C•R•O•W

PCN PROCEDURE FOR TECHNICAL EVALUATION OF FLEXIBLE AND RIGID PAVEMENTS

The PCN-method presented in this worked example is known as the *Technical* evaluation method, and requires knowledge of the pavement and its traffic, as well as a basic understanding of engineering methods that are used in pavement evaluation in order to be successfully implemented. PCN assignment is related to the analytical pavement design methodology. Inverse pavement design is the basis for PCN assessment. 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 a PCN based on this method. The procedure is well documented in CROW's Guideline on PCN Assignment. Appendices 1 to 3 of the CROW Guideline are helpful to derive the material properties.

In case of a pavement design, the PCN is evaluated based on the design assumptions used to calculate the (initial) pavement life. A newly constructed pavement can also be evaluated just after completion of the construction works. In this case, the strength determination method best relies 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 case of an in service pavement, the strength is assessed in a similar manner. However, the past traffic is deducted from the initial pavement life.

The PCN method presented herein is appropriate to the pavement construction type to determine the structural capability of a pavement to support proposed aircraft loads and traffic levels. 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 allowable 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. A summary list of the steps to follow in a PCN assignment of flexible and rigid pavement is given below. These steps can also be recognized in the worked examples presented hereafter.

1. **General:**
   - Select the PCN-pavement life course to use up the structural capacity of the pavement.

   An assigned PCN indicates that the pavement can bear the forecasted aircraft and frequencies without weight restrictions. However, every aircraft consumes a little of the structural pavement capacity or structural life. By definition, the PCN is the ACN-load of the critical aircraft that consumes the total structural pavement life in a certain period of time. Hence, the selected period of time (called 'the PCN-pavement life course') and the forecasted traffic that wears out (consumes) the pavement are input parameters in the PCN-calculation. Note that the PCN-pavement life course can differ from the pavement design life .

2. **Pavement Structure**:
   - Assess the pavement structure in terms of constructed thickness', elastic moduli and Poisson ratio's.

   The bearing capacity is derived from the characteristics of the pavement structure .The pavement is broken down into distinct layers and subgrade with structural parameters (Young's modulus, Poisson ratio and thickness).

3. **Paved Materials**:
   - Determine the pavement's layer fatigue properties, including subgrade CBR.

   A pavement deteriorates gradually. Like other materials, pavements materials and subgrade are subject to fatigue. In an analytical design approach every aircraft pass consumes a bit of the structural pavement life. The end of the structural life is reached when the accumulated Miner pavement damage is 1.0. The fatigue deterioration per pass is calculated using strength based, and performance related transfer or fatigue functions.

4. **Aircraft traffic**:
   - Determine the traffic volume in terms of type of aircraft and number of past and future operations of each aircraft that the pavement had and will experienced over its PCN pavement life course;
   - Look up or calculate the ACNs of the aircraft at its operating empty (OEW) and maximum weight and at maximum takeoff weight (MTOW);
   - Determine the degree of lateral wander for the pavement under consideration;

- Determine the critical pavement layer i.e. the constructed layer with the lowest bearing capacity or highest damage factor;
- Determine the critical aircraft of the forecasted fleet mix in terms of structural damage by simply taking the aircraft with the highest ACN or by determining the damage factors by means of calculation. A damage factor is the reciprocal value of the allowable number of allowable aircraft passes. The ACNs at OEW and MTOW of that so-called critical aircraft are to be used in the PCN evaluation.

  The PCN is based on the actual fleet mix that uses the pavement. Lateral wander has a positive influence on the pavement life. Wander effects are addressed with a normalized beta-distribution. The degree of the lateral wander depends on the type of pavement, aircraft mode and width of the pavement (see Table 2). Using a linear elastic program for flexible pavement or a plate model for a rigid pavement, the critical pavement layer (having the highest Miner damage of all pavement layers and subgrade) and the critical aircraft (i.e. the aircraft with the highest damage factor) are easily discerned.

