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Application of Statistical Principles to the Evaluation of Airport Pavement Bearing Capacity and Determination of Pavement Classification Number

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Outline

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- II. Review of ACN/PCN Methodology
- III. Goodness Study of Existing Backcalation Results
- IV. Application of NDT Test Data
- V. Development of A Robust Approach
- VI. A Case Study for Rigid Pavements
- VII. Concluding Remarks

I. Introduction

- ACN/PCN Method Adopted by ICAO
  - for reporting airfield pavement bearing capacity
- Selecting Evaluation or Design Inputs
  - Should consider the mean and standard deviation, but currently only the mean value was used (AC 150/5370-11A)
  - "For a more conservative evaluation and design, the mean value minus one standard deviation (or the so-called 85% confidence level) may be used" (AC 150/5320-6D, AC 150/5370-11A)
- Research Approach ➔ The concepts of random sampling, central limit theorem, and confidence intervals for hypothesis testing were adopted to derive a more consistent and repeatable PCN value

II. Review of ACN/PCN Methodology

ACN Determination

- Expressing the relative structural effect of an aircraft on a specified pavement type and a standard subgrade category
- By equating the thickness derived for a specified airplane landing gear to the thickness derived for a single wheel load (DSWL) at a standard tire pressure of 181 psi (1.25 MPa)
- Flexible Pavement
  - Boussinesq elastic layer solution
  - Four levels of subgrade strength (CBR)
  - 10,000 coverages
- Rigid Pavement
  - Westergaard interior loading solution on Winkler foundation
  - Four levels of subgrade strength (k)
  - Concrete working stress = 399 psi (2.75 MPa)
- ACN = 2 * DSWL (in 1000 kg)

Subgrade Strength Category

Subgrade Category Code	Flexible Pavement	Rigid Pavement	
	Subgrade CBR	Subgrade k-value (MN/m^3)	Subgrade k-value (pci)
A (High)	15 (CBR□13)	150 (k □ 120)	552.6 (k □ 442)
B (Medium)	10 (8 < CBR < 13)	80 (60 < k < 120)	294.7 (221 < k < 442)
C (Low)	6 (4 < CBR□8)	40 (25 < k □ 60)	147.4 (92 < k □ 221)
D (Ultra Low)	3 (CBR□4)	20 (K □ 25)	73.7 (k □ 92)

PCN Determination

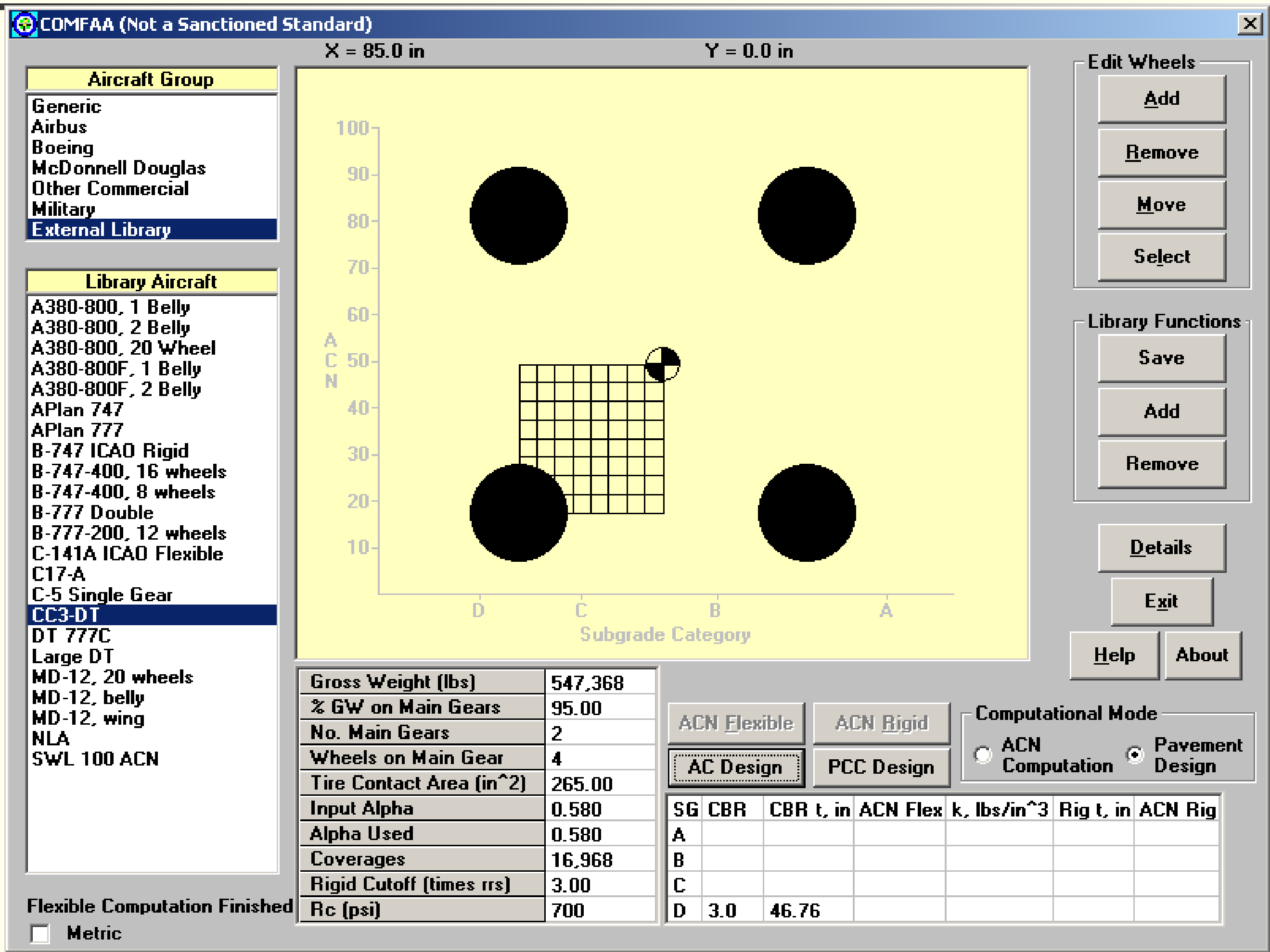
- Expressing the relative load-carrying capacity of a pavement in terms of a standard single wheel load

