CORRESPONDENCE BETWEEN ICAO ACN OVERLOAD CRITERIA AND CUMULATIVE DAMAGE FACTOR CALCULATIONS

By:

Gordon F. Hayhoe
FAA Airport Technology R&D Branch, AJP-6312
William J. Hughes Technical Center
Atlantic City International Airport, NJ 08405
USA
Phone: (609) 485-8555
gordon.hayhoe@faa.gov

PRESENTED FOR THE
2010 FAA WORLDWIDE AIRPORT TECHNOLOGY TRANSFER CONFERENCE
Atlantic City, New Jersey, USA

April 2010

ABSTRACT

Criteria for overload evaluation of airport pavements are contained in ICAO documents Annex 14, Attachment A and the Aerodrome Design Manual Part 3, and are stated in terms of the amount the ACN of an overload airplane can exceed the listed PCN of the pavement. But most modern airport pavement design procedures define the level of pavement deterioration in terms of cumulative damage factor (CDF). A mathematical relationship between an increment of ACN and an increment of CDF is derived so that overload operations evaluated by a CDF-based design procedure can be compared directly with the ICAO criteria. The relationship states that, if the allowable value of the ACN of an overload aircraft relative to the PCN of the pavement is taken to be given by, for example, a ratio of 1.1, then this represents an allowable change in CDF of approximately 0.5 due to the addition of an overload aircraft relative to the design condition of CDF = 1. The numerical value of the ratio of change of CDF to change of ACN varies with the sensitivity of the CDF-based design procedure to changes in airplane loading. The relationship can be calibrated for the CDF-based design procedure if desired.

INTRODUCTION

Criteria for overload evaluation of airport pavements are contained in ICAO documents Annex 14, Attachment A (reference 1) and the Aerodrome Design Manual Part 3 (reference 2), and are stated in terms of the amount the ACN of an overload airplane can exceed the listed PCN of the pavement. Specifically, Chapter 2 of the Design Manual states:

> For those operations in which magnitude of overload and/or the frequency of use do not justify a detailed analysis the following criteria are suggested:
>
> a. For flexible pavements occasional movements by aircraft with ACN not exceeding 10 per cent above the reported PCN should not adversely affect the pavement;
> b. For rigid pavements, in which a rigid pavement layer provides a primary element of the structure, occasional movements by aircraft with ACN not exceeding 5 per cent above the reported PCN should not adversely affect the pavement;
> c. If the pavement structure is unknown the 5 per cent limitation should apply; and
> d. The annual number of overload movements should not exceed approximately 5 per cent of the total annual aircraft movements.

Higher levels of ACN-to-PCN ratios, up to a factor of 2, are recommended in practices reported for three member states, Canada, France, and the United Kingdom. This paper considers only the 10 and 5 percent recommendations, although the general methodology can be extended to higher ratios.

Annex 14 specifies that ACN values shall be computed with only two design procedures:

1. For flexible pavements, the procedure is based on the USACOE ESWL CBR method of design using alpha factors adopted by ICAO in October 2007. Thickness is computed for 10,000 coverages.
2. For rigid pavements, the procedure is based on the PCA Westergaard interior stress method of design. Thickness is computed for 10,000 coverages.

The traffic models used with the CBR and the PCA methods are usually based on converting each of the aircraft in the mix to an equivalent number of departures (or coverages) of a design aircraft. Computation of ACN is also based on a traffic model in which traffic is fixed at 10,000 coverages. However, recently developed airport pavement thickness design procedures are typically based on a traffic model which computes a cumulative damage factor (CDF) for each of the aircraft in the mix. Adding an overload aircraft to a mix will provide an increment due to that aircraft to the total CDF which can be used to evaluate the level of incremental damage caused by the overload aircraft. The ACN-to-PCN ratio method of evaluating the load rating of overload aircraft has been in use for many years and a reliable way of converting the ACN-to-PCN ratio to an equivalent CDF would provide backward compatibility with the ACN-PCN method.

The ACN-to-PCN ratio method and the CDF method are incompatible in two respects:

1. ACN is computed independently of the existing pavement structure's thickness whereas CDF is computed from the existing pavement's thickness.
2. ACN is computed for a fixed level of traffic of 10,000 coverages whereas CDF is computed for the applied level of traffic.

