-scale research projects have been being undertaken in Moscow, France and the U.S., which will contribute to the development of an alternate procedure, which is likely to be based on a mechanistic-empirical basis using layered elastic design approaches (LEA).
At the initiative of FAA and Boeing the 1970 Multi Wheel Heavy Gear Load (MWHGL) data were updated with new full-scale pavement tests at the NAPTF in 2002. The National Airport Pavement Test Facility (NAPTF) was built to produce reliable pavement performance and failure data for a variety of pavement structures, subgrade strengths and landing gear configurations. Similar full-scale pavement testing had been performed at the MWHGL, using the same failure mode as in the MWHGL tests (deflection or upheaval at the level of the subgrade interface) was conducted at the NAPTF. The 21 billion USD program is funded and conducted entirely by the FAA and Boeing. Test runs were conducted on four (4) flexible pavements of variable thickness constructed over a CBR 3% subgrade. The Terms of Reference of FAA stated that the goal was to establish a definite alpha factor for six wheel bogies. The 2002 data from the NAPTP indicates by any measure and on any scale that the 6-wheel gear exhibits improved pavement loading characteristics as compared to 4-wheel performance. The resulting alpha factor of 0.679 at 10,000 coverages is a clear indication of the improved load distribution characteristics of six-wheel gear aircraft.

Gear type	Alpha factor MWHGL	Interim Alpha factor	Alpha factor NAPTF
1-wheel	0.995		
2-wheels	0.900		
4-wheel alpha	0.825		0.776
6-wheel alpha (inception to 1995)	0.788		
Interim 6-wheel alpha (1995 to present)		0.720	0.679
Current 12-wheel alpha	0.722		

Table 3 Alpha factor for 10,000 coverages

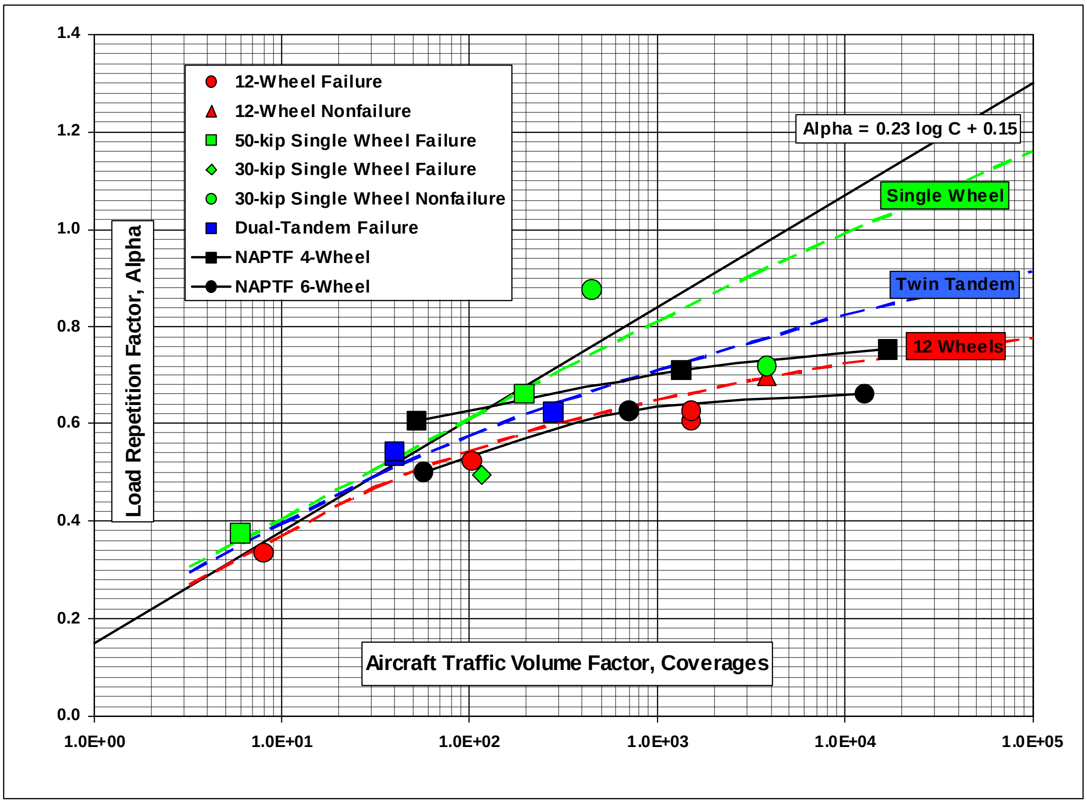

Figure 1 Alpha factors - Averaged CBR's

The ICAO ACNsg met in November 2003 to decide on a definite 6-wheel alpha factor. As can be depicted from **Fout! Verwijzingsbron niet gevonden.**, the NAPTF 6-wheeled alpha factor is smaller than the interim factor. Hence the ACN and pavement thickness requirement would also be smaller. Note that the alpha factor of the 4-wheel bogie is also smaller than that of the original MWHGL data too. Considering the lower NAPTF 4-wheel alpha factor, the meeting decided that revision of the 6-wheel interim factor *without addressing the 4-wheel factor* would lead to inconsistent ACN values. Revision of the latter would have a profound impact on the ACN-PCN system. The meeting adjourned with a new action: an investigative study into the impact that revised ACNs would have on current ACN-PCN method in light of the full-scale pavement load tests conducted by France and the United States.

The FAA responded on their position and recommends that the current alpha factor value for the 4-wheel gear configuration remain at the current value of 0,825 since final analysis from the FAA National Airport Pavement Test Facility (NAPTF) indicates that the current value is consistent with current and historical full scale test results. The FAA has prepared a final report titled “Alpha Factor Determination from NAPTF Test Data” which details the adjustments to total pavement thickness to establish equivalency with MWHGL tests (Ref 41). Based upon the conclusions of this report, the historical performance of real world pavements, and the realization that the test data unavoidable scatter, the FAA further recommends that the 6-wheel alpha factor be permanently established at the current interim value of 0,72 (Ref 42).

3.2 More fundamental approach to ACN procedure

It is now widely recognized that the Corps CBR method cannot adequately compute pavement damage caused by new large aircraft. Although the layered elastic method has been available for more than 20 years, it has not been used as a primary design method for aircraft pavements until recently. The requirement to understand pavement performance has resulted in an demand for accurate site testing systems that will allow accurate prediction of pavement deterioration with time and will ensure that any deterioration of the pavements is identified as early as possible so as to minimize the requirement for major reconstruction work.

It is believed that *more advanced structural models* are capable of better representing the response interaction from New Generation Aircraft (NGA) landing gears, but these have not been verified with field data. In 1999 the FAA's National Airport Pavement Test Project facility (NAPTP) initiated full-scale testing to establish mechanistic-empirical design criteria for the current trend in NGA gears. The FAA are proceeding with a US$ 50 billion pavement research project which includes extensive full scale accelerated tests to quantify the effects of more than four wheels on a strut and interaction effects between closely spaced struts. The (NAPTF) testing vehicle can simulate repeated loading by aircraft weighing up to 1.2 million pounds. Data from NAPTF will be used to develop advanced failure models that are applicable to the new generation of aircraft, including the six-wheel B-777 and future models.

Accurate analysis of the pavement response to a given aircraft load is necessary but not sufficient for design. In addition, it is essential to have reliable predictions of the failure life of a pavement. In the advanced FAA design procedures, failure models are in the form of regression functions relating levels of strain produced by a passing aircraft gear to the number of coverages to failure. The strain response is based on a mechanistic analysis such as the three-dimensional finite element method, while the failure models are based on traffic tests of full-scale pavement structures. Hence, this methodology belongs to the family of mechanistic-empirical design methods.

Calibrated design criteria are also being developed at the A380 Pavement Experimental Program (A380 PEP) in Toulouse (Ref. 35) and by Progresstech in Moscow which will contribute to the development of an alternate ACN procedure. The results of these full-scale pavement test facilities will also form the basis for a mechanistic-empirical design approach that can lead to a revision of the ACN-PCN rating system.

When multi-layer elastic systems are used, the analysis is normally based on the peak tensile strain at the bottom of the asphalt layer. The problem with this approach is that with multiple wheel configurations it is not clear whether one should take into account the number of strain peaks as a number of load repetitions or the number of gear passes. Another problem with such analysis is that the pavement materials are certainly not linear elastic, they are non linear elasto-visco plastic. World-wide research is under way to develop improved damage initiation and progression models using the material behavior for bituminous materials. The Asphalt Concrete Response (ACRe) model is a Finite element model based on CAPA-3D and Desai's model for material characterization. It uses Desai's model in combination of a set of constitutive relations developed to facilitate the description of asphalt concrete response. The parameters of the ACRe model of the Delft University of Technology can be obtained from compression and tension tests. The ACRe model can be utilized to derive a more realistic flexible ACNs (Ref. 40).

3.3 Advanced FAA pavement design tools under way

The FAA is currently developing a new generation of PC-based airport pavement design tools that will employ advanced computer programs based on the three-dimensional finite element method (FEM). These procedures will be capable of designing the future airport pavements to serve new aircraft types, including new large aircraft with 6 or more wheels per gear now in the conceptual stages. The three-dimensional FEM can handle greater detail and more complex characterizations of construction materials than can layered elastic analysis. It is particularly useful for modeling rigid pavements, since the slab edges and joints that are often the critical components in rigid pavements can be modeled directly, which is not possible in LEA (LEDFAA, Ref. 24). In addition, 3D FEM can incorporate nonlinear and non-elastic material models not available in LEA.