60 / R / B / W / T

PCN Value	Pavement Type	Subgrade Category	Allowable Tire Pressure	Method Used
A Numerical Value	R (Rigid) F (Flexible)	A (High) B (Medium) C (Low) D (Ultra Low)	W (No limit) X (□ 1.5 MPa) Y (□ 1.0 MPa) Z (□ 0.5 MPa)	T (Technical) U (Using Aircraft)

- A particular PCN value can support an aircraft that has an ACN value equal to or less than the pavement’s PCN value for unrestricted operations without weight restrictions

COMFAA Software



Ref: AC 150/5335-5A

Factors Affecting PCN Assignment

- PCN method used
- Use of empirical or mechanistic based methods
- Evaluation method used
- Pavement structural life
- Method to derive an annual traffic volume
- Method to backcalculate material properties
- Different transfer functions, etc.

Note: PCN values can vary over 200% using different theories and evaluation technologies (Stet 2005)

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
- Vencon 1992	71	RCWT

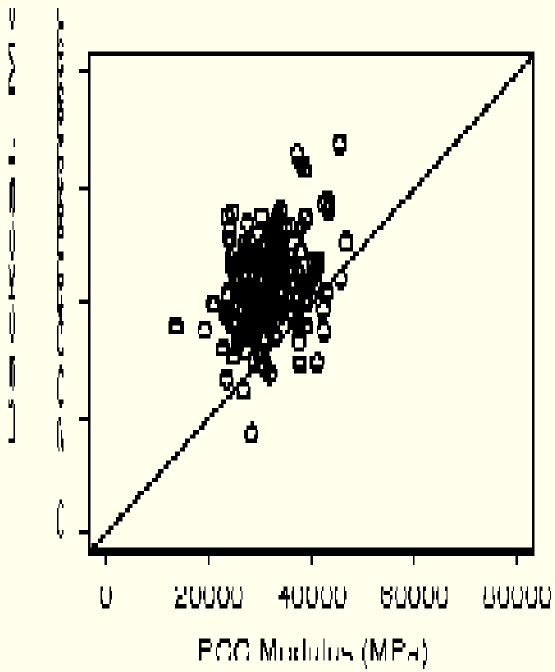
Note: Flexible ACN of B747-400 at MTOW/OEW is 64/22; Rigid ACN of B747-400 at MTOW/OEW is 7

III. Goodness Study of Existing PCC Backcalation Results

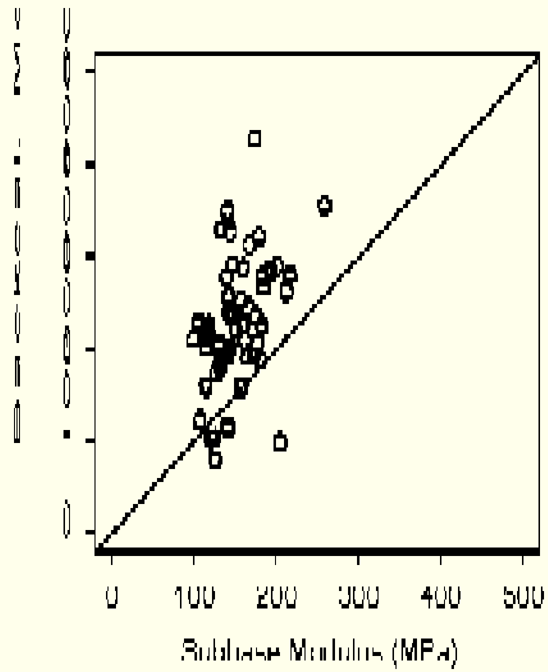
(Using LTPP DataPave Release 18.0)

Comparison of Lab Tested vs. Backcalc. Layer Moduli (1/2)