In order to derive a relationship between the ACN-to-PCN ratio and the CDF of an overload aircraft, a relationship between ACN and pavement thickness is derived, a relationship between change in pavement life and change in pavement thickness is stated, and it is assumed that CDF is a general expression of accumulated damage and that the same numerical value can represent either the additional damage caused by additional traffic from the design (or critical) aircraft and the additional damage caused by traffic from an aircraft other than the design (or critical) aircraft. The term design aircraft refers to the equivalent aircraft for design and the term critical aircraft refers to the equivalent aircraft used in load evaluation (computation of PCN). as used in this paper, the two terms are interchangeable.

RELATIONSHIP BETWEEN ACN AND THICKNESS

ACN is defined in terms of the damage caused by the aircraft in question divided by the damage caused by a reference single-wheel load, according to the following relationship:

$$ACN = \frac{2 \times DSWL}{1000}$$

Where DSWL is the Derived Single Wheel Load in kg and is equal to an equivalent single-wheel load for the aircraft in question and for which the contact tire pressure is 1.25 MPa (see reference 2). The reference single-wheel load is 2 / 1000 = 500 kg. It follows that the ratio of the

ACNs of two different aircraft can be found by elimination of the reference load from the ACN versus reference load relationship.

For flexible pavements, the CBR equation directly provides the following equation:

$$\frac{ACN_2}{ACN_1} = \left(\frac{t_2}{t_1}\right)^2 \tag{1}$$

Where:

t_1 = the design thickness for aircraft 1 at 10,000 coverages
t_2 = the design thickness for aircraft 2 at 10,000 coverages

A simple relationship as in equation 1 cannot be derived for rigid pavements. However, figure 1 shows that equation 1 closely represents the ACN versus slab thickness relationship for rigid pavements, particularly when ACN is greater than 60. Equation 1 can therefore be used for rigid pavements if it is remembered that the relationship is not exact.