5. **PCN Assessment: pavement life and PCN calculation**
   - Calculate the accumulated pavement damage in terms of Palmgren-Miner due to the forecasted fleet (incl. wander and for the PCN-pavement life course).
   - Compute the Allowable Gross Weight (AGW) of the critical aircraft by varying the load of the undercarriage of the critical aircraft resulting in the same Miner damage as computed in the previous step;
   - Once the allowable load (or weight) is established, the determination of the PCN value is a process of converting that load to a standard relative damage value (i.e. ACN). Look up the ACN using the published ACN data, and calculate the ACN of the critical aircraft at its allowable, maximum weight;
   - Assign the ACN of the critical aircraft at the allowable, maximum weight to be the PCN of the pavement. Should the PCN exceed the ACN of the critical aircraft, the PCN-life course can either be prolonged or limited to the ACN-value of the critical aircraft.

   The PCN numerical value for a particular pavement is determined from the allowable load-carrying capacity of the pavement. The PCN is defined as the ACN-value of the critical aircraft operating with an AGW, that consumes the PCN-pavement life.

The steps are explained in full detail in the worked example.

WORKED EXAMPLE FLEXIBLE PAVEMENT

A flexible runway pavement with a width of 60 meters comprises of a 270 mm thick asphalt layer resting on a 350 mm thick cement treated base layer. The pavement is newly constructed. The fleet comprises of a total of eight narrow and wide bodied aircraft. The departure level is 15.400 per annum, resulting in total of 308.000 movements in a 20-year pavement course. The example explains the PCN calculation procedure in a step by step manner. The procedure is demonstrated using the summarised list of steps presented earlier. The evaluator’s input is printed in blue.

1. **General:**
   - Select the PCN-life course to use up the structural capacity of the pavement.

     20 years

2. **Pavement Structure**:
   - Assess the pavement structure in terms of constructed thickness’, elastic moduli and Poisson ratio’s. The material properties to use are listed the CROW Guideline.

Pavement model	Thickness (mm)	Poisson’s constant	Stiffness (MPa)
Asphalt	270	0.35	7,500
Cement Treated Base	350	0.20	10,000
Subgrade	∝	0.35	80

3. **Paved Materials**:
- Determine the pavement's layer fatigue properties, including those of the subgrade CBR and pavement thickness. Properties can be determined from material testing or literature. Pavers® has pre-defined performance functions which were taken from literature. In this example, we selected a Shell criterion for the asphalt layer, Starr Kohn's criterion for the cemented base layer and Shell's subgrade criterion.

The asphalt is characterised as a S78/F78, having a stiffness of 7,500 MPa and a F-78 fatigue behaviour. The average transfer function for asphalt is:

$$\log\left(N_{asph}\right) = 27.676 - 7.327\log\left(S_{mix}\right) + 0.769\log^2\left(S_{mix}\right) - 5.351\log\left(\varepsilon_r\right)$$

The cement treated base has a compressive strength of 10.0 MPa. The flexural strength is 2.00 MPa. The fatigue transfer function of CTB has a reliability level of 85%.

$$log\left(N_{bt}\right) = 11.782 - 12.120\left(\frac{\sigma_{bt}}{f_{bt}}\right)$$

The fatigue transfer function selected for the subgrade is the well known Shell-relation:

$$log\left(N_s\right) = 17.289 - 4.00\,log\left(\varepsilon_z\right)$$

The CBR is derived from the stiffness of the subgrade using the rule of thumb: CBR = Stiffness x 0.10 = 8%. A CBR of 8 % indicates a medium subgrade strength i.e. subgrade category 'B'.

4. **Aircraft traffic**:
- Determine the traffic volume in terms of type of aircraft, and number of future operations of each aircraft that the pavement will experience over its PCN pavement life course;
- Look up or calculate the ACNs of the aircraft at its operating empty (OEW) and maximum weight and at maximum takeoff weight (MTOW);
- The ACNs at OEW and MTOW of the critical aircraft are to be used in the PCN evaluation.
- Determine the degree of lateral wander for the pavement.

