TOWARDS CALIBRATION OF APSDS FOR SIX WHEEL GEAR LOADS

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ABSTRACT

The empirical basis for aircraft pavement thickness determination is the full scale trafficking tests performed by the US Corps of Engineers between the 1940s and 1970s. This culminated in the publishing of the S77-1 design method, which relates subgrade deflection to the number of allowable repetitions of that deflection. Pavement life was found to depend not only upon the magnitude of deflection, but also upon the aircraft wheel configuration that produced that deflection. Consequently, different pavement thickness adjustment factors, called Alpha Factors, were required for each different wheel configuration.

APSDS uses strain as its indicator of pavement damage. The APSDS relationships between strain and pavement life were not obtained by direct calibration against the Corps' full-scale trafficking tests, but by calibrating against S77-1. The initial APSDS calibration considered only dual and dual-tandem aircraft at maximum weight, and two coverage levels of 10,000 and 100,000. The relationships (subgrade failure criteria) were found to depend upon subgrade CBR. It was, however, assumed that the failure criteria were independent of wheel configuration.

Calibration of APSDS has been repeated using a range of aircraft operating weights, and aircraft passes ranging from 100 to 100,000. The six wheeled undercarriages of the B777 and A380 were also included. Most importantly, the aircraft were considered according to their different wheel configurations.

The agreement between APSDS calculated thicknesses and S77-1 thicknesses is significantly improved when aircraft with different wheel configurations are considered separately. This indicates that pavement life depends on both the magnitude of strain as well as the wheel configuration that produced that strain. This is not consistent with the current FAA design methodology, for which the relationship between induced strain and allowable coverages is a function only of induced strain.

INTRODUCTION

Aircraft pavement thickness design, even when performed with mechanistic-empirical tools, remains tied to the results of full scale testing conducted between the 1940s and 1970s by the US Army Corps of Engineers. This testing culminated in the publishing of the S77-1 design method in 1977 [1], which remains the basis for calibration of most flexible aircraft pavement design methods today. For layered elastic and other mechanistic-empirical design tools, one or more failure criteria are required to relate the indicator of damage to an allowable number of repetitions of that magnitude of damage. Calibration of such tools involves determining failure criteria that produce calculated pavement thicknesses that are, on average, as close as possible to the empirical relationship.

The recalibration of APSDS to S77-1 is presented for CBR 6% subgrade. This forms the basis of a methodology for the full recalibration of the software. The importance of wheel configuration on pavement thickness is demonstrated and justifies the need to treat one, two, four and six wheel aircraft gears separately during the calibration process.

The input parameters are detailed following discussion regarding the limitations of the original calibration effort. A wide mesh of trial calibration constants is detailed and the iterative concentration on the area of minimum average difference is presented. The analysis is repeated with aircraft separated by their wheel configuration and the results are compared to those that would be obtained if the original calibration constants were retained.

S77-1 PAVEMENT DESIGN

S77-1 relates subgrade deflection under a single load event to the allowable number of repetitions of that deflection, based on full scale test results. In the development of S77-1, pavement life was found to depend not only upon the induced deflection but the configuration of the wheels that induced that deflection. Consequently, pavement thickness correction factors, known as Alpha Factors, were introduced for different aircraft wheel configurations. Some researchers have hypothesised that the need for Alpha Factors could be avoided by the adoption of a strain-based damage indicator.

The S77-1 curve provides a pavement thickness of a predetermined composition. The standard S77-1 pavement structure is shown in **Figure 1**. P401, P209 and P154 are standard designations for the described materials, utilised by the US Federal Aviation Administration (FAA) for design and specification purposes [2]. It is noted that the S77-1 curve is a best-fit curve to the full scale test data, with no built-in factors of safety. COMFAA [3] was used for the calculation of S77-1 pavement thicknesses.

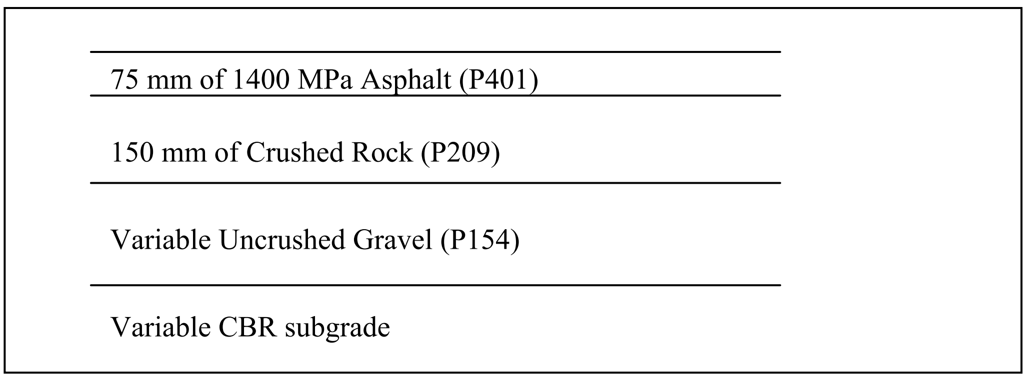

Figure 1. Standard S77-1 Pavement Structure

AIRPORT PAVEMENT STRUCTURAL DESIGN SYSTEM

Mechanistic-empirical or (layered elastic) design for aircraft pavement thickness determination was introduced into regular practice in the mid 1990s by the introduction of the of the FAA's LEDFAA software [4]. At about the same time the Australian developed Airport Pavement Structural Design System (APSDS) also became commercially available [5]. Both LEDFAA and APSDS utilise strain as the indicator of damage.