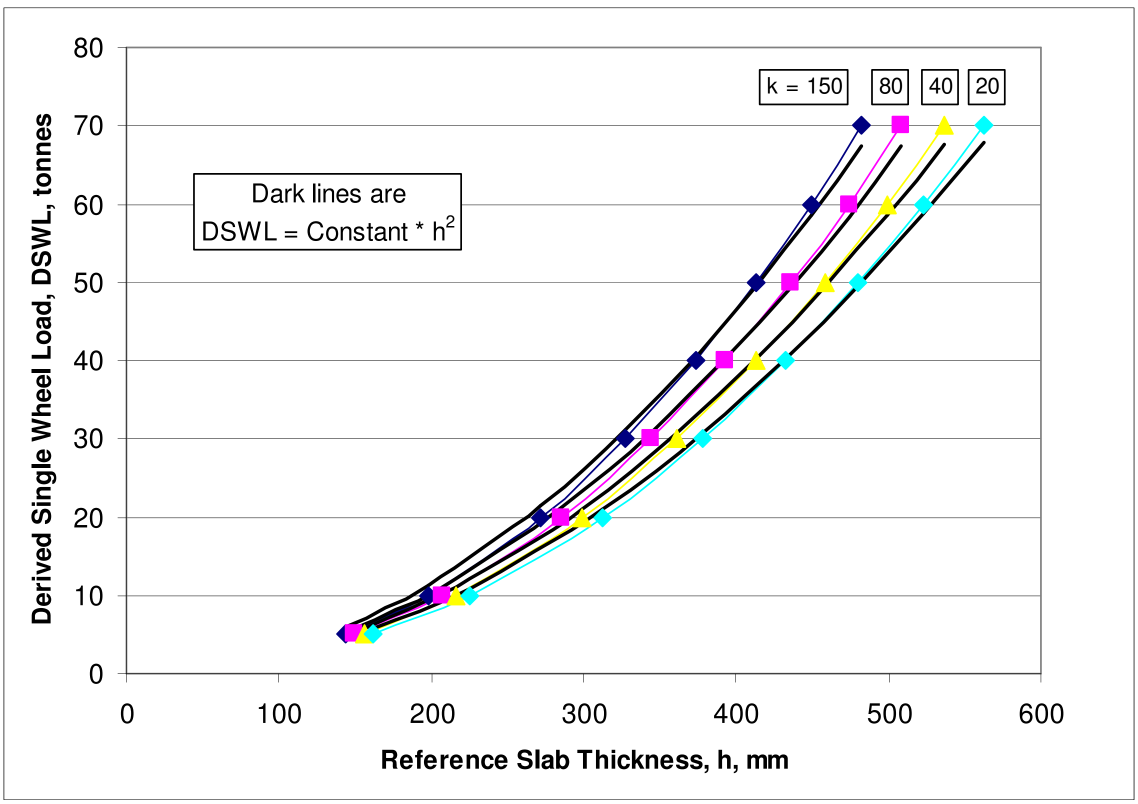

Figure 1. Relationship between DSWL and slab thickness for rigid pavements on the four standard support strengths. Units for k are MN/m^3.

SENSITIVITY OF PAVEMENT LIFE TO THICKNESS

The sensitivity of change in pavement life to change in pavement thickness is defined as follows (see the appendix for more information on the derivation of sensitivity and typical values):

$$S_t = \frac{\Delta L}{\Delta t}\frac{t}{L} = \frac{\Delta N}{\Delta t}\frac{t}{N} \text{, or} \tag{2}$$

$$\frac{N_2 - N_1}{N_1} = S_t\left(\frac{t_2 - t_1}{t_1}\right) \tag{3}$$

Where:

S_t = sensitivity of change in pavement life to change in pavement thickness
L = pavement life in years
N = pavement life in coverages = L times the number of annual coverages
N_1 = pavement life for thickness t_1 and for a defined load
N_2 = pavement life for thickness t_2 and for a defined load

DEFINITION OF CUMULATIVE DAMAGE FACTOR

CDF is derived from Miner's Rule, which states that the damage induced in a structural element is proportional to the number of load applications divided by the number of load applications required to fail the structural element. In airport pavement design, load applications are usually counted in coverages, so the relationships are all defined in terms of coverages. Conversions to, and from, departures can always be made if the pass-to-coverage ratio of an aircraft is known.

$$CDF = \frac{N}{N_F} \tag{4}$$

Where:

N = number of coverages applied to a pavement by a given aircraft on a given pavement
N_F = number of coverages to failure for the same aircraft on the same pavement

RELATIONSHIP BETWEEN ACN-TO-PCN RATIO AND CDF

Let:

t_1 = total design thickness of the existing pavement by the CBR method
= total thickness for 10,000 coverages of the design aircraft used to determine the PCN of the pavement
ACN_1 = PCN of the existing pavement
= ACN of the design aircraft
t_2 = total design thickness for 10,000 coverages of the overload aircraft by the CBR method
ACN_2 = ACN of the overload aircraft

Then the ratio of the ACN of the overload aircraft to the PCN of the pavement is:

$$ACN_R = \frac{ACN_2}{ACN_1} = \left(\frac{t_2}{t_1}\right)^2 \tag{5}$$

Now assume that:

T_2 = total design thickness for N_2 coverages of the design aircraft (aircraft 1)
N_1 = 10,000 coverages (as used in the calculation of the ACN of the design aircraft)
N_{1F} = number of coverages to failure for the design aircraft
= 10,000 (as used in the calculation of the ACN of the design aircraft)

From the definition of sensitivity (equation 3):

$$\frac{N_2 - N_1}{N_1} = S_t\left(\frac{t_2 - t_1}{t_1}\right) \tag{6}$$

and, from equation 5:

$$t_2 = t_1\sqrt{ACN_R} \tag{7}$$

Substituting for t_2 in equation 6:

$$\frac{N_2 - N_1}{N_1} = S_t\left(\sqrt{ACN_R} - 1\right) \tag{8}$$

The above derivation is for the following conditions:

1. N_1 and N_2 are the coverages to failure for the same airplane operating on two different pavement thicknesses.

2. ACN_R is the ratio of the ACN of the overload aircraft to the ACN of the design aircraft, where the ACN of the overload aircraft is computed with the same pavement thickness as used to compute N_2 coverages to failure.

But if the left hand side of equation 8 is interpreted in the CDF sense, it can be rewritten as $\frac{N_2 - N_1}{N_{1F}}$ since, by definition, $N_1 = N_{1F} = 10{,}000$.