Table 1 Technical evaluation critical airplane determination

Airplane	Annual Departures	Operating weight (kg)		ACN Flexible Subgrade category B		Tire pressure (MPa)
		MTOW	OEW	MTOW	OEW	
B727-200 Adv	400	86,636	44,347	50 FB	22 FB	1.06
B737-300	6,000	61,462	32,904	33 FB	16 FB	1.34
A319-100AT	1,200	64,000	40,100	36 FB	19 FB	1.31
B747-400	4,500	395,987	178,459	64 FB	22 FB	1.41
B767-300ER	2,000	172,819	87,926	53 FB	22 FB	1.31
DC8-63/73	800	162,386	72,002	59 FB	19 FB	1.34
MD11	1,500	274,650	127,000	70 FB	26 FB	1.41
B777-200	300	288,031	138,346	54 FB	20 FB	1.51

The critical aircraft is the MD-11, having ACNs of 70 and 26.

Table 2 Lateral Wander according to HoSang

Pavement	Width (m)	Mode	Std. Deviation (mm)	Recommended value (mm)
Runway	60.0	Landing	2,700 – 3,400	3,000
		Take-off	2,300 – 2,500	2,400
	45.0	Landing	2,100 – 3,100	2,600
		Take-off	1,800 – 2,500	2,400
Taxiway	30.5	Taxi	1,800	1,800
	22.8	Taxi	760 – 1,200	1,000

The Take-Off mode is more critical than the landing mode. Therefore, the lateral wander for the runway pavement is 2,400 mm.

- Determine the critical pavement layer i.e. the constructed layer with the lowest bearing capacity or highest damage factor.

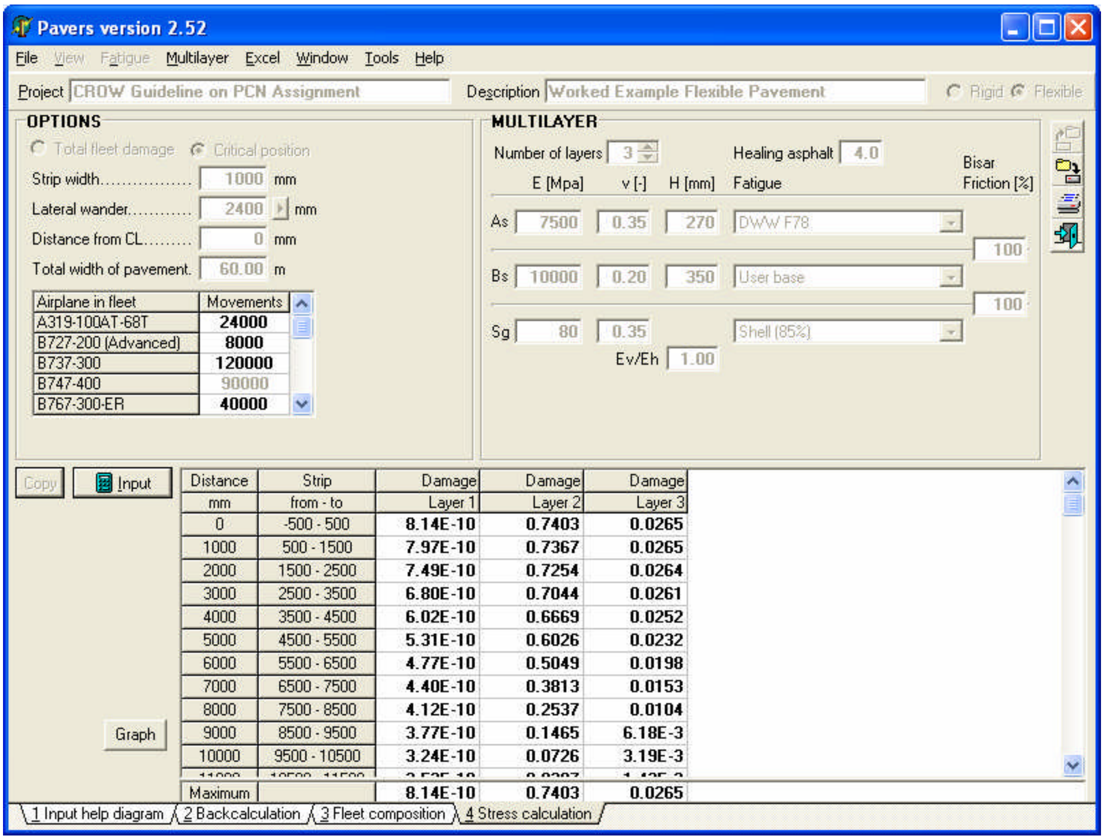
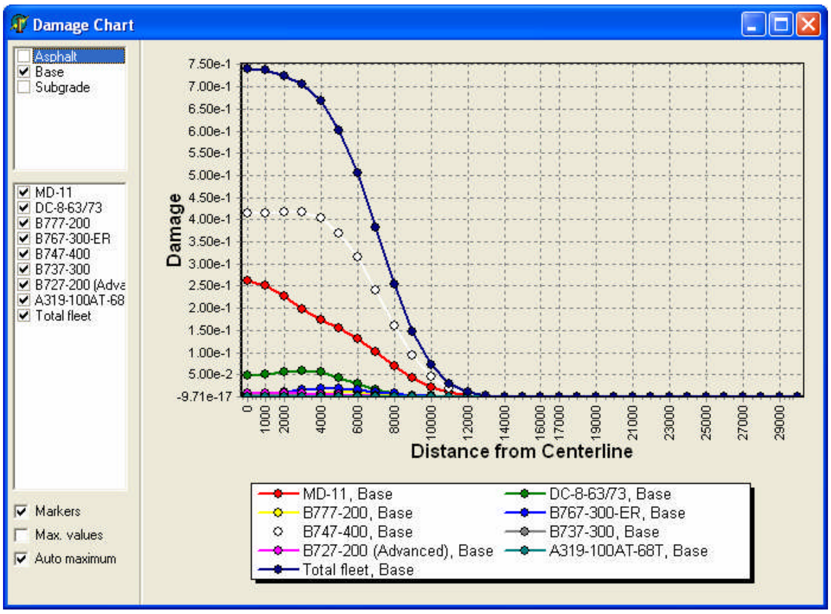