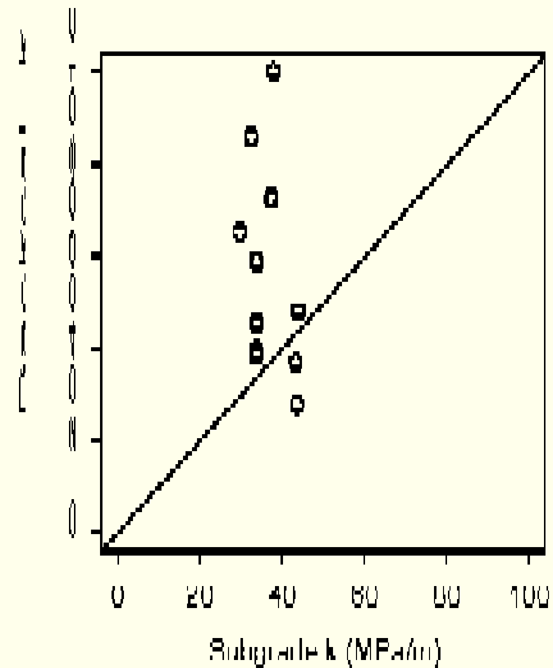
(a) PCC surface layer



(b) subbase layer



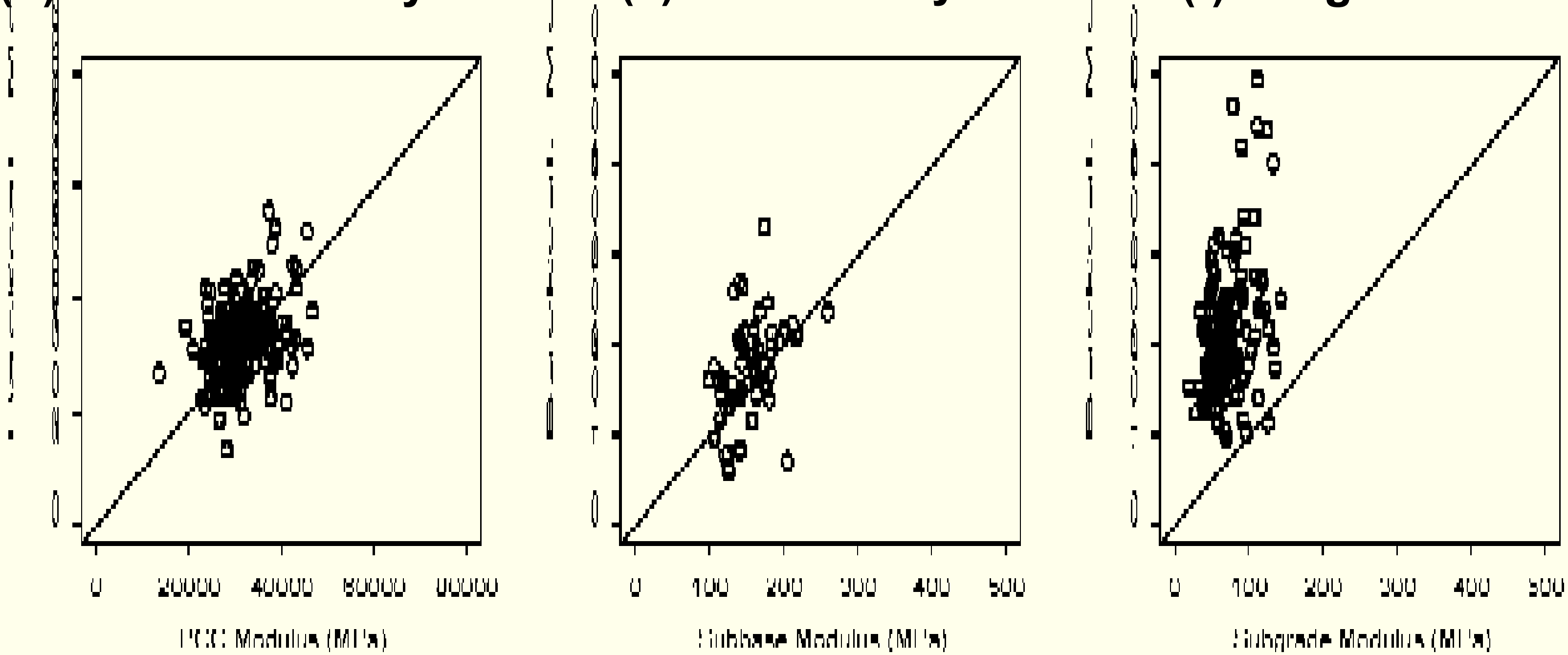
(c) subgrade



Winkler Foundation (Average ratios about 1.4, 1,5, 1.5)

Comparison of Lab Tested vs. Backcalc. Layer Moduli (2/2)

(d) PCC surface layer (e) subbase layer (f) subgrade



Elastic Solid Foundation (Average ratios about 1.0, 1,1, 3.0)

Relationship of Elastic Modulus and Modulus of Subgrade Reaction (1/3)