APSDS is a specialised version of the road design tool Circly [6]. APSDS incorporates the unique feature of modeling all the aircraft in all their wandering positions across the pavement surface. This approach negates the requirement for the traditional Pass-to-Cover Ratio (PCR) and provides a Cumulative Damage Factor (CDF) for all aircraft at all locations across the pavement width. When an APSDS pavement thickness is compared to a S77-1 calculated thickness, a PCR is required to convert the modeled number of aircraft passes (in APSDS) to an equivalent number of coverages (for S77-1).

CHICAGO CRITERIA

The original calibration of APSDS was performed not against full scale test results of the US Army Corps of Engineers, but against S77-1 pavement thicknesses. This calibration exercise is reported by Wardle, *et al* [7]. Calibration involved determining APSDS failure criteria that optimised the difference in total thickness between APSDS and S77-1 for a range of aircraft and a number of subgrade moduli.

The original calibration constants are commonly known as the Chicago Criteria. The Chicago Criteria were derived based on the assumption that pavement life was independent of aircraft wheel configuration. A number of other limitations have been identified in the generation of the Chicago Criteria. These limitations include:

- **Aircraft**. Only aircraft with two and four wheel gear configuration were considered. With the introduction of the B777 and the A380, six wheel gears are now also important. Designing for single wheeled aircraft such as the military F111 and FA18 is also considered to be important.
- **Aircraft Passes**. Only two levels of aircraft coverages were considered for each aircraft. These were 10,000 and 100,000 coverages. In practice pavements are designed to cater for a much greater range of aircraft numbers.
- **Aircraft Masses**. All aircraft were modeled at their maximum mass. Aircraft commonly operate at significantly below their maximum mass.

The Chicago Criteria are all of the form shown in **Equation 1** and the values of the Chicago Criteria calibration constants are detailed in **Table 1** for select subgrade CBRs.

$$N = (k/\varepsilon)^{b} \qquad \text{Equation 1}$$

Where: N = the predicted life in terms of repetition of subgrade strain ε.
ε = the induced vertical strain at the top of the subgrade.
k = material constant, a calibration constant.
b = material exponent, a calibration constant.

Table 1.
Chicago Criteria calibration constants

Subgrade CBR (%)	k	B
3	0.0032	9.5
6	0.0030	10.9
10	0.0024	15.0
15	0.0020	23.6

For the Chicago Criteria, the differences between APSDS and S77-1 thicknesses have a median of around 60 mm. Some scatter between APSDS and S77-1 thicknesses is always expected, primarily resulting from the difference in utilising strain (in APSDS) and deflection (in S77-1) as the indicator of damage [7]. Deflections attenuate much slower than strains as one moves horizontally away from under an aircraft tyre. This results in greater wheel interaction being modeled by deflection-based design tools.

CALIBRATION METHODOLOGY

Ideally, APSDS and other aircraft pavement thickness design tools would be calibrated directly against the results of full scale testing performed by the Corps. However, the Corps' test data for higher strength subgrades and lighter aircraft was very limited, making a broader direct calibration of APSDS problematic [7]. S77-1 has been used over many years to design pavements. The performance of the pavements has generally been satisfactory, and therefore this experience constitutes an extension to the original empirical test data. On this basis, in this study APSDS has been calibrated against S77-1 pavement thicknesses to produce a layered elastic design tool that is appropriate for all subgrade strengths. This use of S77-1 as a source of calibration data effectively accepts the S77-1 as a true representation of the empirical pavement performance data. S77-1 was used for the original calibration of APSDS [7] as well as the original version of LEDFAA. As the more recent full scale test data become available in the form of a revised S77-1 curve or replacement Alpha Factors, this calibration should be repeated.

CALIBRATION PROCESS

The calibration process initially required the selection of aircraft and pavement variables. A number of trial calibration constants were then selected and pavement thicknesses generated both in APSDS and from S77-1 (using COMFAA). Thicknesses were compared until the calibration constants optimised the difference between the APSDS and S77-1 thicknesses. As a part of the calibration process, a number of other issues were considered to be worthy of investigation. These included:

- **Comparison with Chicago Criteria**. As this calibration process was designed to generate calibration constants that would replace the Chicago Criteria, comparison of the accuracy of the new constants to that of the Chicago Criteria was considered essential. New constants that resulted in a greater average difference would not be justified.

- **Importance of Wheel Configuration**. The presence of the Alpha Factor in the S77-1 design procedure indicated that the number of wheels on each aircraft gear had an affect on the pavement thickness required. It was considered that the calibration of APSDS to S77-1 may therefore also be aircraft wheel configuration specific. Whether a significant improvement in the calibration would be obtained by generating separate calibration constants for each aircraft wheel configuration was considered worthy of investigation.

- **Precision of Calibration Constants**. The current calibration constants have two and three significant figures for k and b respectively. The more precise the calibration constants, the greater effort required to determine them in an iterative manner. The improved level of agreement between APSDS and S77-1 achieved with additional calibration constant precision was considered worthy of evaluation against the additional effort required to obtain more precise constants.