Figure 1 Calculating the structural pavement life to discern the critical pavement layer.

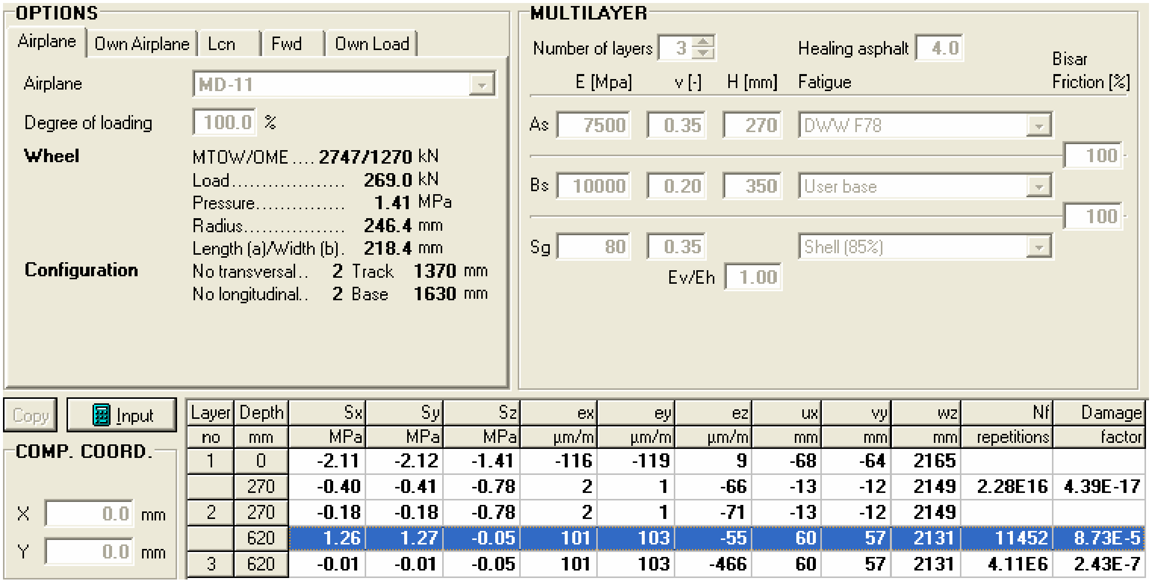


The critical pavement layer is the Cement Treated Base. Including a lateral wander of 2400 mm, the Miner sum after 20 years will be 0.74 or 74 %.

It can also be depicted that the asphalt layer and the subgrade hardly suffer from strain related fatigue damage. The damage is graphically presented in Figure 2.