- **FHWA-RD-00-086 Report (2001):**
  Backcalculation of layer parameters for LTPP Test Sections using GPS and SPS data

$$k = 0.296E_s$$

$$\text{Statistics}: R^2 = 0.872, \text{SEE} = 9.37, N = 596$$

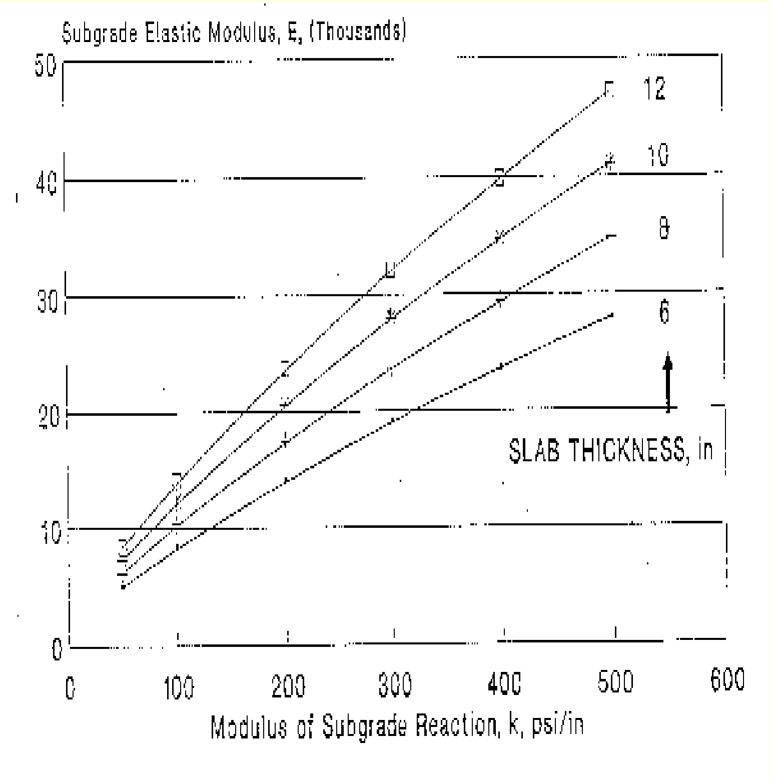
Relationship of Elastic Modulus and Modulus of Subgrade Reaction (2/3)

- Barenberg (2000) indicated the theoretical difference using elastic solid and dense liquid foundations

$$w_e = \frac{P\ell_e^2}{3\sqrt{3D}} = w_k = \frac{P\ell_k^2}{8D}$$

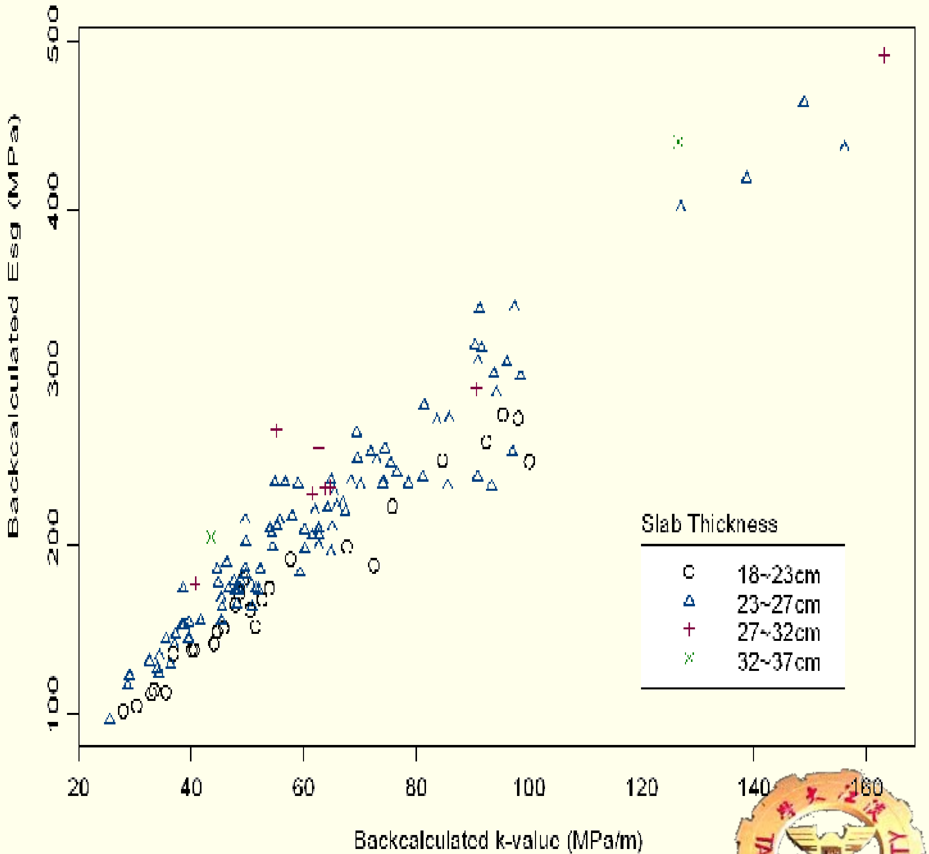
➔ $$0.6495 * \ell_k^2 = \ell_e^2$$

➔ $$E_s^{4/3} = 283.7 * h * k$$



Relationship of Elastic Modulus and Modulus of Subgrade Reaction (3/3)