In finite element modeling, the structure is divided into a large number of smaller parts, or "elements." Elements may be of different sizes, and may be assigned different properties depending on their location within the structure. By breaking down the structure into elements, the pavement structural problem is transformed into a finite set of equations that can be solved using a computer. Because a structure can be broken down into finite elements, or "discretized," in any number of ways, it is essential that any design standard incorporating finite elements include rules for systematic three-dimensional meshing. To be a true standard, the model must have specified element formulations, material properties and element sizes for each of the layers, since all of these factors can affect the predicted response and the design engineer will expect consistent behavior from the design tool. At the same time, the design program should be as "user-friendly" as possible, with all modeling decisions such as element sizes and shapes made transparently to the end user at the programming level.

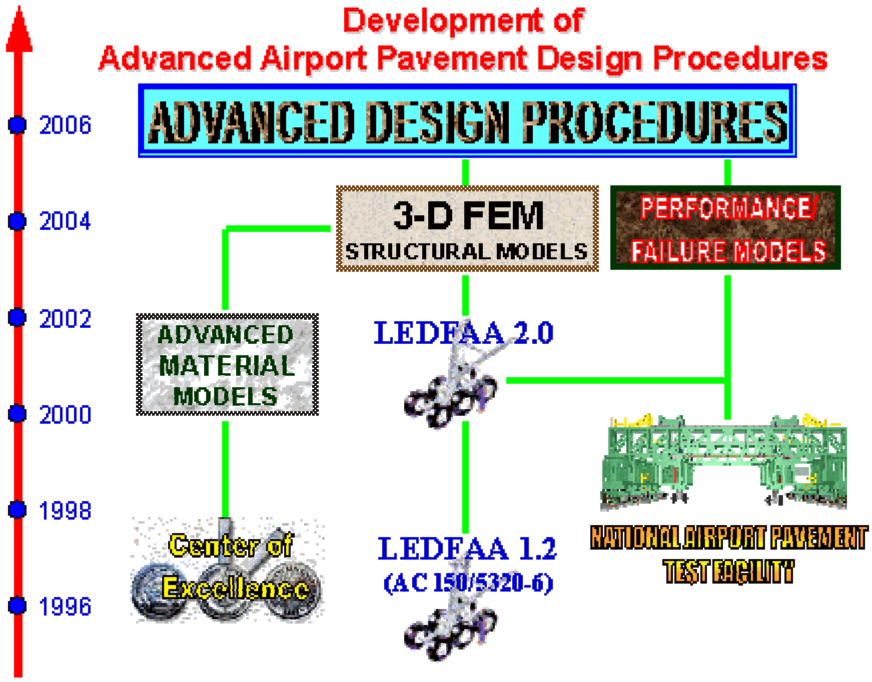

Figure 2 Towards advanced airport pavement design procedures

The FAA plans to produce a 3D FEM based design procedure (called FAARFIELD) as a new design standard for release in 2006. At the present time (2003), the FAA has developed a three-dimensional finite element structural model for rigid pavements (called FEDFAA) that provides automatic discretization of the structure and also incorporates key structural concepts such as finite slabs, joints, multiple structural layers and realistic interfaces between adjacent layers. The model incorporates existing 3D finite element software in the public domain (NIKE3D, originally developed by the U.S. Dept. of Energy's Lawrence Livermore National Laboratory.) This structural model has been extensively verified with in-service field data obtained from the Denver International Airport (DIA) instrumented runway project. A model comprising of an infinitely deep foundation based on special “infinite” elements is currently under development (FAARFIELD). Much work remains to be done before the developed 3D FEM structural model becomes part of a standard design program.

Over the next several years FAA will:
- Extend the structural model to cover flexible as well as rigid pavements.
- Incorporate non-linear material models such as stress-dependent moduli for unbound layers.
- Develop suitable structural models for flexible and rigid overlays.
- Target the FEM model size to anticipated PC performance levels for the 2006 time frame.
- Integrate the structural model with suitable traffic models and failure criteria.
- Develop an easy-to-use interactive graphical user interface (GUI) for Windows based on the successful LEDFAA model.

4 NATO requirements and perspective on ACN-PCN

NATO is in the transition from the LCN/LCG system to the ACN-PCN system. NATO wishes to determine in a reasonably short time a single methodology for establishing PCN values.

4.1 NATO moves towards ACN-PCN system

NATO defines their military requirements for airfield pavement strength in terms of the Aircraft Classification Number (ACN), following the ICAO international system of load bearing strength reporting. Because ICAO lays down the method of determining ACN for both flexible and rigid pavements, this step has been achieved easily. NATO has published individual ACN values for the range of aircraft likely to use its airfields in Standard NATO Agreement 7131 ACN-PCN (STANAG; Ref. 8). NATO's has replaced the older Load Classification (LCN) system in NATO Criteria and Standards for Airfields with ACN.

NATO considers the reporting of three (3) load bearing strength values. A standard PCN is used to compare bases within NATO. A mission PCN is used to manage pavements at the local base, whereas a contingency PCN is used for mission planning. For NATO nations or individual civilian airport authorities, PCN values are determined as an extension of existing national pavement design and evaluation technologies. Since NATO is an Alliance of nations, such an approach would lead to uneven consequences. Many of its pavements are constructed using common funding provided by the Nations as a whole. For the funding of new construction and restoration works and for determining cost shares for joint NATO and national use, there is a need to develop a uniform methodology to determine PCN values for all NATO airfield pavements, rather than leaving it to each member of the Alliance, or to the individual airfield authorities. From the NATO perspective, it is considered to be impractical to attempt to harmonize the various national design and evaluation procedures into a common single methodology. Even nations that use methods which, at first sight appear to be the same, introduce assumptions and variations attuned to national needs. These methods have long histories and, even if harmonization was possible or desirable, the process would take many years since national design is not limited to military airfields. Considering that PCN is not a design method, but solely intended as a strength reporting value related to published ACNs, a single NATO method for its determination should be possible while leaving national design procedures and practices intact. Already, most nations base rigid pavement design on reasonably common grounds and there is likely more similarity in flexible methods than generally appreciated.

NATO wishes to determine in a reasonably short time a single methodology for establishing PCN values so that existing methods and terminology are preserved to the greatest extent possible among the NATO members while establishing a strength to load relationship which lies as close as possible to that which might be determined using national methods alone. In effect, the NATO PCN methodology would allow all nations to use whatever national procedures are considered to be suitable for national purposes, but to subsequently report such determinations to NATO using that common new methodology. In this way, NATO members could communicate to each other in a single pavement reporting language, which would lead to satisfactory

conclusions on the safe use of its airfield pavements or for uniform and fair funding arrangements for restoration and new construction.
The NATO Airfield Services Working Group (ASWG) has discussed on several occasions a NATO wide methodology for determining the PCN. As no NATO STANAG for the evaluation of airfield pavements yet exists, the Netherlands proposed and submitted their national defense standard (Ref. 15) for enquiry as a possible STANAG for pavement PCN evaluation and reporting strength of NATO airfields. Since the military traffic is not precisely known, often a number of passes is used instead. The Dutch PCN is based on 10,000 passes (no lateral wander) of a fictitious PCN evaluation aircraft using a statistical concept. However, the U.S. Army and U.S. Corps of Engineers suggested to consider their evaluation method, which is in fact based on the empirical ICAO methodology for determining ACN (Refs. 13 and 14). The allowable load used for U.S. Air Force airfield evaluations is to be based on 50,000 passes of the C-17 aircraft. Several nations opposed the underlying design ICAO methodology of Refs. 13 and 14 for determining ACN, as suitable for extension into the determination of PCN. Layered approach is preferred, rather than the empirical Westergaard and CBR relations.

The February 2003 ASWG meeting decided to let nations use their own national design theories to determine PCN. Though additional information such as the number of aircraft passes used to make the calculation must be provided (runway only). Nations shall provide the following information:

- Airfield name, runway(s) and PCN value(s);
- Type of aircraft for which the PCN values are based;
- Number of aircraft passes used to make the calculation.

The additional information allows NATO to use the U.S. evaluation method to determine an internal common and comparable NATO airfield strength values as required. The ASWG meeting also recognized *the layered elastic method as the future NATO evaluation method* to be used to determine a common pavement strength value. Hence, AEP-46a (Ref. 8) was ratified for limited time only and does not describe a NATO wide PCN assignment method. According to the U.S. representatives, introduction and implementation of a layered elastic PCN method to NATO will be feasible within a period of five (5) to six (6) years.

4.2 Questionnaire on design and evaluation of airfield pavements

It has been noticed that PCN assessment can be done in several ways. To gain insight in the methods used in the design, evaluation and PCN assessment of airfield pavement, the NATO ASWG and the CROW working group on ACN-PCN prepared a questionnaire. This questionnaire must provide insight in the motivation for the choice of a certain design system and the experiences in practise. It should also lay bare a common need for improvement. Information is requested on the design methodology used, the conditions during construction, possible specific problems occurring with solutions etc. In brief: what are your experiences associated to design, evaluation and practice with airfield pavement?