Figure 2 Graphical presentation of the damage across the pavement section

5. **PCN Assessment: pavement life and PCN calculation**:
   - Convert the fleet mix into a number of movements of the critical aircraft resulting in the same Miner damage. Use this number to calculate the PCN of the pavement.

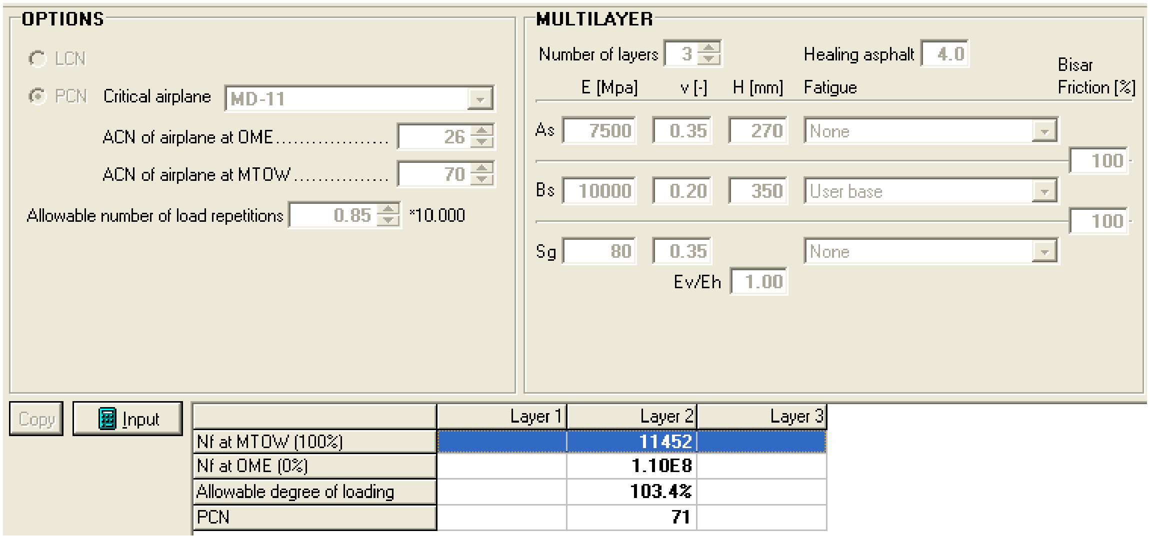


Layer no	Depth mm	Sx MPa	Sy MPa	Sz MPa	ex µm/m	ey µm/m	ez µm/m	ux mm	vy mm	wz mm	Nf repetitions	Damage factor
1	0	-2.11	-2.12	-1.41	-116	-119	9	-68	-64	2165		
	270	-0.40	-0.41	-0.78	2	1	-66	-13	-12	2149	2.28E16	4.39E-17
2	270	-0.18	-0.18	-0.78	2	1	-71	-13	-12	2149		
	620	1.26	1.27	-0.05	101	103	-55	60	57	2131	11452	8.73E-5
3	620	-0.01	-0.01	-0.05	101	103	-466	60	57	2131	4.11E6	2.43E-7

Figure 3 Calculating the allowable load repetitions of the critical aircraft (MD-11)

Calculate the allowable number of MD-11 movements resulting in a total Miner damage of 74.03%. As can be depicted from Figure 3, a total of 11,452 MD-11 movements are allowable for the pavement under consideration, consuming the total pavement structural life. However, during the 20 year pavement course, the accumulated Miner damage is 74.03%. Hence, the number of MD-11 movements is 0.7402 times 11,452 gives a total of 8,479 MD-11 movements.

- Calculate the allowable ACN-load of the critical aircraft by varying the gross weight of the aircraft until the same Miner damage is gained during the PCN life course;
- Calculate the corresponding ACN that refers to the allowable mass using the published ACN data of the critical aircraft.



	Layer 1	Layer 2	Layer 3
Nf at MTOW (100%)		11452	
Nf at OME (0%)		1.10E8	
Allowable degree of loading		103.4%	
PCN		71	

Figure 4 Calculating PCN

The pavement can sustain an Allowable Gross Weight of 103.4 % compared to its MTOW, i.e. a weight of 283.988 kg. The ACN data of an MD-11 are 26 at an OEW of 1,270 kN and 70 at a MTOW of 2,747 kN. The ACN at an allowable load of 2,810 kN (103.4 times 2,747 kN), the ACN is 71.