- The aforementioned relationship was further verified by comparing the backcalculated Es and k values from the LTPP database
- Slab thickness did have significant effects on this relationship

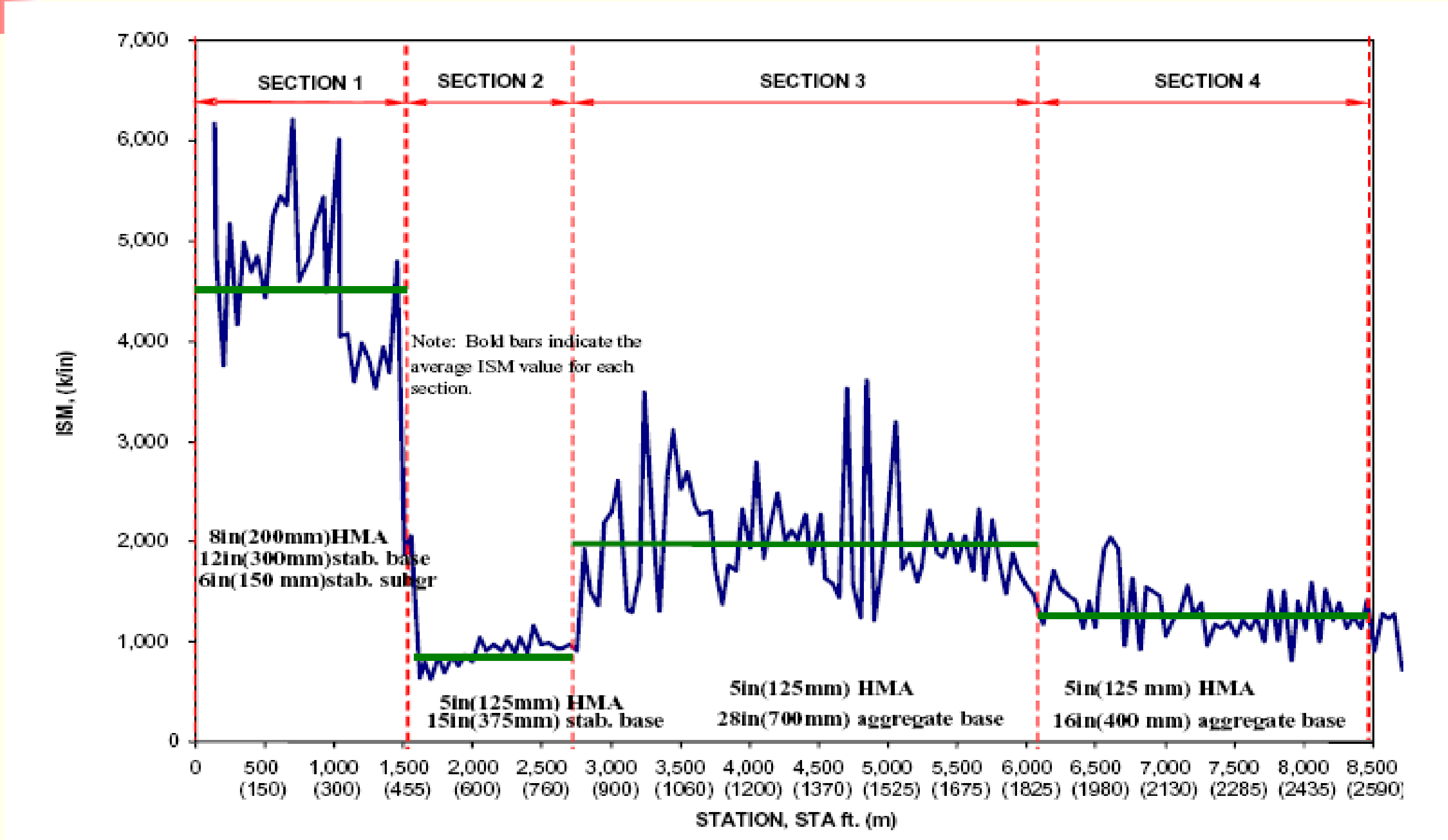


$$E_s = 0.9015(k * h)^{3/4}$$

$$\text{Statistics}: R^2 = 0.9524, SEE = 15.87, n = 138$$

IV. Treatment & Application of NDT Test Data

Subdivide the Raw NDT Data Into Several Homogeneous Sub-Sections

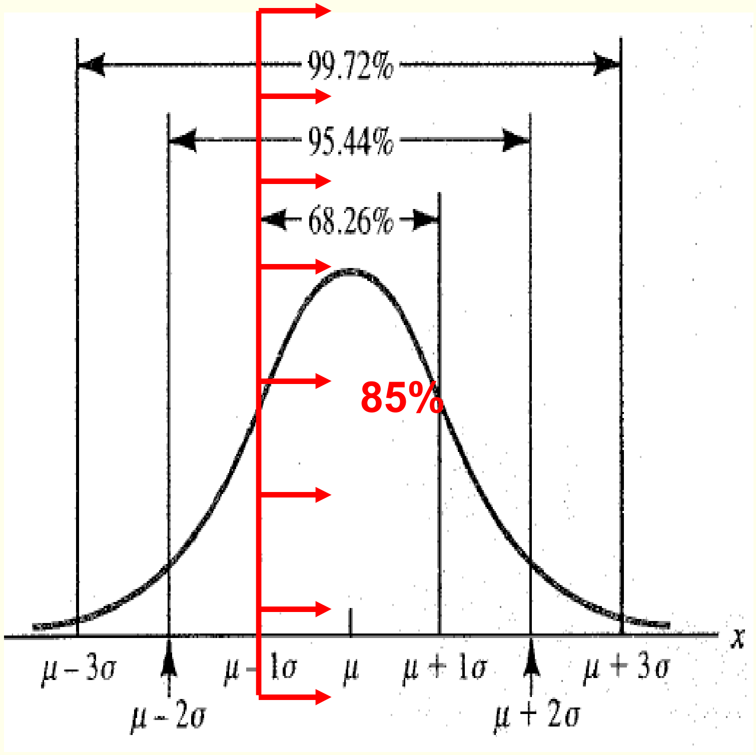


Question: How many sub-sections?

Obtaining a Representative Evaluation or Design Input (1/2)

- Based on the assumption of normal distribution, "the mean value minus one standard deviation (or the so-called 85% confidence level) may be used" (AC 150/5370-11A)

- $Pr(-1<Z<0) + Pr(0 < Z < \infty) =$ 0.3413 + 0.5 □ 85%



Obtaining a Representative Evaluation or Design Input (2/2)

- What if the probability distribution function of the population is unknown and is not always normally distributed?

  ➔ Chebyshev's Rule: the probability that any random variable differs from its mean by at least *k* standard deviations is less than or equal to $1/k^2$, in which $k > 1$