The questionnaire has been distributed to the official NATO ASWG correspondence list and to known national Airfield Pavement Points Of Contact (APPOC's). Also active and corresponding members of CEN TC 227 Ad Hoc Working Group Airfields received the questionnaire.

Furthermore this questionnaire was sent to a number of national airfield pavement experts and to airfield administrators. A total of twelve (12) respondents co-operated and replied to the questionnaire: Belgium, Czech republic, Germany, Hungary, Netherlands (two reactions), Portugal, United Kingdom, US Navy, US Army and Sweden. The results, summarised in table 4 Design and evaluation of flexible pavement and table 5 Design and evaluation of rigid pavement will be presented at the 2005 European Airport Pavement Workshop organised by CROW.

Both tables show that NATO nations use different PCN procedures, mostly relying on national design procedures. The methods used vary from either fully empirical to mechanistic-empirical. As there is no common agreement to a NATO wide design and/or PCN evaluation standard, some respondents find it important that *guidance is given on* the characterisation and assessment of material fatigue transfer functions as well as on the determination of pavement material properties. An inquiry of the U.S. Corps amongst several nations learned that the pavement design method used by individual nations lead to different pavement thickness (and PCNs). *Consequently, different nations get different results. This, and the fact that the PCN reporting system does not reflect the actual pavement life are considered as shortfalls of the ACN-PCN system.*
However, with the current World situation there is an increasing need for NATO standards with respect to airfield pavement design to support joint military operations. It is critical to mission planners that methods steps are taken to insure that global methods for reporting the structural capacity of an airfield are available. Several Nations have implemented mechanistic design/evaluation systems with criteria that appear to be yielding reasonable results. Many of these procedures are based on linear, elastic theory coupled with empirical relationships for relating computed stress/strain to allowable aircraft load. This approach is well understood and well documented. The elastic layer mechanistic/empirical methods are also very adaptable to new criteria. For example, it is not very difficult to add/remove/modify the criteria (fatigue relationships or transfer functions). This makes it attractive since results from continuing research and development could be incorporated as necessary. With the current emphasis and requirements for better design/evaluation methods, a NATO standard could be established that would be well accepted among the Nations.

Flexible Pavement	Belgium	Czech Republic	Germany	Hungary	Finland	Netherlands #1	Netherlands #2	Portugal	United Kingdom	US Navy US Army	Sweden
Design Method	CBR acct. ICAO	Multi Layer	Multi layer	CBR acct. ICAO	CBR	Multi-layer	CBR (FAA) or Multilayer	CBR and multi-layer	CBR	CBR and LED	Multi-layer
Software code	none	LayEps	Buma, proprietary	UVATERV RT based on Ref. 1.	N/A	Pavers, BisarPC, APSDS	US Corps, Circly, APSDS, Kenlayer, Bisar	PCASE, LEDFAA	Modified US Army CBR	PCASE	Yes
$Ea_{sph} = f(T,t)$	N/A	Yes	Yes	N/A	N/A	Yes. Shell	Shell	Shell	N/A	LED only	yes
Annual Avg. Temperature and climate conditions	N/A	4 seasons considered	4 seasons considered	Annual avg.	N/A	MMAT or WMAAT	WMAAT	Average temperature	N/A	LED only	yes
Characterisation of pvmt materials and subgrade	CBR	E, μ, h, friction	EV2-modulus	CBR	Odemark Equiv. Theory	E, μ, h, friction	E, CBR (FAA criteria)	CBR and E is used in PCASE	CBR and equiv. factors	CBR and E-modulus	E, μ, h
Mixed traffic by	Equivalent traffic critical aircraft	Fleet mix	Fleet mix, no wander	Equivalent traffic critical aircraft	Equivalent traffic critical aircraft	Whole fleet mix, variable wander, CDF based on Miner	Whole fleet. APSDS Inc wander based on CDF	Mixed traffic critical aircraft, fixed lat.wander LEDFAA	Critical aircraft and equivalent passes	Critical aircraft and equivalent passes	ESWL concept for PCN
Material fatigue considered	No	Yes, asphalt	Yes, asphalt strain	No, (15 y)	No, (20 y)	Yes, all pavemnt materials	Unbound CBR, bound by Emod	Yes, by PCI	No	No	Yes, asphalt and subgrade strain
Consider crack growth in design	No	No	No	No	No stab base used	In special cases: Cracktip, & Capa2D FEM	Occasional FEM,	No	No	No	N/A
Use SAMIs	Yes	No	Not in design	No, geogrid	No	Yes if applicable	No, pre-cracked base preferred	No	No	Not usual in Navy	N/A
Address surface friction in design	No	No	No	No	No	No	No	No	No	No	N/A
Manuals available	Yes, BRRC	No	BFR & Merkblatt	Yes, 58	No	Yes, Ref.17	Yes completed with literature	PCASE manual	PSA (Ref 29) and Defence Draft Guides	UFC 3-260-02 (Ref. 16)	Ref. 34
Evaluation Method In-situ testing	Plate test	Pri-2100 FWD	Plate test, FWD	CBR (10y interval)	FWD	H/FWD, GPR	CBR-test and DCP	HWD	CBR, coring, DCP, plate load.	DCP, HWD GPR	HWD 140 kN
Related tests used	None	GPR, DCP	Coring, CBR, Soil classification	GPR and FWD envisaged	N/A	Coring,	no plate loading due to logistic problems, FWD	Static plate bearing	Occasional. HWD, NAT lab test, GPR, ITSM	Standard and electric cone Penetrometer	N/A
Software code	None	Rosy, LEEP, PCASE	N/A	None	Rosy & Elmod	Pavers, Miss (BISAR-based)	N/A	NA	N/A reversed design	PCASE	N/A
Temperature measurement	None	Yes	Yes	Yes	yes	yes	N/A	yes	N/A	Yes via HWD	N/A
PCN assignment	Ref. 16	Related to traffic level, damage and FWD-result	Reversed design using model and strengths	Related to traffic level, damage and FWD-result	Using Carlbro & Dynatest software	Variable coverage's (+10,000), fleet mix and/or critical ACN aircraft passes	If CBR based on ICAO various coverage levels + ICAO 10,000.	PCI	Reverse Design based on test results and visual condition	Calculated to predict pvmnt life to support given traffic and time period	10,000 passes of ACN load is PCN
Material fatigue considered	No	No	Yes	Yes	No	all pvmnt materials	If mechanistic: only subgrade fatigue	ASTM tests	Only in respect of overall fatigue	Yes, included in program	N/A
Reliability concept used	No	Avg.	No	Avg.	Avg.	Yes, Bootstrap or Rosenblueth	85%	95%	No	Average strength	N/A
Nation Standard	ITAC	None	BFRs & Merkblätter	Yes, 58	None	Mil. (Ref. 17)	N/A	US AFJMAN & ASTM	Defence Estate Draft Guides on Strength Eval.	UFC 3-260-02 (Ref. 16)	Ref. 34