Recommendations could then be made for application during the full recalibration of APSDS, which would also incorporate the six wheel gear arrangement for other subgrades.

INPUT VALUES AND CONSTANTS

Much effort was made in ensuring that the input values were consistent for both APSDS and COMFAA. This was particularly important where the inputs are expressed in difference ways, such as aircraft wander in APSDS and the PCRs used for calculating equivalent aircraft coverages in COMFAA. Input values and constants were selected as follows.

Aircraft Variables

In order to allow the calibration process to cater for the widest possible range of aircraft types, single, dual, dual-tandem and dual-tridem gear configurations were considered. Two aircraft of each wheel configuration were selected as detailed in **Table 2**.

Table 2.
Aircraft details

Aircraft	Gear Configuration	Maximum Mass (t)	Tyre Pressure (MPa)
FA18	Single	24	1.72
F111	Single	51	1.48
BAe146	Dual	41	0.88
B737-800	Dual	79	1.36
B747-400	Dual-tandem	397	1.38
A340-600	Dual-tandem	366	1.38
B777-200	Dual-tridem	244	1.28
A380-800	Dual-tridem	562	1.34

Only the six wheel gear of the A380 was considered. Similarly, the belly gear of the A340 was omitted and only one of the two sets of B747 gears was included.

For each aircraft, 100%, 80% and 60% of the maximum mass was considered to allow the calibration to cover the range of typical operating masses of each aircraft. Tyre pressures were maintained at the standard pressure for each aircraft as is understood to be common operational practice. Aircraft passes spanned the range of typical designs from 100 to 100,000 passes of each aircraft.

Aircraft wander was set to a standard deviation of 773 mm. This was selected as being the aircraft wander statistic for taxiways in APSDS. For COMFAA, a PCR was required for each aircraft. PCRs were calculated using the method prescribed by the US Army Corps of

Engineers [1]. For a constant tyre pressure, PCRs vary with aircraft mass, as a result of the changing width of the tyre contact area. However, designers commonly adopt a single PCR for each aircraft, reasoning that the effect on calculated pavement thickness is usually negligible and some design methods, including LEDFAA, consider aircraft at their maximum mass only.

For any aircraft at 100% and 60% of its maximum mass, a difference in PCR of 29% will result. For a B747 aircraft at 10,000 coverages on a subgrade CBR 6% pavement, this difference resulted in a 26 mm (or 2%) difference in pavement thickness. It was therefore considered that the additional effort in calculating and applying mass-specific PCRs for the conversion of passes to coverages was justified for calibration purposes. The PCRs utilised are shown in **Table 3**.

Table 3.
Pass-to-Cover Ratios

Aircraft	PCRs		
	100% Mass	80% Mass	60% Mass
FA18	8.70	9.70	11.20
F111	5.50	6.16	7.12
BAe146	3.90	4.36	4.65
B737-800	3.63	4.06	4.69
B747-400	1.72	1.92	2.22
A340-600	1.85	2.09	2.39
B777-200	1.34	1.43	1.73
A380-800	1.30	1.46	1.68

Pavement Details

To allow direct comparison with the S77-1 curve, the standard S77-1 pavement was considered in all cases. This is shown in **Figure 1**. Crushed rock base and uncrushed gravel sub-base were sub-layered and assigned moduli values utilising the Barker and Brabston method [9]. For this initial stage of the recalibration, only CBR 6% subgrade was considered. Other subgrades will be considered in a future stage. Subgrade moduli values were calculated using **Equation 2**.

$$Modulus\ (MPa) = 10 \times CBR\ (\%) \qquad \text{Equation 2}$$

Trial Calibration Constants

A number of calibration constants were selected and trialed. The values selected were designed to span the range of those in the current Chicago Criteria as detailed in **Table 1**. The initial trialed calibration constants ranged as follows:

- Material constant (k) ranged from 0.0016 to 0.0040.
- Material exponent (b) ranged from 6 to 34.

DESIGN OF PARAMETRIC RUNS

The input variables for the calibration are detailed in **Table 4**. These include 96 aircraft scenarios and 25 calibration constant combinations. The fully factorial analysis required 2,400 parametric runs of APSDS.

Table 4.
Input variables

Variable	Values				
Aircraft Mass	100%	80%	60%		
Aircraft Passes	100	1000	10,000	100,000	
Gear Type	Single	Dual	Dual Tandem	Dual Tridem	
Aircraft	FA18 F111	A320 B737	B767 A340	B777 A380	
k	0.0016	0.0022	0.0028	0.0034	0.0040
b	6	13	20	27	34

PAVEMENT THICKNESS DETERMINATIONS FOR COMPARISON

Performance of Parametric Runs

The parametric runs were performed using APSDS (version 4.0 k). The various input parameters were entered and the required thickness of natural gravel sub-base was calculated using the 'design selected layer' option. This sub-base thickness was then recorded in an Excel spreadsheet and the total pavement thickness calculated.

Following the initial 2,400 runs, it became evident that the mesh of k and b values was too wide to provide a meaningful calibration. A localised finer mesh was then analysed until a combination of k and b returned a localised minimum average difference between the APSDS and S77-1 thicknesses.