- Assign this ACN as being equal to the pavements PCN. Should the PCN be higher than the ACN of the critical aircraft, the PCN-life course can either be prolonged or limited to this ACN-value. Should the PCN be smaller than the required ACN of the critical aircraft, either a smaller PCN life course should be selected or the pavement must be strengthened in order to meet the requirements.
- **The PCN reporting format is 71 F/B/W/T**.

WORKED EXAMPLE OF A RIGID PAVEMENT

A rigid runway pavement of a width of 60 meters comprises of a 320 mm thick concrete layer resting on a 300 mm thick crushed concrete base layer (betongranulaat). The pavement is newly constructed. The fleet comprises of a total of eight narrow and wide bodied aircraft ranging from B727-200 to B747-400. The departure level is 15.400 per annum, resulting in total of 462.000 movements in a 30-year pavement course.

1. **General:**
   - Select the PCN-life course to use up the structural capacity of the pavement.

     30 years

2. **Pavement Structure**:
   - Assess the pavement structure in terms of constructed thickness', elastic moduli and Poisson ratio's. The material properties to use are listed in appendix 2 and 3.

	Thickness (mm)	Poisson's constant	Stiffness (MPa)
Cement concrete C35/45	320	0.15	33,500
Betongranulaat	300	0.35	800
Subgrade	∝	0.35	60

   - The modulus of subgrade reaction is 0.10 MPa/mm

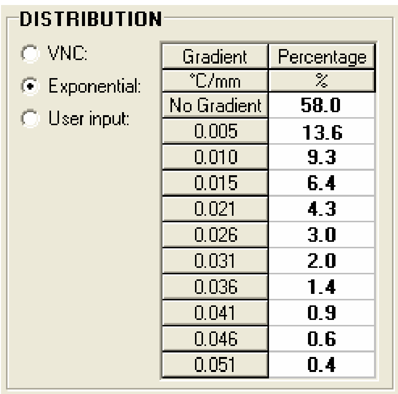
3. **Paved Materials**:
   - Determine the pavement's layer fatigue properties, including those of the subgrade CBR and pavement thickness.

The average flexural concrete strength of concrete under dynamic loading can be estimated from the 28-day compressive strength:

$$f_{br} = 1.3(1.6 - h)(1.05 + 0.05(f'_{ck} + 8))/\gamma_m$$

The 28-day flexural strength value is 5.13 MPa. The design concept of plain concrete is to limit the stresses induced by traffic and temperature to such an extend, that the desired number of load repetitions can be permitted. In the Netherlands the behaviour under repetitive loading is expressed in the following relationship:

$$\log N_f = \frac{12.903\left(0.995 - \frac{\sigma_{max}}{f_{br}}\right)}{1.000 - 0.7525\frac{\sigma_{min}}{f_{br}}}$$ with boundaries of $0.50 \leq \frac{\sigma_{max}}{f_{br}} \leq 0.833$



Gradient	Percentage
°C/mm	%
No Gradient	58.0
0.005	13.6
0.010	9.3
0.015	6.4
0.021	4.3
0.026	3.0
0.031	2.0
0.036	1.4
0.041	0.9
0.046	0.6
0.051	0.4

The load transfer is set at 70% (30 percent of the load is transferred to the adjacent slab). The spectrum of temperature gradient is presented in Figure 5.

The modulus of subgrade reaction underneath the slab is 0.04 MPa/mm. This modulus is upgraded to a value of 0.100 MPa/mm or 100 MN/m^2/m. Based on a modulus of subgrade support of 100 MN/m^2/m, the subgrade can be classified as a subgrade category 'B' i.e. medium strength.

Figure 5 Spectrum of thermal gradients for a 320 mm thick concrete slab

4. **Aircraft traffic**:
   - Determine the traffic volume in terms of type of aircraft, and number of future operations of each aircraft that the pavement will experienced over its PCN pavement life course;
   - Look up or calculate the ACNs of the aircraft at its operating empty (OEW) and maximum weight and at maximum takeoff weight (MTOW).