Table 4 Design and evaluation of flexible pavement

Rigid Pavement	Belgium	Czech Republic	Germany	Hungary	Finland	Netherlands #1	Netherlands #2	Portugal	United Kingdom	US-Navy, US Army	Sweden
Design Method	Westergaard equations	Finite Element Code	Westergaard	Modified Westergaard	Westergaard equations	Van Cauwelaert modifiedWstgrd	Van Cauwelaert modifiedWstgrd	Layered elastic	Westergaard equations	LED, Westergaard	N/A
Critical position load	n/a	edge	Centre, edge, corner	n/a	N/a	Wander on slab, but edge critical	Wander on slab, but edge critical	Edge	Centre, edge, corner	Edge	N/A
Software code	none	NE10-SOILIN, own use	Yes, not available to public	UVATERV Rt based on PCA for own use	None	Pavers, Kola for special cases. Comm. available	UECSlab	PCASE and LEDFAA (FE)	Tes, not available to public	ERES-PCA, LED	N/A
Support Characterisation	k and CBR	(k,G)	k	k	k	(k,G)	(k,G)	E, CBR	k	k	N/A
Typical concrete Modulus	N/A	25,000 MPa	DIN EN 206	N/A	Compressive strength 75 MPa (90d)	VBC 1995	30,000 to 35,000 depending on compressive strength	35,000 MPa	30,000 MPa	ACI-318 relation based on compressive strength	N/A
Typical concrete strength	7 MPa	3.5 MPa	DIN EN 206	N/A	6.0 MPa (90d)	VBC 1995	4.5 to 5.0 (28d)	4.5 MPa	3,5 – 5,0 MPa	650psi (4,5MPa)	N/A
Geometry considered	N/A	Yes, l*b	Yes	N/A	N/A	yes	yes	yes	N/A	yes	N/A
Material fatigue considered	Stress ratio	Transfer function	Smith's diagram	Stress ratio	No	Yes, relation used depends on nation standards	Yes, PCA or Domenichini	Yes, PCA (CDF)	Yes, PCA (CDF)	Yes	N/A
Mixed traffic by	4 different levels	Equivalent traffic critical aircraft	Fleet mix, no wander	Equivalent traffic design aircraft	Equivalent traffic critical aircraft	Whole fleet mix, variable wander	Equivalent traffic design aircraft, variable wander	Equivalent traffic design aircraft fixed wander	Critical aircraft and equivalent passes	Cumulated damage (CDF) and P/C	N/A
Manual, guidelines	AF 88-6, Chpt. 3	None	BFRs & Merkblätter	Yes	PSA, Ref. 33.	Windows help	Too large to list	AFJMAN, ASTM	PSA (Ref. 29) Def. Estate Darft	UFC 3-260-02 (Ref. 16)	N/A
Black top overlay design	no	NE10-SOILI	No	crack &seat	N/A	Layered design	Layered analysis	No	Yes, empirical	No, empirical	N/A
Evaluation Method	Westergaard equations	Finite Element Code	Westergaard	Modified Westergaard	Westergaard equations	Van Cauwelaert modifiedWstgrd	Some times plate loading	Layered elastic	Westergaard equations		N/A
In-situ testing	Plate test	FWD	Plate test, FWD	FWD	FWD	FWD	coring	HWD	See asphalt	HWD	N/A
Related tests	None	DCP, GPR	Coring, CBR, Soil classification	GPR	N/a	GPR, material testing for strength, DCP	Concrete tensile strength	CBR, core drilling, static plate tests	Occasional. HWD, NAT lab test, GPR, ITSM	GPR to find buried drains	N/A
Software code	None	Rosy, LEEP, PCASE	Proprietary	UVATERV Rt based on PCA for own use	Rosy & Elmod	Pavers, commercially available	N/A	Kuab software	N/A	PCASE	N/A
PCN assignment	Ref. 16	Related to traffic level, damage and FWD-result		Related to traffic level, damage and FWD-result	ICAO principles, consultant propriety	Reversed design, Fleet mix and/or variable critical ACN aircraft passes	By reversed design	Kuab	Reverse Design based on test results and visual condition	Calculated to predict pvnmt life to support given traffic and time period	N/A
Material assessment	coring			testing	Odemark Equiv Theory	Ultrasonic Edyn, μ. Flex. strength	FAA unbound, stabilised mat. E	testing	testing		N/A
Reliability concept used	No	Avg.	No	Avg.	85%	Yes, Bootstrap or Rosenblueth	85%	95%	No	Average strength	N/A
Nation Standard	AFM 88-6	None	No	Yes, 58	No	Military, Ref. 17	NA	No	Defence Estate Draft Guides.	UFC 3-260-02 (Ref. 16)	N/A
Need for Uniform Design and Evaluation Standard in EU or NATO ?	Yes	No, general guidance only	No, on national level sufficient	Reluctant	Reluctant	No, but describe general material characteristics	Possible, agree on material and fatigue properties	Would welcome standard on tests and assessment	In theory yes, in practice difficult	Yes, for NATO: comparable PCN with fixed traffic	NA

Table 5 Design and evaluation of rigid pavement

5 Design concepts and PCN software

PCN assigments are related to design methologies. Inverse pavement design is ofter the basis for PCN assessment. In order to appreciate the differtent PCN methods in use, a brief introduction is presented regarding design concepts. An overview of computer programs available is presented too.

5.1 Design concepts

As has been stated previously, the method of PCN evaluation is left up to the airport authority (or regulating CAA). Since the introduction of the ACN-PCN method in the early the eighties, pavement engineering and design has evolved enormously, thus the accuracy of a PCN evaluation rating has improved too. An established and industry recognized engineering method appropriate to the pavement construction type should be used to determine the structural capability of a pavement to support aircraft loads and traffic levels. However, in most states, PCN values are determined as an extension of existing national pavement design concepts and evaluation technologies. Although layered elastic methods has been available for more than 20 years, it has not been used as a primary design method for airport pavements until recently. The majority of ICAO states and NATO nations use the empirical derived CBR-method and Westergaard equations for PCN evaluation. This implies that assignment of PCN can either be determined on an empirical or layered elastic analysis basis. A brief introduction on design concepts is thought necessary, before discussing PCN evaluation methods.

The US Army Corps of Engineers empirical relationship between load, subgrade CBR and required pavement thickness is the basis of most of the world’s *aircraft pavement design methods*, including that of the FAAs AC 150/5320-6 (Ref. 13) and ICAOs ACN calculation. The methodology to produce the thickness design is that for a given subgrade CBR and a given number of coverage’s for the design aircraft, total pavement thickness is computed based in CBR design charts. The user has to determine the designer aircraft and make the conversion from aircraft departures to design aircraft coverage’s. Conversion of layer thickness must be done using equivalent thickness factors for bound materials.
Rigid pavement thickness design follows the same methodology used to produce thickness design charts published in FAA AC 150/5320-6. That is, for a given modulus of subgrade reaction and a given number of coverage’s for the design aircraft, total pavement thickness is computed by Westergaard edge stress method with FAA failure criteria. The user has to determine the design aircraft and make the conversion from aircraft to design aircraft coverage’s. Conversion of support layers to effective modulus of subgrade reaction must also be done by the user.

Application of empirical methods is restricted to the conditions under which the experience was obtained. The CBR method for the design of aircraft pavements was calibrated against full-scale trafficking test on unbound pavements conducted 30 years ago. CBR flexible design methods are predicated on an empirical failure mode which consist of surface rutting caused primarily by overstressing the subgrade. This method used single layer analysis and therefore had no direct mechanism for measuring the superior load spreading characteristics of the bound layers. Bound layers were increasingly being used, however, and were typically accounted for within the empirical design by using layer equivalency factors.

Layered elastic design was first introduced in the mid 1980's and is quite common in Europe nowadays. It is because of the complexities of structural behavior and material properties that empirical procedures have endured for so long in pavement engineering. However, with the knowledge now available from research, a mechanistic-empirical procedure based on layered elastic design can be applied to asphalt and rigid pavements. Following the load input into the model, the stresses and strains are calculated at the design positions. For flexible pavements these are at the bottom of the bituminous layer (fatigue cracking), the top of the subgrade (rutting) and in a cement bound base at the bottom of this layer (reflective cracking). For concrete pavements the edge-loading position is critical. Stresses and strains are calculated at the edge position using Westergaard incorporating temperature induced stresses and the measured load transfer. By means of fatigue relationships or transfer functions the (residual) allowable number of standard axles and thus the residual pavement lives are calculated. The assessment process also corrects the results for seasonal variations (eg. flexible material/concrete temperature, subgrade variations etc).

5.2 Computer programs available

Public freeware and commercial layered elastic programs for pavement design are largely available: a/o NLAYER, NOAH, JULEA, BISAR, WESLEA, ELSYM5, CIRCLY, SPDM, UECSLAB, PAVERS, FEDFAA, LEDFAA, KENLAYER, KENSLAB, APSDS etc, etc, not to mention the huge number of Finite Element programs that are available. Some are special purpose airport pavement design programs (LEDFAA www.airporttech.tc.faa.gov, winPCN www.dynatest.com/software/acn_pcn.htm, PCASE, www.pcase.com, APSDS www.mincad.com.au, UECSLAB www.crow.nl, and PAVERS www.pavers.nl), others are general purpose linear elastic *design* programs for calculating pavement response due to loads. The aforementioned programs must be considered expert tools, which allow the engineer to assign elastic properties to various pavement layers and use or define calibrated failure criteria for all pavement materials.

The layered elastic method was introduced into regular airport design practice for flexible pavements in the mid-1990's, with the release of the computer program LEDFAA by the U.S. Federal Aviation Administration (Ref. 24). Linear elastic design facilitate the treatment of bound layers, eliminating the need for the 'equivalent single wheel load', and removed the requirement for 'design aircraft' and 'the alpha factor' traffic count modifiers. The damage prediction is based on the more rational 'cumulative damage factor' (CDF), or Miner's rule. LEDFAA is now an FAA standard intended for use in *designing pavements* (not for evaluation) catering for aircraft mixes that contain the new Boeing 777. LEDFAA computes damage caused by the 6-wheeled gear of the B777 that is similar to that calculated by traditional empirical CBR-based methods. The default values of the elastic properties used by LEDFAA have been so chosen to produce pavement thickness' that are similar to those obtained by using the traditional CBR empirical method and layer equivalencies specified in FAA's Advisory Circular (Ref. 12). This is considered to be a transitional measure, and it is expected that modulus values will be changed over time to better model the pavement as NAPTF performance data becomes available (see Chapter 6). One benefit of layered elastic design is that pavement-load interaction is analyzed for each aircraft and each layer and giving more realistic results.

WinPCN is propriety of Dynatest A/S and can calculate a PCN value based on aircraft ACN values and subgrade CBR values. It uses the deflection data files from H/FWD equipment to calculate PCN by reversed design using the standard ICAO procedures for flexible and rigid ACN calculation. The conventional method is described in AC 150/5335-5 (Ref. 12).