Following some analysis of the data, further parametric runs were performed to generate specific k and b values that minimised the average difference between APSDS and S77-1 thicknesses for each wheel configuration (single, dual, dual-tandem and dual-tridem). This was performed to allow consideration of the potential improvement in calibration achieved by adopting wheel number specific calibration constants.

With consideration given to the data obtained, additional parametric runs were performed to provide more precise values of k and b. This was performed to allow an analysis of the reduced average difference to be gained from increased precision of the calibration constants.

Finally, the Chicago Criteria were used to calculate APSDS pavement thickness for the 96 aircraft scenarios considered. These were calculated to allow a comparison of the average difference of the Chicago Criteria and the criteria resulting from this recalibration process.

S77-1 Pavement Thicknesses

S77-1 pavement thicknesses were calculated using COMFAA. The various input parameters were entered and the required total pavement thickness was returned and recorded in Excel. For the single, dual and dual-tandem wheel gear configurations, the use of COMFAA is relatively simple. For the six wheel (dual-tridem) gear configurations of the A380 and B777, Alpha Factors created a complexity.

The International Civil Aviation Organisation (ICAO) changed the 10,000 coverage Alpha Factor for six wheel landing gear to 0.720 in 1996 in recognition that a six wheel gear load should be assigned the Alpha Factors previously assigned to twelve wheel gears [4]. Whilst COMFAA defaults to this new Alpha Factor for 10,000 coverages, for other coverage levels, the original values are still applied. COMFAA-generated twelve wheel Alpha Factors were used for the six wheel gear in this analysis, as an approximate for ICAO's change to the six wheel gear's Alpha Factor.

ANALYSIS OF RESULTS

Following the initial 2,400 parametric runs of APSDS, the difference between the APSDS and the S77-1 pavement thickness was calculated for all 96 aircraft scenarios for each of the 25 combinations of k and b. For each combination of k and b, the average and median magnitude of difference was calculated. In addition, the percentage error was calculated for each scenario and the average percentage difference determined. The square root of the average of the square of the differences was also calculated to provide a statistic which was weighted heavily by larger differences.

The selection of the preferred k and b values was based on the minimum average difference. Use of the minimum sum of the square of the differences returned the same values for k and b. The selection of k and b based on minimum average percentage difference would have returned very similar values. Whilst the average difference was biased towards aircraft requiring thicker pavements, this was considered appropriate as these aircraft would govern any practical design scenario where multiple aircraft are considered. The average difference is shown in **Figure 2** as a function of k and b.

Figure 2 suggested that a minimum difference would occur at around k = 0.0028 and b = 15. It was also concluded from **Figure 2** that the mesh for values of k and b was far too wide to accurately determine k and b values and therefore a fine mesh was considered in the area around the point where the minimum average difference appeared to occur.

Following further trial combinations of k and b in a fine mesh, a distinct minimum average difference was determined. Combinations of k and b were selected by iteratively bisecting the previous interval. To ensure that the actual minimum average difference had been located, the surrounding eight combinations of k and b were also trialed and all were found to have a higher average difference. The average differences for the fine mesh are shown in **Figure 3**.