Therefore:

$$\frac{N_2}{N_{1F}} - \frac{N_1}{N_{1F}} = S_t\left(\sqrt{ACN_R} - 1\right) \tag{9}$$

Where:

$\frac{N_1}{N_{1F}}$ = CDF of the design aircraft operating for N_1 coverages on a pavement of thickness t_1

= 1 since $N_1 = N_{1F}$

$\frac{N_2}{N_{1F}}$ = CDF of the design aircraft operating for N_2 coverages on a pavement of thickness t_1

Therefore the change in the accumulated damage in the pavement structure due to the change in the number of coverages of the design aircraft from N_1 to N_2 is:

$$\frac{N_2}{N_{1F}} - 1 = \Delta CDF = S_t\left(\sqrt{ACN_R} - 1\right) \tag{10}$$

The appendix shows that, for the examples considered there, values of sensitivity to change of pavement thickness range from about 10 to about 30, with an average for large airport operations of about 20.

Assume that $S_t = 10$ and $ACN_R = 1.1$

Then $\Delta CDF = 10$ (1.049 – 1) = 10 x 0.049 = 0.49

And for $ACN_R = 1.05$

$\Delta CDF = 10$ (1.0247 – 1) = 10 x 0.0247 = 0.247

If it is assumed that $S_t = 20$, then the corresponding values of ΔCDF are about 1.0 and 0.5.

But CDF is a general expression of accumulated damage and the same numerical value can represent either the additional damage caused by an overload aircraft other than the design aircraft or the additional damage caused by additional traffic applied by the design aircraft (as was assumed in the derivations).

Therefore, if the allowable value of the ACN of an overload aircraft relative to the PCN of the pavement is taken to be given by a ratio of 1.1, then this represents an allowable change in CDF relative to the design condition of CDF = 1, due to the addition of an overload aircraft, to be approximately in the range of 0.5 to 1.0. This is for the ICAO recommendation stated in the introduction for flexible pavements. For rigid pavements the corresponding allowable change in CDF would be approximately in the range of 0.25 to 0.5.

CONCLUSIONS

A derivation has been given of an approximate relationship between the ICAO ACN-to-PCN ratio and an incremental CDF due to the addition of an overload aircraft to an existing mix. The relationship is approximate in the case of flexible pavements because the assumed value of the sensitivity of pavement life to change in pavement thickness varies with pavement and aircraft properties. For rigid pavements there is additional uncertainty from the ACN versus thickness relationships not being exactly quadratic, as assumed in the derivation. Nevertheless, reasonable guidelines are provided to give backward compatibility between the newer CDF-based design procedures and their equivalent-design-aircraft-based predecessors.

ACKNOWLEDGEMENTS

The work described in this paper was supported by the FAA Airport Technology Research and Development Branch, AJP-6310, Dr. Satish K. Agrawal, Manager. The contents of the paper reflect the views of the author, who is responsible for the facts and accuracy of the data presented within. The contents do not necessarily reflect the official views and policies of the FAA. The paper does not constitute a standard, specification, or regulation.

REFERENCES

1. "Annex 14 to the Convention on International Civil Aviation, Aerodromes, Volume 1, Aerodrome Design and Operations, ," International Civil Aviation Organization, Montreal, Canada, Fourth Edition, July 2004.
2. "Aerodrome Design Manual (Doc 9157-AN/901), Part 3, Pavements," International Civil Aviation Organization, Montreal, Canada, Second Edition, 1983.

APPENDIX – Sensitivity of Pavement Life to Variation in Pavement Thickness

The sensitivity of pavement life, *L*, to any variable *x* is defined as the proportional change in life of a pavement structure due to a proportional change in the value of the specified parameter, or:

$$S_x = \frac{\Delta L}{L}\frac{x}{\Delta x} \qquad \text{(A-1)}$$

where:

S_x = sensitivity to parameter x
x = value of the parameter x
Δx = small change in the parameter x
L = pavement life in years
ΔL = change in pavement life due to the change Δx

For very small changes, equation A-1 can be rewritten as:

$$S_x = \frac{\partial L}{\partial x}\frac{x}{L} \tag{A-2}$$

Using this definition, and given a particular design procedure, the effect on pavement life of any variable x incorporated in the design procedure can be quantified. For this paper, the sensitivity to variations in total pavement thickness is of interest and the discussion will be restricted to the effect of this variable only. The failure model of the equivalent single wheel load CBR flexible pavement design procedure has an analytic solution for variation in pavement thickness if the CBR equation in use prior to publication of the Multiple Wheel Heavy Gear Load (MWHGL) report is used. The equation derived in the MWHGL study gives almost the same results as the earlier equation except at the extremes of subgrade strength and when ignoring the change to alpha factor curves to describe traffic. The earlier equation is therefore used as an example of deriving sensitivity analytically.