PCASE (Ref. 14) is part of the Engineered Management System (EMS) software of the U.S. Department of Defense and is available to the public on the web. The PCASE project was established to develop and provide computer programs for use in the design and evaluation of transport systems. PCASE programs include rigid and flexible airfield design by conventional and layered elastic methodologies, rigid and flexible road design, as well as railroad design and evaluation programs. EMS comprises of PCASE v 2.06 and MICROPAVER v 5.1, the latter being the industry standard for pavement condition management. PCASE is a complete design and evaluation tool. It can not only be used for layered elastic design and evaluation, but also for the classical CBR method and Westergaard K-criteria approach. The conventional methodologies are mandatory for U.S. Department of Defense pavement design and evaluation of transport systems (Refs. 9 & 10). The tool can handle FWD-data for evaluation. It is self-explanatory and comes with tutorial video instructions. An utility program, WinJULEA, for multi-layer calculations has also been added to the software package.

A major research project has been conducted in Australia in the 1990’s to overcome some of the limitations of current airport pavement design systems. This has culminated in the development of APSDS (Airport Pavement Structural Design System), a propriety computer program based on layered elastic analysis (Ref. 25). One of its unique features is that it rationally takes account of aircraft wander. This is the statistical variation of the paths taken by successive aircraft relative to runway or taxiway centerlines, or to the lead-in lines to parking positions. Increased wander reduces pavement damage by different amounts that depend upon pavement thickness. This treatment of aircraft wander is more realistic than methods that are based on the simplified 'coverage' concept. Its method for dealing with aircraft wander meant that the 'pass-to-cover ratio' was no longer required. The user can define his fatigue transfer functions in the design of flexible pavement. APSDS is not suitable for concrete pavement design, nor is fit for FWD-based flexible or concrete pavement evaluations.

UECSLAB (Ref. 36) is a product of a CROW working group on the evaluation of concrete airfield pavement and is distributed by CROW in the Netherlands only. The publication describes in detail the evaluation methodology to be used for PCC pavement evaluation. As part of the methodology, it comes with the software tool UECSLAB which uses closed form integral solutions to model a concrete slab-on-grade as a classical Westergaard slab on a Pasternak foundation. This model overcomes the classical discrepancy between the Westergaard-Winkler (joints) model and the layered elastic Burmister model (no joints). By using closed formed solutions, it is possible to calculate the response of multiple loads placed at random positions on a slab, thus overcoming the ESWL-concept. Version 2.0 has been released in 2001 as a derivative of version 1.0 of the PAVERS program.

PAVERS (Ref. 26), an acronym for PAVement Evaluation and Reporting Strength, was initially developed as part of the airport pavement evaluation methodology of the Dutch Ministry of Defense (Ref. 17, 27). The developers of PAVERS, i.e. Van Cauwelaert, Thewessen and Stet teamed up, improved and extended several models, built a tool-kit and implemented them in the latest versions of the program. PAVERS software and its models are propriety of its developers. The program contains a linear elastic multi layered model, which allows for the assessment and design of flexible pavement. The layers are isotropic except for the bottom layer where anisotropy is addressed by different moduli in the horizontal and vertical direction. The interface between two adjacent layers can be varied between full friction to full slip using the BISAR or Van Cauwelaert's WESLAY definition. Improvements to the slab model a/o include a thermal stress model, a multi-layer slab model which is required for pavement design with cemented bases and several material and load libraries. Note: FAA recommends the use of cemented bases when aircraft with an operating mass over 45 tons use the pavement. The tool was created to give pavement specialists a definite tool for the structural design and evaluation of road, airport and industrial rigid and flexible pavement. The tool does not dictate a certain design methodology, but allows the pavement engineer to define or use *calibrated* failure criteria for all pavement materials. The effect of different pavement materials, strengths, load or complex load mixes can quickly be explored.

The unique rigid model code of UECSLAB and PAVERS allows to use the same method for dealing with aircraft wander as for asphalt pavements, eliminating the pass-to-load repetition concept for rigid pavements. These programs and APSDS (flexible pavement only) rationally take into account variable lateral aircraft wander, which is believed to be more realistic than the coverage concept. LEDFAA and PCASE adopt taxiway wander, but the user cannot specify any other degrees of aircraft wander.

An overview of the capabilities of the software available is presented in Table 6.

Design theory	LEDFAA	WinPCN	PCASE	APSDS	UECSlab	PAVERS
Conventional Design						
- CBR-method [1)]	-	+	+	-	-	-
- Classical Westergaard [2)]	-	+	+	-	+	+
- PCN assessment	-	+	+	-	+	+
Linear Elastic Design						
- Flexible multi-layer	+	-	+	+	-	+
- Rigid multi-layer	+	-	+	-	-	+
- Slab-on-Grade model	-	-	-	-	+	+
- Traffic library	+	-	+	+	+	+
- Fatigue function library	-	-	-	+	+	+
- Backcalculation FWD-data	-	-	+	-	+	+
- Lateral wander	+/-	-	+/-	+	+	+
- PCN assessment	-	-	+	-	+	+

[1)] ICAO ACN-program based on S-77-1 (Ref. 4);
[2)] ICAO ACN program based on PCAs PDILB program (Ref. 5)

Table 6 Overview of capabilities of airport pavement software

5.3 Reliability concept

Deviation in material strength and constructed thicknesses have a profound influence on the pavement's life, and hence on a technical derived PCN. Most design methods are based on a deterministic approach, failing to give insight how these deviations effect the design life. In the deterministic method, each design factor has a fixed value based on the factor of safety assigned by the designer. Application of this traditional approach can result in over or under design or PCN assigment, depending on the magnitudes of the safety factors applied and the sensetivity of the desgn procedures.

However, probabilistic techniques do give insight in the sensitivity of parameter deviations. Basically, reliability is a means of incorporating some degree of certainty into the design or evaluation process to ensure that the various design alternatives will last the analysis period. In the probabilistic method each design factor is assigned a mean and a variance. The factor of safety assigned to each design factor and its sensetivity to the final design are automatically taken care of the reliability of the design vcan be evaluated. Reliability is defeined as the probability that the design will perform its intended function over its design life. The level of reliability to be should increase as the volume of traffic or functional availability of the pavement or the importtance of the infrastructure increase.

Several probabilistic techniques can be used in deriving a statistically based PCN. The UEC-method recommends the Bootstrap method, suitable for evaluation purposes only. The Rosenblueth approximation technique is a general estimation technigue for pavement design and evaluation, hence could be applied for PCN assignment. Furthermore its by far faster than the Monte Carlo estimation technigue.

6 Assignment of the PCN

A number of methods can be used by an airport authority to determine the rating of a pavement in terms of PCN. The first method discussed, known as the Using aircraft method, can be applied with limited knowledge of the existing traffic and runway characteristics. The terminology *Using* aircraft simply means that the PCN is based on the aircraft currently and satisfactorily using the pavement, and there are no engineering methods or technical analysis employed to arrive at this sort of PCN. The second method, known as the *Technical* evaluation method, requires a much more intimate knowledge of the pavement and its traffic, as well as a basic understanding of engineering methods that are utilized in pavement evaluation in order to be successfully implemented. All of the factors that contribute towards pavement analysis, such as existing and forecasted traffic, aircraft characteristics, pavement design parameters, and engineering experience are applied in arriving at an evaluation as a basis for determining PCN based on this method.

6.1 The *Using* aircraft method

The *Using* aircraft method is presented in the following steps. As mentioned above, this method can be used when there is limited knowledge of the existing traffic and runway characteristics. It is also useful when engineering analysis is neither possible nor desired.

Accuracy of ratings based on using aircraft is by nature less than for a Technical evaluation, but PCNs can be assessed more quickly and with minimal cost. There are two basic steps required to arrive at a Using aircraft PCN:

1. Determine the airplane with the highest ACN in the traffic mix using the runway. This is the critical airplane.
2. Assign the ACN of the critical airplane as the PCN.

The pavement should tentatively be rated at the PCN of step 2, assuming that the pavement is performing satisfactorily under the current traffic. If the pavement shows obvious signs of distress, then this rating must be adjusted downward at the discretion of the airport authority. If the rating is lowered, then one or more the aircraft will have ACNs that exceed the assigned rating. This may require a restriction in allowable gross weight for those aircraft or consideration of pavement strengthening.

6.2 The *Technical* evaluation method

The *Using* aircraft method should be considered as, at best, a close approximation. This method was introduced in the ACN-PCN method for general world-wide acceptance of the method. The *Technical* evaluation method of determining PCN should be used when there is reliable knowledge of the existing traffic and pavement characteristics. No need to mention that accuracy of ratings based on a technical evaluation is better than based on the using aircraft method, but at a greater cost in terms of financial expenditure and time. The PCN better reflects existing conditions when based on the technical evaluation method.

The PCN numerical value for a particular pavement is determined from the allowable load-carrying capacity of the pavement. Once the allowable load is established, the determination of the PCN value is a process of converting that load to a standard relative value. The allowable load to use is the maximum allowab1e load of the most critical aircraft that can use the pavement for the number of equivalent passes expected to be applied for the remaining life.

No matter how good the pavement and load models might be, mechanistic-empirical data is still required to tie the life of a pavement to the computed stress or strain response. It is important to carefully calibrate the function so that the predicted distress can match with field applications. Implementation of calibrated design criteria into modern software tools allow the designer to access the full advantages of the layered elastic method, including treatment of wander, and quickly produce designs for complex aircraft mixes and layered structures that are consistent with the original design concept.