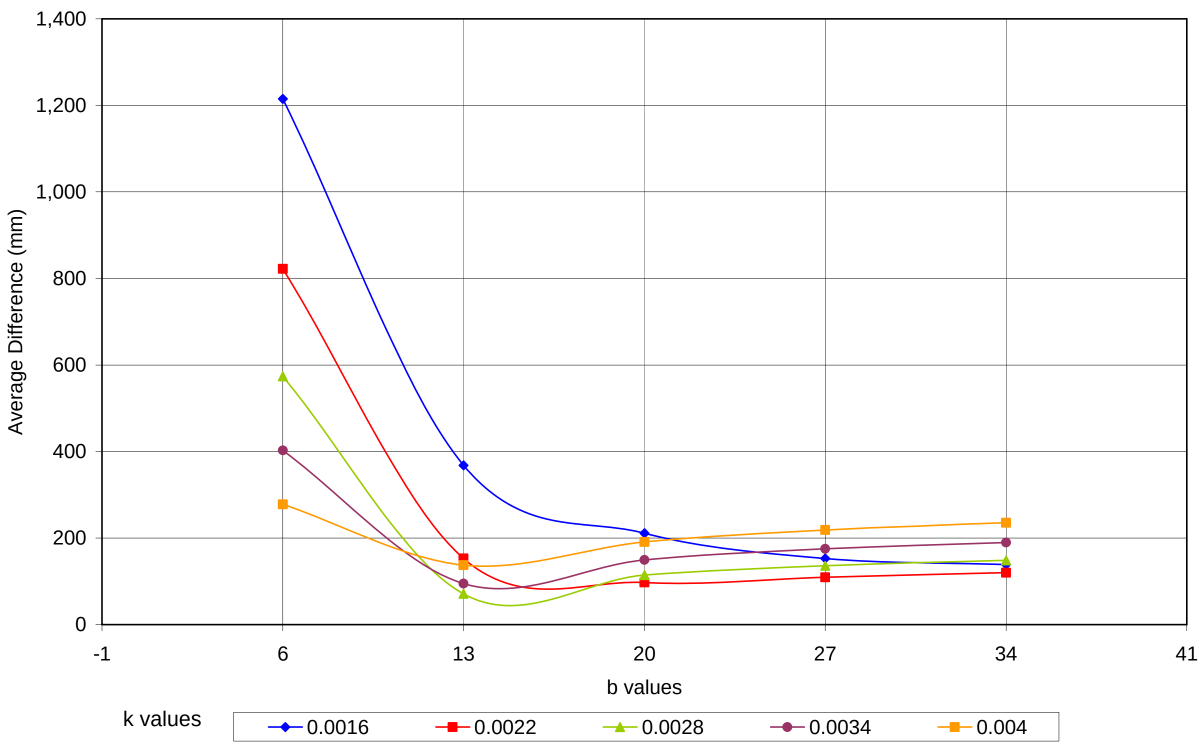

Figure 2. Average difference for wide mesh

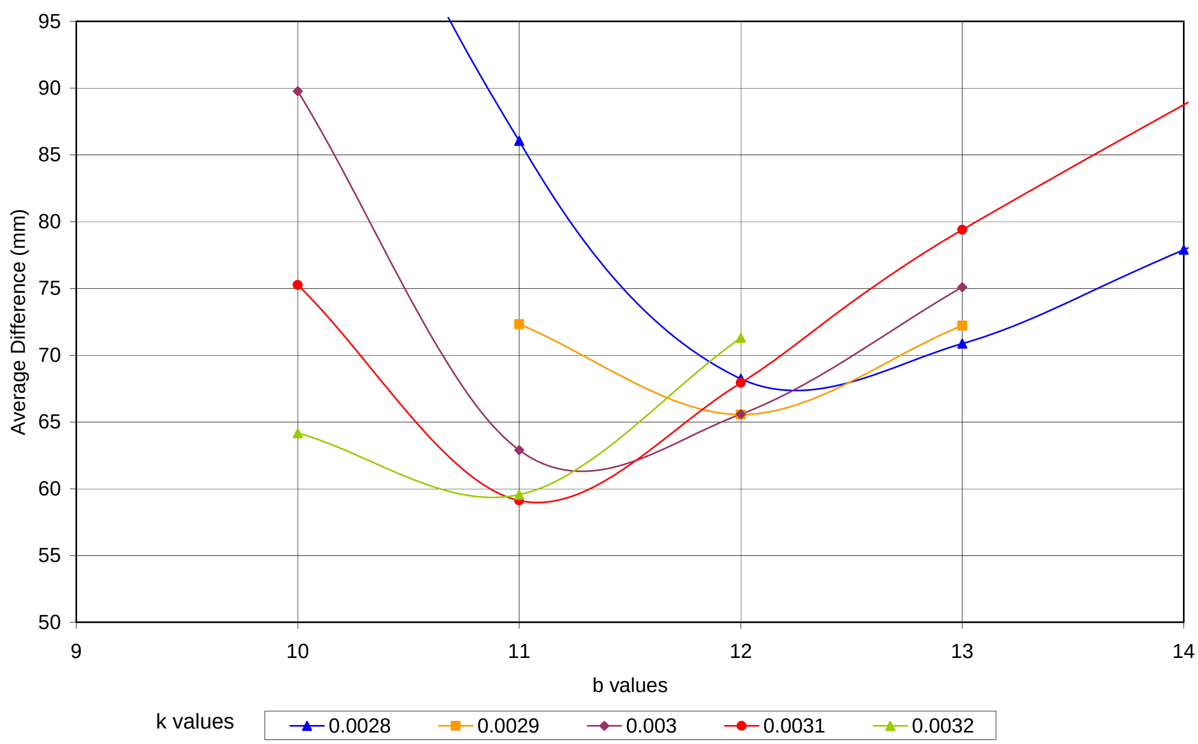

Figure 3. Average difference for fine mesh

From **Figure 3** it was determined that the minimum difference occurred at k = 0.0031 and b = 11. For these calibration constants, the average difference was 59 mm and the median difference was 46 mm.

Comparison with Chicago Criteria

The Chicago Criteria were used to generate APSDS thicknesses for the 96 aircraft scenarios considered. Summary statistics of the differences are shown in **Table 5**. **Figure 4** shows the APSDS thicknesses for the Chicago Criteria and the new criteria against S77-1 pavement thicknesses.

Table 5.
Chicago Criteria and new criteria difference statistics

Statistic	Chicago Criteria	New Criteria
Average	64 mm	59 mm
Median	54 mm	46 mm
Maximum	231 mm	217 mm
Inter quartile range	66 mm	60 mm