The earlier CBR equation for flexible airport pavement thickness design is:

$$t = \left(0.23\ \mathrm{Log}_{10}(N) + 0.15\right) P^{1/2} \left(\frac{1}{8.1\,CBR} - \frac{1}{p\,\pi}\right)^{1/2} \tag{A-3}$$

where:

t = total pavement thickness
N = coverages to failure for the design aircraft
P = equivalent single wheel load (ESWL) for the design aircraft
p = contact pressure for the equivalent single wheel
P/A
A = contact area of a single tire on the design aircraft
= contact area of the equivalent single wheel

$$\text{But, } \mathrm{Ln}(N) = \mathrm{Ln}(10).\mathrm{Log}_{10}(N)$$
$$= 2.3026\ \mathrm{Log}_{10}(N), \text{ and}$$

$$0.23\ \mathrm{Log}_{10}(N) = \frac{\mathrm{Ln}(N)}{10} \text{ with very little error} \tag{A-4}$$

Substituting A-4 into A-3 gives:

$$t = \frac{1}{10}\left(\mathrm{Ln}(N) + 1.5\right) P^{1/2} \left(\frac{1}{8.1CBR} - \frac{1}{p\pi} \right)^{1/2} \quad \text{(A-5)}$$

And, rearranging:

$$\mathrm{Ln}(N) = 10\, t . P^{-1/2} \left(\frac{1}{8.1CBR} - \frac{1}{p\pi} \right)^{-1/2} - 1.5 \quad \text{(A-6)}$$

Differentiating with respect to *t*:

$$\frac{\partial\, \mathrm{Ln}(N)}{\partial\, t} = 10P^{-1/2} \left(\frac{1}{8.1CBR} - \frac{1}{p\pi} \right)^{-1/2}$$

But: $\frac{\partial N}{\partial t} = N \frac{\partial \mathrm{Ln}(N)}{\partial t} = 10N.P^{-1/2} \left(\frac{1}{8.1CBR} - \frac{1}{p\pi} \right)^{-1/2}$

Now using:

$$N = a_T.CP.L \text{ and } \frac{\partial L}{\partial N} = \frac{1}{a_T.CP}$$

where:

a_T = equivalent annual departures for the design aircraft
CP = coverage to pass ratio for the design aircraft

Gives:

$$\frac{\partial L}{\partial t} = \frac{\partial L}{\partial N} \frac{\partial N}{\partial t} = 10 \frac{a_T.CP.L}{a_T.CP} P^{-1/2} \left(\frac{1}{8.1CBR} - \frac{1}{p\pi} \right)^{-1/2} = 10\, L.P^{-1/2} \left(\frac{1}{8.1CBR} - \frac{1}{p\pi} \right)^{-1/2}$$

Sensitivity to thickness is given by:

$$S_t = \frac{\partial L}{\partial t} \frac{t}{L} = 10\, L.P^{-1/2} \left(\frac{1}{8.1CBR} - \frac{1}{p\pi} \right)^{-1/2} . \frac{t}{L}$$

Substituting for *t* from equation A-5:

$$S_t = 10\, L.P^{-1/2} \left(\frac{1}{8.1CBR} - \frac{1}{p\pi} \right)^{-1/2} . \frac{1}{L} . \frac{1}{10} \left(\mathrm{Ln}(N) + 1.5\right) P^{1/2} \left(\frac{1}{8.1CBR} - \frac{1}{p\pi} \right)^{1/2}$$

And:

$$S_t = \mathrm{Ln}(N) + 1.5 \quad \text{(A-7)}$$

Sensitivity to load is, therefore, for the CBR equation, a function of only coverages to failure, *N*, (but remember that coverages to failure is a function of all of the other parameters in the CBR equation, including the implied aircraft gear configuration and load). Figure A-1 charts the relationship. The value of sensitivity increases as coverages increase. Over the typical range of airport operation, the value lies within the range of about 10 to 14, with an average of about 12.