6.2.1 Technical evaluation for flexible pavements using the CBR-method (S-77-1)

A summary list of the steps required for flexible pavements as based on the Technical evaluation method is as follows:

1. Determine the traffic volume in terms of type of aircraft number of operations of each aircraft that the pavement will experience over its life.
2. Convert that traffic into a single critical airplane equivalent.
3. Determine the pavement characteristics, including the subgrade CBR and pavement thickness.
4. Calculate the minimum allowable gross weight of the critical aircraft on that pavement.
5. Look up or calculate the ACN of the critical aircraft at its maximum weight.
6. Assign the PCN to be the ACN of the critical aircraft.

Worked Example (courtesy Ed Gervais, Boeing, Ref 39.)
An airport pavement has a flexible surface with a subgrade CBR of 9 and a total thickness of 32.0 inches (813 mm), and comprises 5 in. (127 mm) Asphalt, 8 in. (203 mm) Crushed gravel and 19. inch crushed gravel and sand (483 mm). The pavement was designed for 20 years.
Note: This example is also used to demonstrate the PCN assignment procedure in § 6.2.2 to § 6.2.7.

It can be seen from Table 7 that the B747-400 airplane has the greatest individual thickness requirement for its total traffic over 20 years, and is therefore the critical airplane. The next step is to convert the departures of other traffic to the critical airplane B747-400 equivalent.

Airplane	Operating Weight, lb	Tire pressure psi	ACN Flexible	Annual Departures	P/C ratio	Required thickness in.
B727-200	185,000	148	48 FB	400	2.92	22.6
B737-300	130,000	195	34 FB	6,000	3.87	23.2
A319-100	145,000	196	35 FB	1,200	3.56	21.1
B747-400	**820,000**	**200**	**60 FB**	**3,000**	**1.72**	**31.2**
B767-300ER	370,000	190	52 FB	2,000	1.82	28.2
DC8-63	330,000	194	52 FB	800	1.66	26.7
MD11	515,000	205	58 FB	1,500	1.83	29.0
B777-200	600,000	215	51 FB	300	1.39	24.9

Table 7 Technical evaluation critical airplane determination

For the purposes of this calculation only, and as recommended in Ref. 6, all wide-body wheel loads were considered to be that of a 300,000 lb dual tandem airplane, or 35,625 lb, including the critical airplane. Gear configuration conversion factors were utilized to determine the equivalent dual tandem gear departures. The B747-400 equivalent annual departures were calculated using the equivalent traffic formula based on load magnitude. Although the B747-400 had only 3,000 annual departures, the effect of the other traffic has increased the number to an equivalent 11,250.

Airplane	Annual Departures	Gear Type	(R2) Equivalent DT departures	(W2) Wheel load, lb	(W1) 747-400 wheel load	(R1) 747-400 Equivalent Departures
B727-200	400	Dual	240	43,940	35,625	440
B737-300	6,000	Dual	3,600	30,875	35,625	2,045
A319-100	1,200	Dual	720	34,440	35,625	645
B747-400	3,000	DT	3,000	35,625	35,625	3,000
B767-300ER	2,000	DT	2,000	35,625	35,625	2,000
DC8-63	800	DT	800	39,190	35,625	1,110
MD11	1,500	DT	1,500	35,625	35,625	1,500
B777-200	300	DT	510	35,625	35,625	510
Total	15,200					11,250

Table 8 Equivalent annual departures of the critical airplane

With the equivalent traffic of the critical airplane known, the traffic cycle ratio can be calculated. For a critical airplane Pass-to-coverage ratio of 1.72 and a pass traffic cycle ratio of 1.0, the traffic cycle to coverage ratio is 1.72. With this information it is now possible to calculate the maximum allowable gross weight of the B747-400 critical airplane on this pavement. The input parameters to the S-77-1 computer program are:

- Critical airplane B747-400
- Pavement thickness 32.0 inches
- Subgrade CBR 9.0 (Code B)
- Tire pressure 200 psi (Code X)
- Percent weight on the main gear 95,0%
- TC/C ratio 1.72
- Annual equivalent departures 11,250
- Pavement life 20 years

The S-77-1 computer program is used to develop data of pavement life versus ACN or use the manufacturers charts of *Airplane Characteristics for Airport planning* manuals (Ref. 6). For these conditions, from the S-77-1 computer program, the calculated allowable gross weight of the B747-400 is 771,000 pounds. From the ICAO ACN program, the B747-400 ACN at this weight is 55.1 FB, for a recommended rating of **PCN 55 FBXT.**

6.2.2 Technical evaluation for flexible pavements using the PCASE-CBR-method

Although the above mentioned steps appear to be quite voluminous in their application, they are straightforward when followed to their conclusion. Several evaluation methods use the principles of the S-77-1 method (Refs. 9 and 10). The method is also coded in PCASE.

PCASE has a design and an evaluation module. Once the mixed traffic has been entered, the user can *design* the required thickness' or evaluate the pavement for strength (PCN). Based on the traffic reported in Table 7, an adequate design would be:

- 4,86 inch of asphalt (123 mm)
- 8 inch (203 mm) unbound base, i.e. CBR 80%
- 19 inch (483 mm) compacted subgrade (cohesionless cut), i.e. CBR 20%

constructed over a natural subgrade of CBR 9%.

This requirement almost matches the pavement under consideration , which comprises of an 5" asphalt layer. The pavement strength can be assessed in the evaluation module of PCASE. The program converts the traffic into 24,710 equivalent passes of a design aircraft, in this case the B727-200. The PCASE evaluation module calculates a **PCN 78 FBWT**, which is substantially higher than needed to accommodate the design traffic (ACN_{max} = 60).

Apparently there is an inconsistency between the design and evaluation modules of PCASE. Only when the CBR-values are reduced to non-standard values of 40 and 15%, the derived PCN is **57 FBWT**.

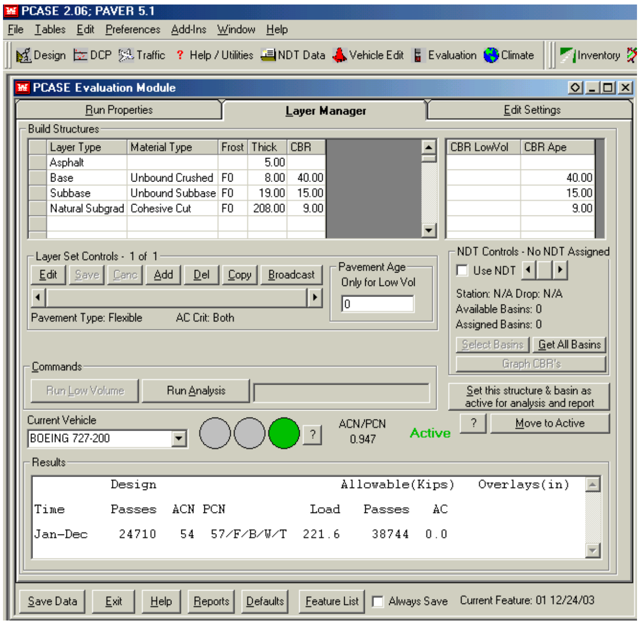

Figure 3 PCASE Evaluation module

6.2.3 Technical evaluation for flexible pavements using PCASE-LEA

For technical evaluation, PCASE uses the LEEP multi layer model developed at WES. The LEA mode also has a design and an evaluation module. In the design mode the following pavement is determined to suit the mixed traffic:

- 102 mm (4") asphalt (5000 MPa, 725,268 psi)
- 203 mm (19 ") unbound base (800 MPa, 116,043 psi);
- 483 mm (19") compacted sub-base (200 MPa or 29,011 psi);

on a 90 MPa (13,055 psi) subgrade.

Note that this pavement is thinner than that of the previous examples. Once material properties are assigned, the PCN can be calculated for the mixed traffic in the Evaluation Module: **PCN 69 FBWT** for a pavement with an 5" (127 mm) asphalt thickness.

6.2.4 Technical evaluation for flexible pavements using multi-layered elastic design

A summary list of the steps required for flexible pavement as based on the Technical evaluation method using a linear elastic design program like APSDS or PAVERS is:

1. Determine the traffic volume in terms of type of aircraft, and number of operations of each aircraft that the pavement will experience over its life (including lateral wander).
2. Determine the critical aircraft, i.e. the aircraft with the highest ACN.

3. Determine the pavement characteristics, including the subgrade CBR and pavement thickness.
4. Determine the critical pavement layer and calculate the Miner pavement damage due to the traffic mix that uses the pavement during the design life.
5. Calculate the Miner damage for the critical aircraft and calculate the equivalent number of passes.
6. Calculate the allowable gross weight of the critical aircraft using the number of passes of step 5 resulting in the same Miner damage as step 4.
7. Look up or calculate the ACNs of the critical aircraft at its operating empty (OEW) and maximum weight and at maximum takeoff weight (MTOW).
8. Determine the ACN that refers to the allowable mass of the critical aircraft.
9. Assign the pavements PCN to be the ACN of the critical aircraft.

The program can also determine the PCN based on a number of passes of an evaluation aircraft. The ICAO method tool does not dictate certain material properties nor dictates the use of certain fatigue transfer functions. As a consequence, several PCN values depending on the material properties and fatigue transfer functions to be assigned to a pavement can be assessed.
This implies that the bearing strength should be determined by a professional engineer or engineering consulting firm experienced in the analysis of the bearing strength of airfield pavements with a proper understanding of the (national) pavement materials used, in determining their ability to support airport loads, and in assessing the effect that aircraft loads are likely to have on the future structural performance and condition of the pavement.