$$P(|X - \mu| \geq k\sigma) \leq \frac{1}{k^2}$$

- The so-called 85% confidence level (or reliability) is only true when the population is normal

V. Development of A Proposed Robust Approach

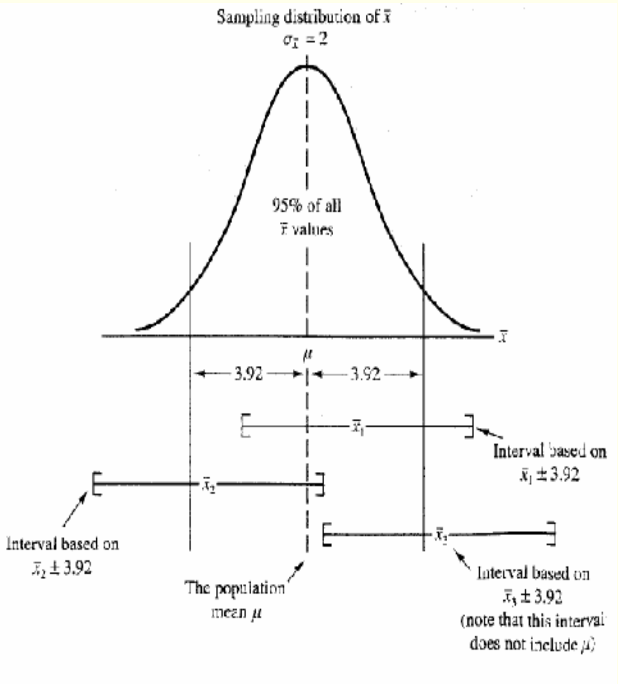
- Use the concepts of random sampling, central limit theorem, and confidence intervals for hypothesis testing
- This robust approach includes:
  - determine the number of sample units to be surveyed
  - determine a representative design input for the entire runway
  - obtain a single PCN value as usual

Determine the Number of Sample Units to be Surveyed

$$\overline{X} - \mu = Z_{\alpha/2} \frac{S}{\sqrt{n}} \leq e$$

$$\overline{X} - \mu = t_{n-1,\alpha/2} \frac{S}{\sqrt{n}} \frac{\sqrt{N-n}}{\sqrt{N-1}} \leq e$$

➔ $$n = \frac{NS^2}{(e^2/4)(N-1) + S^2}$$



Note: Already adopted by the ASTM (D5340-98) in pavement condition index (PCI) procedure (Shahin 1994)

Determine a Representative Evaluation or Design Input

- A single representative design input for the entire runway pavement may be determined by the lower limit of 95% confidence level (1-tail)