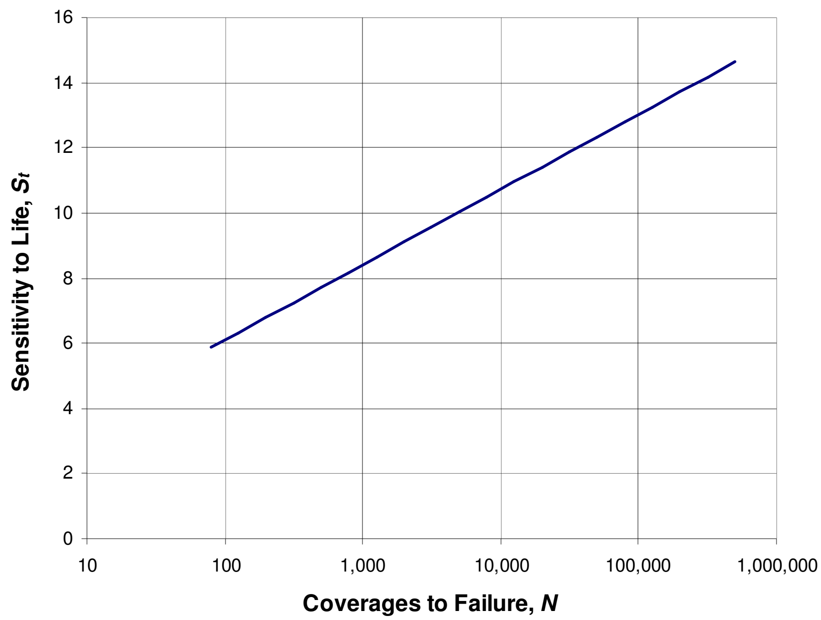

Figure A-1. Sensitivity of life to total thickness versus coverages to failure, flexible pavement, analytic solution.

The latest version of the CBR design procedure, as implemented in the computer program COMFAA 3.0, is now used to provide examples of numerically deriving values of sensitivity to change of pavement thickness. The derivation procedure in general terms is as follows:

1. Select aircraft and pavement properties necessary to compute pavement thickness.
2. Compute, or otherwise determine, pavement thickness, t_1.
3. Increase pavement life by a small amount from L_1 to L_2.
4. Find pavement thickness, t_2, for life L_2.
5. Compute sensitivity from equation 2 given in the main body of the paper.

$$S_t = \frac{\Delta L}{\Delta t}\frac{t}{L} = \frac{\Delta N}{\Delta t}\frac{t}{N}, \text{ or}$$

$$S_t = \frac{(N_2 - N_1)}{(t_2 - t_1)} \frac{t_1}{N_1} \qquad \text{(A-8)}$$

A single-wheel 50,000 lb (22.68 tonnes) aircraft load was selected in COMFAA 3.0 and subgrade strength for flexible design set at 10 CBR. Thickness design was executed with "Flex 20yr Covs" set at 50, 500, 5,000, 50,000, and 500,000 coverages. The thickness designs were repeated with the 20-year coverages increased by 1 percent (50.5, 505, etc.) and values of S_t computed for each set of coverage values according to equation A-8. The single-wheel load was then replaced by the ICAO example 747 aircraft, with gross weight set at 777,996 lbs (352.9 tonnes), and the exercise repeated. The results are shown in figure A-2, where it can be seen that, at high coverage levels, the values of sensitivity are considerably higher than those shown in figure A-1. It can also be seen that the sensitivity for the four-wheel gear is much higher than for the single wheel at the higher coverage levels. The average value of sensitivity for close to 10,000 coverages is about 16.