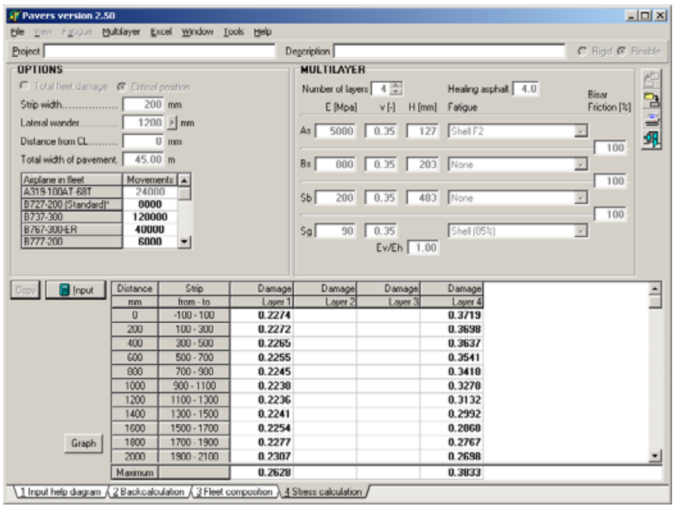

Figure 4 Example of pavement life calculation (step 3).

Table 9 reports PCN values for different fatigue transfer functions based on the traffic mix and a wander of 1,200 mm. The PCN is based on the subgrade, being the critical layer. Please note that PCN is based on the pavement structure given in Figure 4, which is not adequate to carry the aircraft according to Dutch design codes (generally regarded as too thin). Therefore the PCNs in Table 9 are illustrative only, explaining the influence of transfer functions to the PCN assignment. Note: ACN of B747-400 at MTOW/OEW is 64/22.

Transfer function	PCN	Code
Shell 85%	86	FBWT
Barker et al	56	FBWT
U.S. Corps of Engineers	64	FBWT
APSDS –MWHGL-data	43	FBWT

Table 9 Flexible PCN assigment based on linear elastic analysis

6.2.5 Technical evaluation for rigid pavement using PCA - PDILB

A summary list of the steps required for rigid pavements as based on the Technical evaluation method is:

1. Determine the traffic volume in terms of type of aircraft number of operations of each aircraft that the pavement will experience over its life.
2. Convert that traffic into a single critical (design) airplane equivalent.
3. Determine the pavement characteristics, including the subgrade soil modulus, k, and the concrete thickness and elastic modulus.
4. Calculate the minimum allowable gross weight of the critical aircraft on that pavement.
5. Look up or calculate the ACN of the critical aircraft at its maximum weight.
6. Assign the PCN to be the ACN of the critical aircraft.

Worked Example (courtesy Ed Gervais, Boeing)

An airport has a rigid runway pavement with an effective subgrade k-value of 200 pci (53,3 MN/m^3) and a slab thickness of 15 inches (381 mm). The concrete has a modulus of rupture of 700 psi (4,92 MPa), an elastic modulus of 4,000,000 psi (28.123 MPa), and a Poisson’s ratio of 0.15. The pavement life is estimated to be 20 years. The traffic shown in Table 10 is the same as in Table 7, but with Pass to load repetitions (P/LR) ratios and annual departures added. The stress ratio varies with load repetitions and is the so-called damage transfer function in the PCA method.

Airplane	Operating Weight, lb	Tire press. (psi)	ACN Rigid	P/LR Ratio	Annual Dept.	Life Load Repetitions	Stress Ratio
B727-200	185,000	148	55 RC	2.92	400	2,740	0.689
B737-300	130,000	195	41 RC	3.87	6,000	31,010	0.602
A319-100	145,000	196	43 RC	3.56	1,200	6.740	0.656
B747-400	820,000	200	67 RC	3.44	3,000	17,440	0.622
B767-300ER	370,000	190	61 RC	3.64	2,000	10,990	0.639
DC8-63	330,000	194	61 RC	3.32	800	4,820	0.668
MD11	515,000	205	71 RC	3.66	1,500	8,200	0.649
B777-200	600,000	215	76 RC	4.17	300	1,440	0.712

Table 10 Rigid pavement technical evaluation traffic

It is now necessary to calculate the required slab thickness for each airplane by utilizing the PCA (PDILB) program. The inputs are the concrete elastic modulus, Poisson’s ratio, and the aircraft parameters of weight, tire pressure, and allowable working stress as calculated from the stress ration. The allowable stress is calculated by multiplying the stress ratio by the modulus of rupture.

Airplane	Operating Weight, lb	Tire press. (psi)	Stress Ratio	Allowable stress (psi)	Required Thickness (in.)
B727-200	185,000	148	0.689	482	11.6
B737-300	130,000	195	0.602	421	11.1
A319-100	145,000	196	0.656	459	10.8
B747-400	**820,000**	**200**	**0.622**	**435**	**13.3**
B767-300ER	370,000	190	0.639	447	12.4
DC8-63	330,000	194	0.668	468	12.1
MD11	515,000	205	0.649	454	13.1
B777-200	600,000	215	0.712	498	12.2

Table 11 Technical evaluation critical airplane determination

Table 11 shows that the critical airplane is the B747-400 based on its required thickness. In this example, the B777-200 is not the critical airplane, even though it has the highest ACN. All departures must be converted to the B747-400 equivalent as shown in Table 12. For the purposes of this calculation, all wide-body wheel loads are considered to be 35,625 lb, including the critical airplane. Note that this table is identical to Table 8 for the flexible pavement worked example.

Airplane	Annual Dept.	Gear Type	(R2) Equiv. DT departures	(W2) Wheel load	(W1) 747-400 wheel load	(R1) 747-400 Equiv. Departures
B727-200	400	Dual	240	43,940	35,625	440
B737-300	6,000	Dual	3,600	30,875	35,625	2,045
A319-100	1,200	Dual	720	34,440	35,625	645
B747-400	3,000	DT	3,000	35,625	35,625	3,000
B767-300ER	2,000	DT	2,000	35,625	35,625	2,000
DC8-63	800	DT	800	39,190	35,625	1,110
MD11	1,500	DT	1,500	35,625	35,625	1,500
B777-200	300	DT	510	35,625	35,625	510
Total	15,200					11,250

Table 12 Equivalent annual departures of the critical airplane

Before the maximum allowable gross weight of the critical airplane can be determined, the effect of all the traffic must be considered in terms of stress ratio and the maximum working stress of the critical airplane. The allowable stress is calculated based on lifetime repetitions 11,250 times 20 years divided by the P/LR = 65,400. Hence the stress ratio is 0.575, resulting in a working stress of 700 times 0.575 is 403 psi (2,83 MPa).

Input parameters to the PCA computer program are:

- Critical airplane — B747-400
- Percent weight on the main gear — 95,0%
- Tire pressure — 200 psi (Code X)
- Slab thickness — 15,0 inches
- Subgrade k-value — 200 (Code C)
- Working stress — 403 psi

For these conditions, the calculated allowable gross weight of the B747-400 is 880,000 pounds. The 747-400 ACN is 76.4 RC, for a recommended runway rating of **PCN 77 RCWT**. Even though none of the aircraft having tire pressures that exceed the limits of Code X, the code for rigid pavement should normally be W.

6.2.6 Technical evaluation for rigid pavement using PCASE

The PCASE Evaluation module has two methods for determining rigid pavement PCN. When the APE criteria are used (Ref. 15), the Westergaard model is used for analysis. When the pavement is in sound condition, **PCN 75 RCWT** can be calculated. When using Layered Elastic Analysis (PCASE utilizes the WES program LEEP) with the same moduli values as given in § 6.2.5, a **PCN 79 RCWT** is assessed.

6.2.7 Technical evaluation for rigid pavement using advanced plate models

The procedure for assigning PCN to a pavement is similar to the flexible method, discussed in § 6.2.4. The UECSlab program calculates an allowable load with respect to the fatigue limit of concrete (stress limit is 50% of flexural strength), whereas PAVERS assigns a PCN based on accumulated Miner damage due to mixed traffic and allowable ACN load of the critical aircraft of the fleet mix. Both programs use the slab dimensions and temperature stress to calculate a PCN. The programs do not dictate a certain fatigue transfer function. Hence, the PCN largely depends on the selected material properties and fatigue relationship (e.g. local design method and materials).

Transfer function	PCN	Code
UEC (Ref. 36)	78	RCWT
Domenichini (Ref. 38)	66	RCWT
Corps of Engineers	81	RCWT
Eisenmann	70	RCWT
Vencon 1992	71	RCWT

Table 13 Rigid PCN assigment based on advanced plate models (Based on a total of 11,250 Equivalent B747-400 departures)

6.2.8 Overview of PCN results

The table below shows that technical derived PCNs are based on different design theories. Consequently, different design methods give different PCN results. Note that according to these design methods, the evaluated pavement cannot adequately support the traffic mix (In case flexible PCN is lower than 64 and for rigid pavements PCN is lower than 75). Therefore it must be borne in mind, that the PCN is not only related to the origin of the design method used, but also to the experience of constructed pavements, the assigned pavement material properties and skills of the pavement engineers.