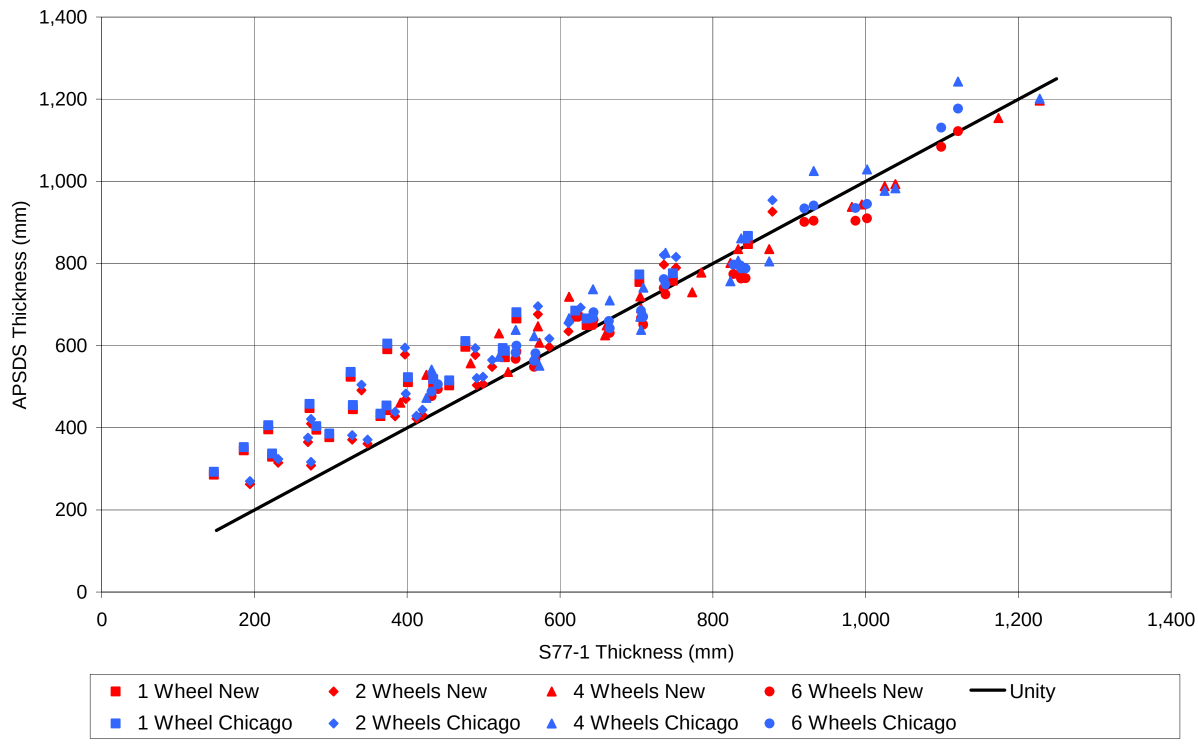

Figure 4. Comparison of Chicago Criteria and new criteria

Overall, the new criterion for CBR 6% subgrades gives thicknesses that are in better agreement with S77-1 than those calculated using the Chicago Criteria. This is achieved with a lesser degree of precision (one significant figure less for b and the same significant figures for k) and before any benefit from separately considering the various wheel configurations is included.

Importance of Wheel Configuration

The iterative trialing of k and b values was repeated for each wheel-per-gear scenario. The combination of k and b returning the minimum average difference are shown in the **Table 6**.

Table 6.
Separate wheels calibration constants

Wheels per Gear	k	b	Average Difference	Median Difference
1	0.0053	8	37 mm	33 mm
2	0.0034	11	39 mm	21 mm
4	0.0033	10	32 mm	26 mm
6	0.0030	11	33 mm	35 mm
For separate	Variable as shown		35 mm	28 mm
For combined	0.0031	11	59 mm	46 mm
Chicago Criteria	0.0030	10.9	64 mm	54 mm

Figure 5 compares the pavement thicknesses returned by the combined and separate calibration constants versus the S77-1 pavement thicknesses.

The separate criteria resulted in an average difference of 35 mm, compared to 59 mm for the combined criteria and 64 mm for the Chicago Criteria. Due to the significant improvement in the calibration that resulted from adopting separate failure criteria for each of the wheel configurations, it was concluded that the separate criteria are justified.

To implement the separate criteria, APSDS would need to be modified to allow the software to automatically determine the number of wheels on the main gear of each aircraft being considered and to invoke the appropriate calibration constants when calculating the allowable number of repetitions by that aircraft gear.

The analysis undertaken indicates that pavement life depends on both the magnitude of the strain induced at the top of the subgrade as well as the wheel configuration that induced that strain. This contrasts with the FAA aircraft pavement design method. The FAA's LEDFAA software has a single failure criterion for all subgrade CBRs and all aircraft types [4]. This implies that the FAA method does not allow the relationship between induced strain and allowable coverages to vary as a function of aircraft wheel configuration. Instead, pavement life is considered to be dependent only upon the magnitude of the strain induced. The validity of the current FAA approach is questioned in light of the findings of this investigation.