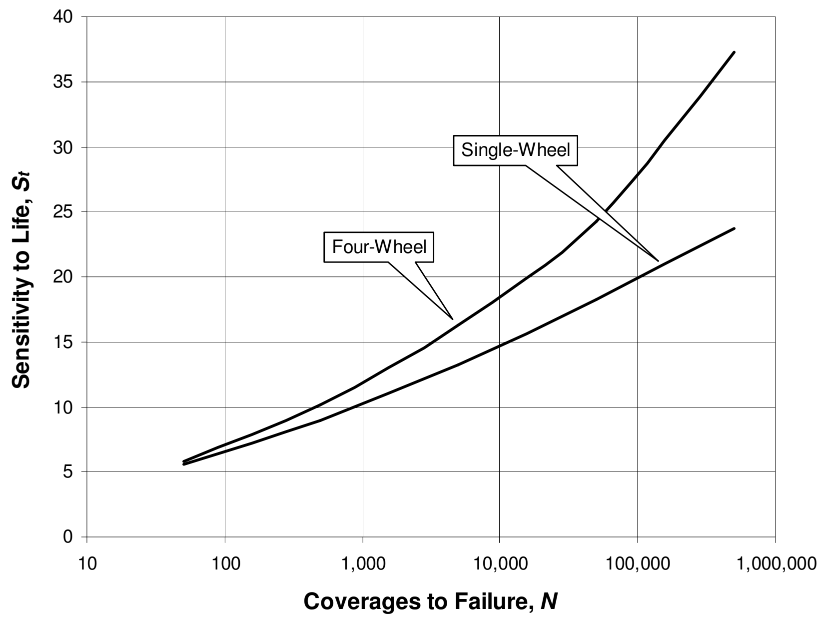

Figure A-2. Sensitivity of life to total thickness versus coverages to failure, flexible pavement, numerical solution using COMFAA 3.0.

The same exercise was repeated with the 747 but for rigid pavement thickness design with the COMFAA 3.0 computer program. PCA and FAA (AC 150/5320-6D) designs were run with support strength set at 297.4 pci (80 MN/m^3) and concrete strength at 650 psi (4.482 MPa). The results are shown in figure A-3. It can be seen that the PCA and FAA trends are opposite and that the FAA trend has a break at 5,000 coverages corresponding to the change in slope of the FAA failure model at 5,000 coverages. An average value of sensitivity for close to 10,000 coverages is about 20.

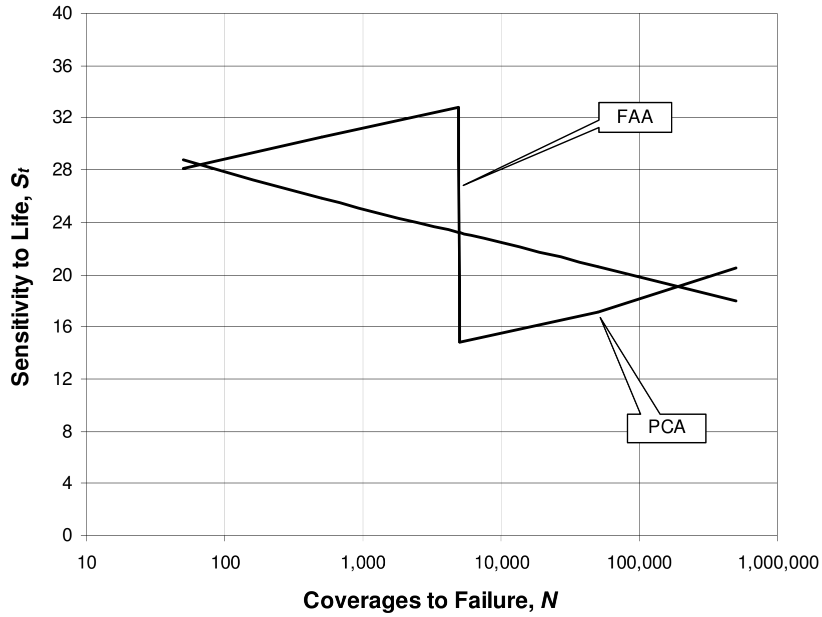

Figure A-3. Sensitivity of life to total thickness versus coverages to failure, rigid pavement, numerical solution using COMFAA 3.0.

More discussion of the application of sensitivity analysis can be found in reference A-1, including application to other design procedures and further results.

REFERENCES

A-1. "Operational Life of Airport Pavements," Report DOT/FAA/AR-04/46, Federal Aviation Administration, December, 2004.