Origin Method	PCN	Code
Flexible Pavement		
- CBR method S-77-1	55	FBWT
- PCASE-CBR	78	FBWT
- PCASE-LEA	69	FBWT
- Shell 85%	86	FBWT
- Barker et al	56	FBWT
- U.S. Corps of Engineers	64	FBWT
- APSDS –MWHGL-data	43	FBWT
Rigid Pavement		
- PCA-PDILB	77	RCWT
- PCASE-Westergaard	75	RCWT
- PCASE-LEA	79	RCWT
- UEC (Ref. 36)	78	RCWT
- Domenichini (Ref. 38)	66	RCWT
- Corps of Engineers	81	RCWT
- Eisenmann	70	RCWT
- Vencon 1992	71	RCWT

Note: Flexible ACN of B747-400 at MTOW/OEW is 64/22; Rigid ACN of B747-400 at MTOW/OEW is 75/25

Table 14 Overview of PCN-values

6.3 PCN, pavement life and overloads

In the life of a pavement, it is possible that either the current or future traffic will load the pavement in such a manner hat the assigned PCN rating is exceeded. As mentioned in § 2.5, ICAO presents a simplified method to account for minor pavement overloading in which the overloading may be adjusted by applying a fixed percentage to the existing PCN. This is subject to a limitation on the number of operations that the overloading airplane will have. However, this gives little guidance to the airport authority as well as to the impact of these adjustments on the pavement in terms of pavement life reduction or increased maintenance requirements.

An established and industry recognised engineering method appropriate to the pavement construction type should be used to determine the structural capability of a pavement to support proposed aircraft loads and traffic levels. The strength determination method should best rely on the results of in-situ pavement strength tests combined with a knowledge of the thickness and strength properties of the various material layers comprising the pavement structure.

In the previous paragraphs, the pavement life has been remained constant at a design life of 20 years. However, the PCN is in fact the allowable ACN load that consumes the pavement life. Hence, the pavement life itself (traffic and number of passes) is also a parameter influencing the PCN i.e. pavement life. A design life of 15 years results in a PCN 71 RCWT. Should a PCN of 100 be required, the structural pavement life is shortened to approximately 10 years.

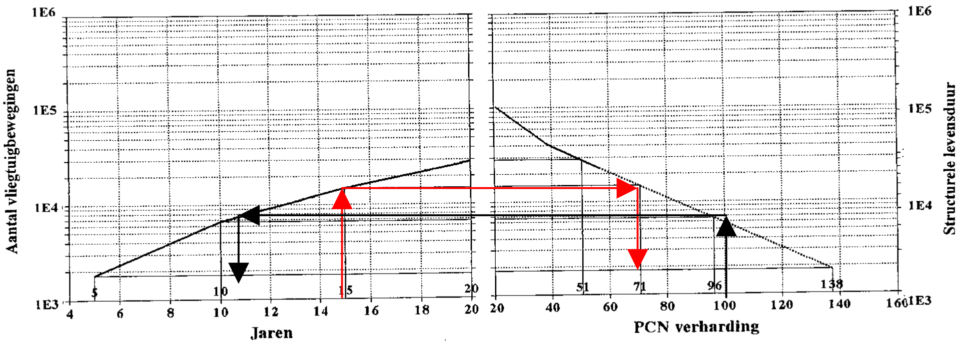

Figure 5 PCN as a function of the desired pavement life

In this perspective, the pavement design life also determines PCN. Pavements with the same bearing strength can be assigned a large PCN with respective small design life, but can also be assigned a small PCN with consequently a higher design life. Since the assignment of PCN is largely a business decision, an airport authority should also report the pavement life to a regulating CAA (Refs. 31, 38).

6.4 Discussion on PCN Assignment and Requirement for Harmonization

ICAOs ACN-PCN system does not dictate a specific design method for PCN assignment. Therefore, technical PCN values are often determined as an extension of existing national pavement design and evaluation technologies. As a consequence, the technical reported PCNs are likely to vary to a great extend.

There are a great number of sources that do have a profound influence on a technical derived PCN. Depending on the choice made in the technical PCN assignment, the PCN can vary over 200 per cent!. The list below is by far not complete, but merely gives an impression on the degrees of freedom in a PCN calculation:

- The PCN method used (either using aircraft or technical evaluation) for design or reconstruction;
- The use of empirical or analytical-mechanistic based methods;
- The evaluation method used in relation to the pavement damage and the preferred transfer relation;
- The pavement structural life accounted for in the PCN assessment i.e. level of traffic as well as the period of time to review PCN;
- The method to derive an annual traffic volume;
- A method to assign load pulses to account for stress or strain cycles due to multiple wheel arrangements with closely spaced wheels;
- The correctness or (lack of) fit of the design, or better say, evaluation method used (how well are our design methods);
- The test methods used to define pavement material characteristics and transfer functions;
- The method used to calculate statistical reliability.

As a continuation of this study, harmonization of the degrees of freedom in the analytical methods to be used is thought necessary. Harmonization is needed for standardization of the pavement models, the calculation steps, the assessment and/or selection of material characteristics (strength, transfer functions), the structural pavement life, the design criterion in relation to the true pavement damage, reliability concept as well as traffic and wander. Since sophisticated design tools already exist, it is recommended to concentrate on harmonization rather than developing software which is already available. In order to arrive at a comparable PCN strength rating on a national level, mutual agreement on the aforementioned engineering 'error' sources is necessary. The calculation steps, given in the previous paragraphs can be seen as a first step to a more uniform PCN reporting method for usage the Netherlands. Such an agreement or Guidance will ultimately lead to an unambiguous PCN assignment method. The Netherlands Civil Aviation Authority can regulatory prescribe the PCN assignment method the be used by national experts and consultants.

Harmonization of PCN derivation must be addressed on a national level first. However, NATO also is moving towards a PCN method based on linear, elastic theory coupled with empirical relationships for relating computed stress/strain to allowable aircraft load. This offers the possibility for a joint development. This option should be pursuit towards the upcoming CROW European Airport Pavement Workshop to be held in 2005.

7 Closure

It is important to have an unambiguous, generally accepted methodology for computing pavement damage, to allow airport operators and pavement engineers to adequately design pavements to accommodate new aircraft, and to allow airlines to anticipate airport pavement weight restrictions in planning their operations and in deciding which aircraft to purchase. An established and industry recognised engineering method appropriate to the pavement construction type should be used to determine the structural capability of a pavement to support proposed aircraft loads and traffic levels.

ICAO does not dictate a specific design method for PCN assignment. As a consequence PCNs can vary depending on the evaluation method used. However, ICAO does relate PCN to the structural pavement life and the volume of traffic to be encountered. The PCN can function as a pavement management tool, and its selection is largely a business decision by the airport authority. However, since ICAO does give guidance on assessing a relation between PCN and pavement life this is not a license for the airport to assign a desired PCN. It is recommended that when an airport authority reports a PCN to CAA, they must also submit the underlying structural pavement life to the responsible CAA. The reported PCN should be reviewed, re-affirmed or re-determined at least every ten (10) years. As part of the review process, consideration should be given to re-testing the strength of the pavement. If the review results indicate that pavement strength values have changed, the airport authority should make the appropriate revisions to the PCN code reported in the AIP manual.
The PCN requirement for NATO differ from civilian use. NATO-PCN reporting requirement consider standard use, mission use and contingency. The NATO nations can use existing national pavement design and evaluation technologies to report PCN. Only one PCN per runway has to be reported, where the type of aircraft and number of passes for which the PCN value is based, must also be provided. The additional information allows NATO to derive the aforementioned requirements for NATO-PCNs from nations reported PCN data.

The standard ACN calculation, particularly in case of flexible pavements, is suspected to improperly model pavement loading of multiple wheel heavy loading landing gear of heavy aircraft. A more fundamental approach which shifts emphasis from CBR subgrade criteria to Linear Elastic Design seems appropriate. One of the benefits is that pavement-load interaction is analyzed for each aircraft and each layer rather than using equivalent passes of a critical airplane, giving more realistic results. As pavement design and evaluation technology evolves using Layered Elastic Analysis and calibrated failure criteria derived from material testing and full-scale pavement tests, pavement prediction performance, design and technical PCN improve. Nevertheless it should be borne in mind that, although layered elastic based procedures, a considerable amount of engineering judgment is still required. It also implies that the bearing strength should be determined by a professional engineer or engineering consulting firm experienced in the analysis of the bearing strength of airfield pavements with a proper understanding of the (local) pavement materials used, in determining their ability to support airport loads, and in assessing the effect that aircraft loads are likely to have on the future performance and condition of the pavement.

As a continuation of this study, the PCN study team felt that harmonization of PCN calculation method and its degrees of engineering freedom, as well as the analytical methods to be used is thought necessary. Harmonization is needed with respect to the pavement models, the calculation steps, the assessment or selection of material characteristics (transfer functions), the structural pavement life, the design criterion in relation to the true pavement damage, reliability concept as well as traffic and wander. Since sophisticated design tools already exist, it is recommended to concentrate on harmonization to arrive at PCNs, rather than developing already available software. The guidance can regulatory be prescribed by national Civil Aviation Authorities to arrive at reproducible and realistic pavement designs and comparable PCNs.

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