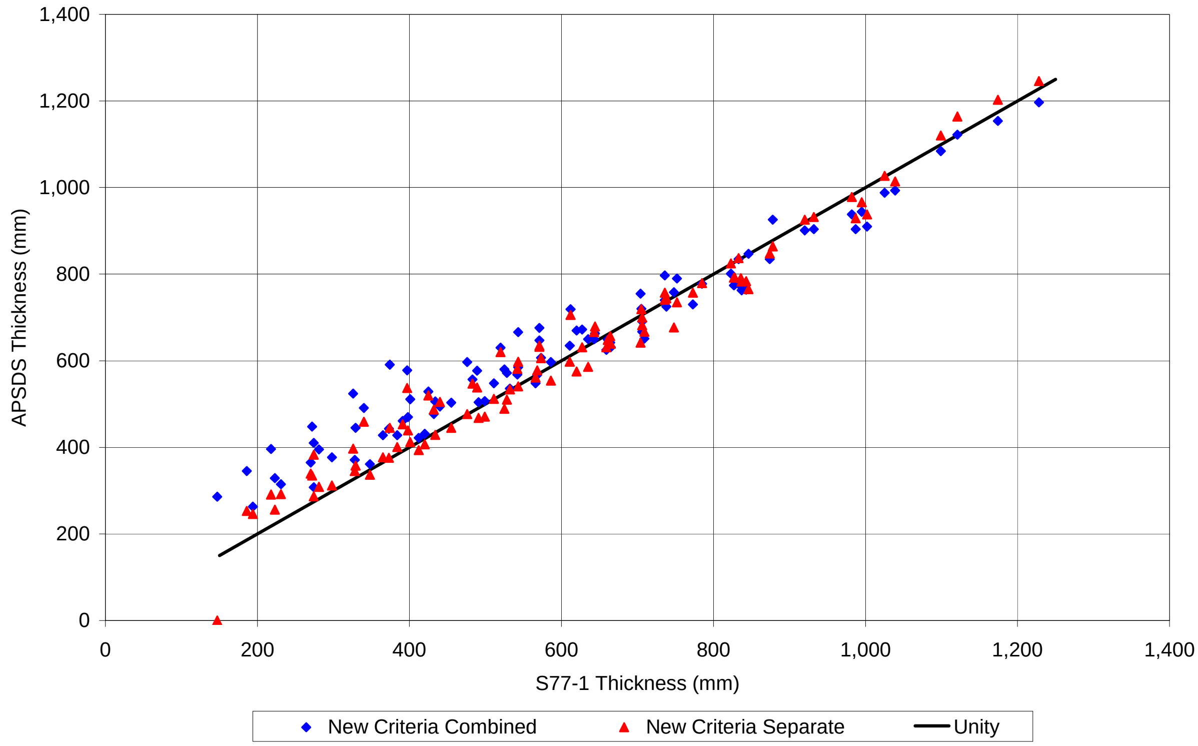

Figure 5. Comparison of combined and separate criteria

Precision of Calibration Constants

The recommended combined wheel configuration thicknesses were compared to those generated for the calibration constant values either side of the recommended values. These values are shown in **Table 7**.

Table 7.
Recommended and adjacent constant values

Constant	Recommended	Other Values	
k	0.0031	0.0030	0.0032
b	11	10	12

The pavement thicknesses returned by the recommended constants and the adjacent constants are presented in **Figure 6**.

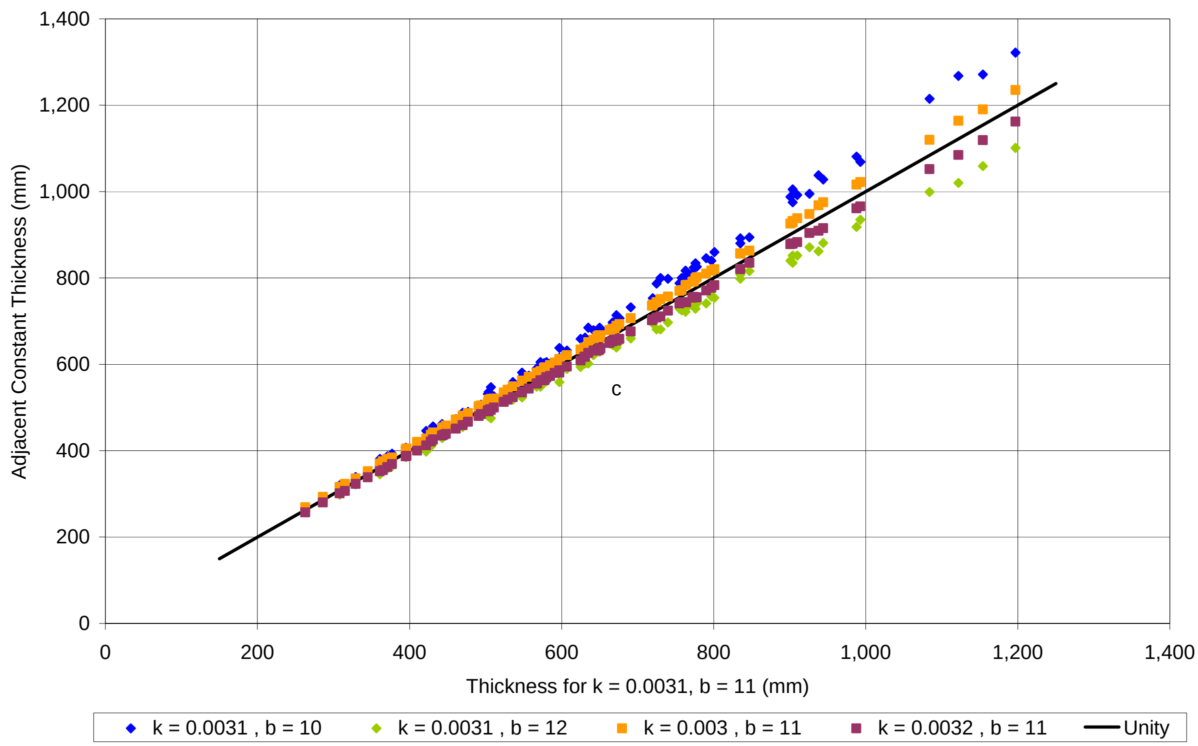

Figure 6. Comparison of combined and separate criteria

From **Figure 6** it can be seen that the adjacent values of k make a significantly smaller difference to the pavement thicknesses than the adjacent values of b. It was therefore considered that the precision of k was appropriate and that an increased level of precision could not be justified. Additional parametric runs were performed to determine the improvement in the calibration resulting from increased precision in the value of b. The minimum average difference occurred at the following values of k and b when an additional significant figure was considered for the value of b:

- k = 0.0032.
- b = 10.6.