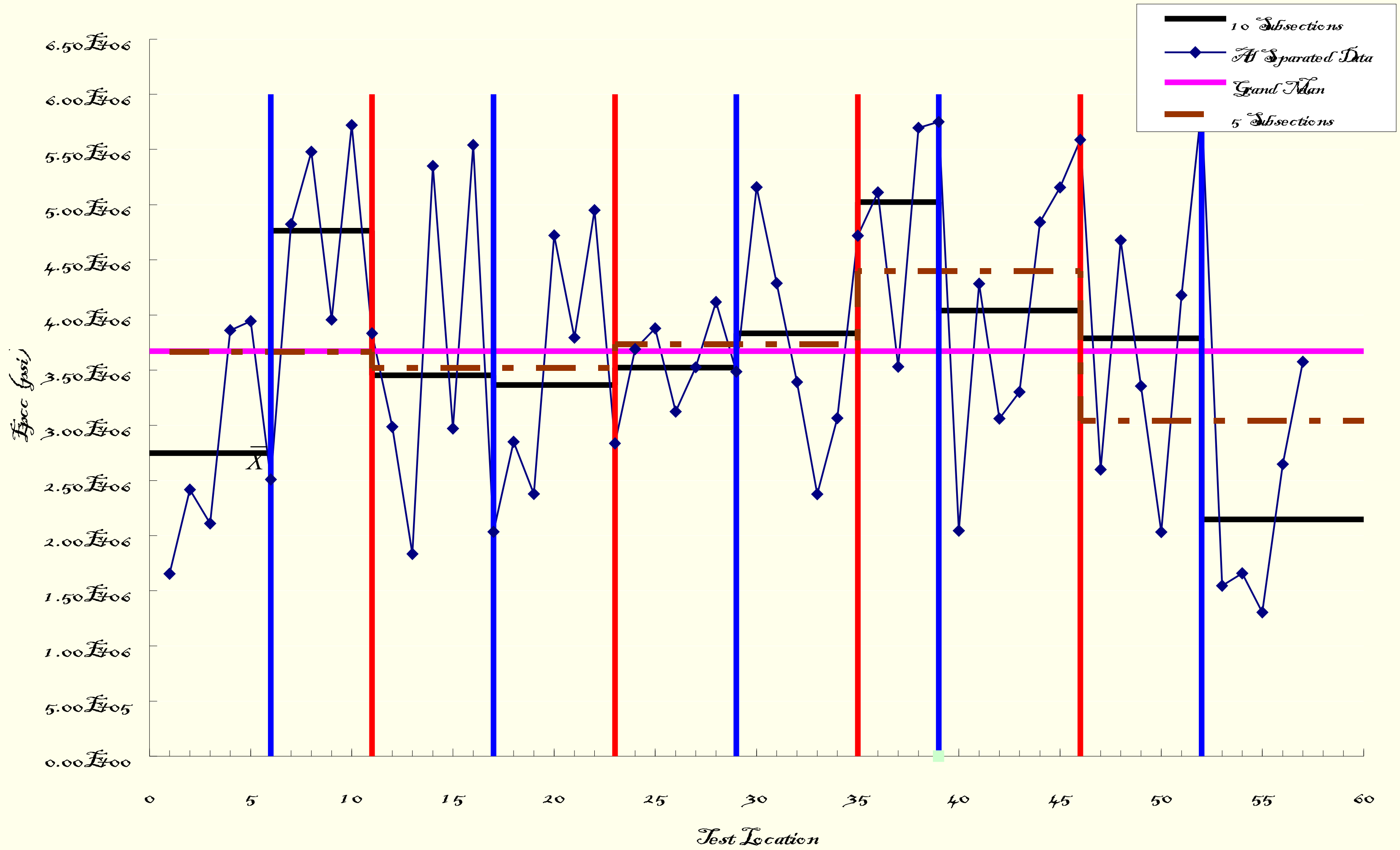
$$\mu = \overline{X} - t_{n-1,\alpha} \frac{S}{\sqrt{n}}$$

VI. A Case Study for Tech. Evaluation of Rigid Pavements

Example Rigid Airfield Pavement Traffic Data

Airplane	Operating Weight, lbs	Tire Pressure (psi)	ACN (R/C)	** P/C	Annual Departures	Coverages
B727-200	185,000	148	55	2.92	400	2,740
B737-300	130,000	195	38	3.79	6,000	31,662
A319-100	145,000	173	42	3.18	1,200	7,547
B747-400	820,000	200	68	3.46	3,000	17,341
B767-300ER	370,000	190	58	3.60	2,000	11,111
DC8-63	330,000	194	62	3.35	800	4,776
A300-B4	370,000	205	67	3.49	1,500	8,595
B777-200	600,000	215	77	4.25	300	1,412

** Rigid P/C determined at 95 percent of gross load on main gear
(effective k =200 pci, h = 14 in., MR= 700 psi, Ec = 4E+06 psi)