The average minimum difference that resulted from this increased level of precision of b was 57 mm. Based on the marginal improvement in calibration achieved by increasing the precision of the values of b, the additional effort in adopting this increased precision was not considered to be justified. The adoption of two significant figures for both k and b is therefore recommended.

Recommendations for Full Calibration

From the analysis performed, the following recommendations are made in moving towards the full recalibration of APSDS:

- The methodology employed in this trial calibration for CBR 6% is readily applicable to all subgrade CBRs.

- Minimum average difference is an appropriate basis for the selection of calibration constants.
- The new criteria provide better fit to S77-1 pavement thicknesses than the Chicago Criteria over the range of aircraft scenarios considered.
- The agreement between APSDS-calculated thicknesses and S77-1 thicknesses is significantly improved when aircraft with different wheel configurations are considered separately.
- The precision of k and b should both be set at two significant figures. The improvement in calibration resulting from increased precision does not justify the additional effort required in the calibration process.

CONCLUSIONS

From the analysis undertaken, it can be concluded that the Chicago Criteria, whilst being the best available at the time, contained significant limitations. The Chicago Criteria did not consider the now common six wheel gear configurations and were derived for a limited number of aircraft types, masses and coverages.

With the introduction of the A380 and B777 aircraft, recalibration of APSDS for six wheel gear configurations was critical to its continuing to be the leading mechanistic-empirical tool for flexible aircraft pavement thickness design. The recalibration process should also address the other limitations of the Chicago Criteria.

Based on the marginal reduction in average difference resulting from the increased precision of the value of the calibration constant, b, the additional effort for calibrating to an increased level of precision is not justified. Two significant figures (two decimal places for k and no decimal places for b) is therefore recommended. This is the same level of precision of k and one less significant figure for b than was adopted by the Chicago Criteria.

For subgrade CBR 6% the calibration constants of k = 0.0031 and b = 11 provide improvement over the original Chicago Criteria. These calibration constants should be adopted for the current version of APSDS where only one set of calibration constants is permitted for each subgrade CBR. Where more recent full scale pavement testing results in a replacement or amendment to the S77-1 design curve, the calibration process should be repeated.

The influence of wheel configuration is significant. Once APSDS is modified to cater for multiple calibration constants per subgrade CBR, the calibration constants shown in **Table 6** should be adopted for aircraft pavement thickness determination. Separation of failure criteria for difference wheel configurations is not provided for in the current FAA layered elastic design approach and LEDFAA software. The validity of LEDFAA's independence from wheel configuration is questioned in light of the findings of this investigation.

REFERENCES

1. Pereira, A. T. (1977). *Procedures for Development of CBR Design Curves.* Instruction Report S77-1. US Army Corps of Engineers. Engineer Waterways Experiment Station. Washington.

2. FAA. (1995). *Airport Pavement Design and Evaluation*. Advisory Circular 150/5320-6D. Federal Aviation Administration of the United States. February. Washington.
3. FAA. (2004). *Computer Program COMFAA Help file*. Version 6/2004. Federal Aviation Administration. William J. Hughes Technical Centre. Atlantic City. Available from www.airporttech.tc.faa.gov/naptf.
4. FAA. (2004). *Computer Program LEDFAA Help file*. Version 1.3. Federal Aviation Administration. William J. Hughes Technical Centre. Atlantic City. June. Available from www.airporttech.tc.faa.gov/naptf.
5. Mincad. (2000). *APSDS 4 Users' Manual*. Mincad Systems Pty Ltd. Richmond. Australia. September.
6. Mincad. (1999). *CIRCLY 4 Users' Manual*. Mincad Systems Pty Ltd. Richmond. Australia. February.
7. Wardle, L., Rodway, B. and Rickards, I. (2001). "Calibration of Advanced Flexible Aircraft Pavement Design Method to S77-1 Method". In *Proceedings Advancing Airfield Pavements. American Society of Civil Engineers' 2001 Airfield Pavement Specialty Conference*. Illinois. 5-8 August. (Buttlar, W. G. and Naughton, J. E, eds.) pp 192-201.
8. White, G. W. (2006). "Material Equivalence for Flexible aircraft Pavement Thickness Design". *Proceedings 2006 Airfield and Highway Pavements Specialty Conference*. Refereed paper number 17121. American Society of Civil Engineers. Atlanta, United States of America. 1-3 May.
9. Barker, W. R. and Brabston, W. N. (1975). *Development of a Structural Design Procedure for Flexible Aircraft Pavements*. Report No S77-17. US Army Corps of Engineers. Waterways Experiment Station, Vicksburg, USA.

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