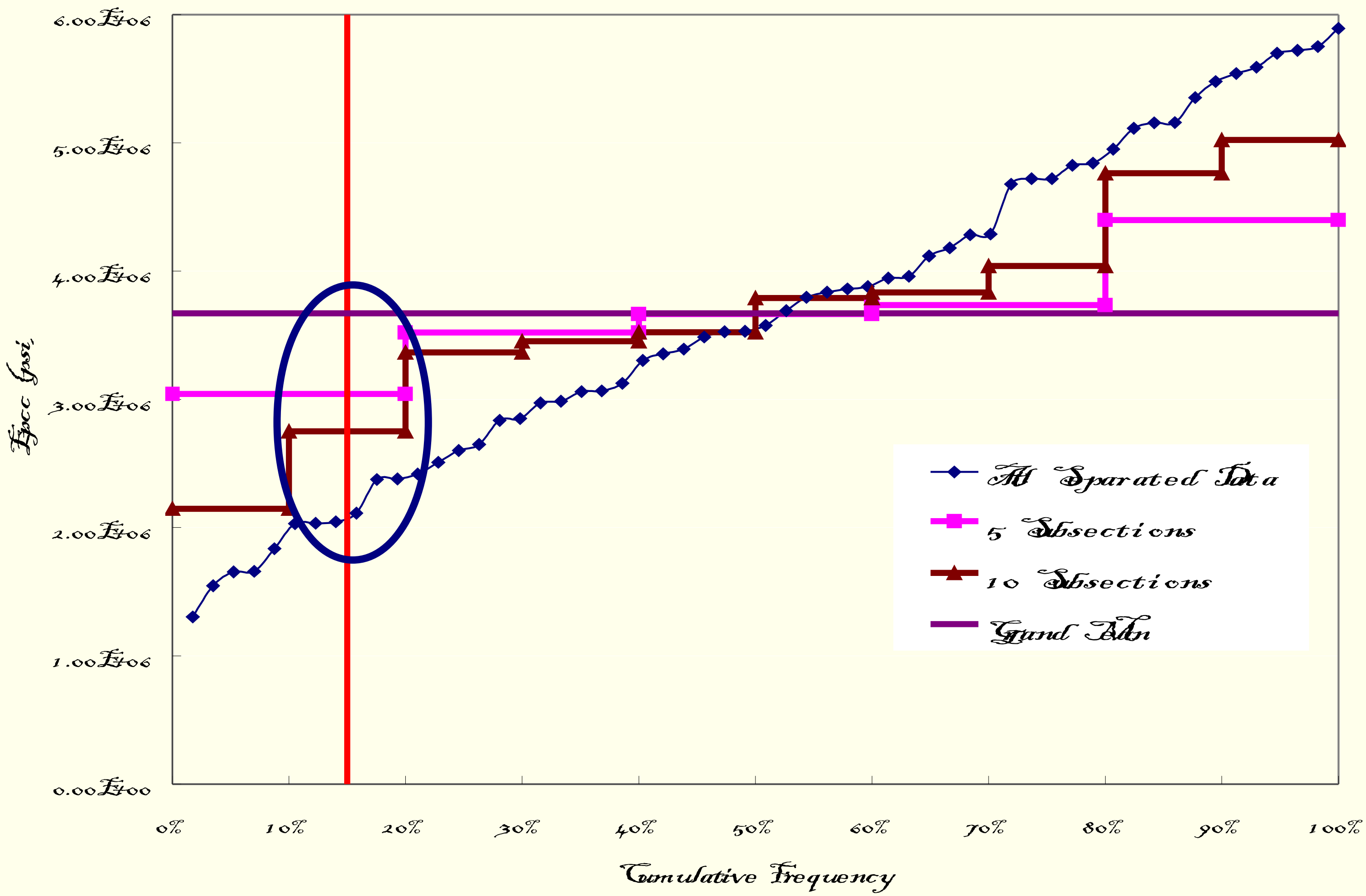


Grand Mean = 3.67 x 10^6 psi

Sample Standard Dev. = 1.27 x 10^6 psi

Sample Size = 57

Subdivide into Different Number of Subsections



Results of Using Different Evaluation Methods

Methods	Different Evaluation Methods	Representative Epcc (psi)	Estimated □ r (psi)	Calculated Allowable Gross Weight (lbs)	PCN
I	Grand Mean	3.67×10^6	648.1	700,000	55.0/R/C/W/T
II	Grand Mean - 1 Std.Dev.	2.40×10^6	592.8	640,000	48.6/R/C/W/T
III	5 Subsections (85%)	3.04×10^6	620.7	671,000	51.9/R/C/W/T
IV	10 Subsections (85%)	2.75×10^6	608.1	656,000	50.3/R/C/W/T
V	All Separated Data (85%)	2.05×10^6	577.7	632,000	47.8/R/C/W/T
VI	95% Confidence	3.33×10^6	633.4	684,000	53.3/R/C/W/T

➔ Methods I ~ V (PCN = 48/R/C to 55/R/C), Method VI (PCN = 53/R/C)

VII. Concluding Remarks (1/2)

- According to AC 150/5370-11A's recommendation, the mean value minus one standard deviation (or the so-called 85% confidence level) may be used to obtain a more conservative evaluation or design input.
- Nevertheless, it was found that this procedure is not based on sound statistical principles especially when the probability distribution function of the population is almost always unknown and is not necessarily normal.

VII. Concluding Remarks (2/2)

- Consequently, the concepts of random sampling, central limit theorem, and confidence intervals for hypothesis testing were adopted.
- It was proposed that a single representative design input for the entire runway pavement be determined by the lower limit of 95% confidence level (1-tail) to derive a more consistent and repeatable PCN value.
- A case study was conducted to illustrate the potential problems of the existing ACN/PCN procedure and the benefits of the proposed revisions.

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Questions?

THANKS FOR YOUR ATTENTION