Table 3 Technical evaluation critical airplane determination

Airplane	Annual Departures	Operating weight (kg)		ACN Rigid Subgrade category B		Tire pressure (MPa)
		MTOW	OEW	MTOW	OEW	
B727-200	400	86,636	44,347	54 RB	25 RB	1.06
B737-300	6,000	61,462	32,904	39 RB	18 RB	1.34
A319-100AT	1,200	64,000	40,100	40 RB	22 RB	1.31
B747-400	4,500	395,987	178,459	63 RB	21 RB	1.41
B767-300ER	2,000	172,819	87,926	51 RB	20 RB	1.31
DC8-63/73	800	162,386	72,002	60 RB	19 RB	1.34
MD11	1,500	274,650	127,000	66 RB	25 RB	1.41
B777-200	300	288,031	138,346	63 RB	22 RB	1.51

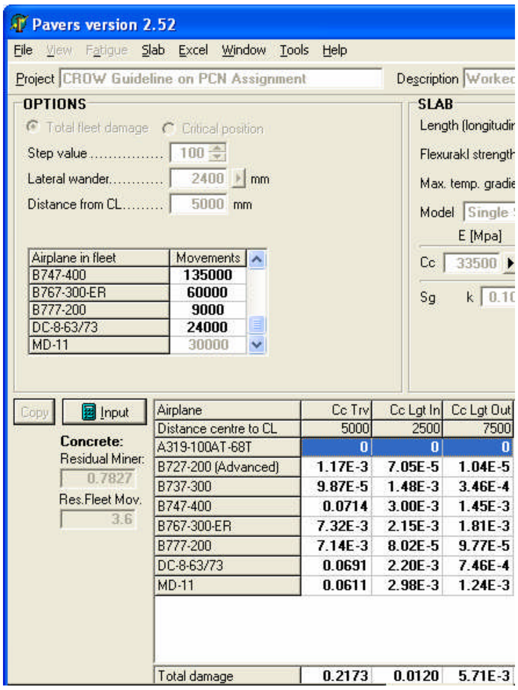
- Next, determine the critical aircraft of the forecasted fleet mix. This is the aircraft with the highest ACNs i.e. relative damage.
  In this case the critical aircraft is the MD-11, having ACNs of 66 and 25 (see Table 3). The ACNs at OEW and MTOW are to be used in the PCN evaluation.

- Determine the degree of lateral wander for the pavement;
  According to HoSang (Ref. 37) the wanders factor is 2400 mm (see Table 2).

- As the concrete pavement is constructed over a granular base, the critical pavement layer is the cement concrete layer itself. The first step is to determine which slab and joint are the most heavily loaded ones. It can be depicted in Figure 6 that the second slab from the centreline is the critical slab and the transverse joint is more trafficked than the both longitudinal joints.

Strip no	CL at mm	Damage Cc Trv	CL at mm	Damage Cc Lgt In	CL at mm	Damage Cc Lgt Out
2	5000	0.2165	2500	0.0134	7500	6.33E-3
3	10000	0.1212	7500	4.21E-3	12500	1.19E-4
4	15000	1.98E-3	12500	5.89E-5	17500	3.71E-8
5	20000	5.51E-7	17500	1.34E-8	22500	1.87E-13
6	25000	1.21E-12	22500	4.12E-14	27500	1.62E-20
7	30000	3.84E-20	27500	1.67E-21	32500	2.38E-29

Figure 6 Determination of the most heavily trafficked slab and joint



- Calculate the pavement damage for the transverse edge The total fleet damage including lateral wander is 21.7 per cent (See Figure 7) .

Figure 7 Pavement damage

5. **PCN Assessment: pavement life and PCN calculation**:
   - Convert the fleet mix into a number of MD 11 movements resulting in the same Miner damage. Use this number to calculate the PCN of the pavement.

A number of 19.929 equivalent MD 11 movements will consume the total structural pavement life (see Figure 8). However, during the 30 year pavement course, the accumulated Miner is only 21.7%. Hence, the number of equivalent MD 11 movements during the PCN-course is 0.2173 x 19,929 = 4,331 movements excluding lateral wander.

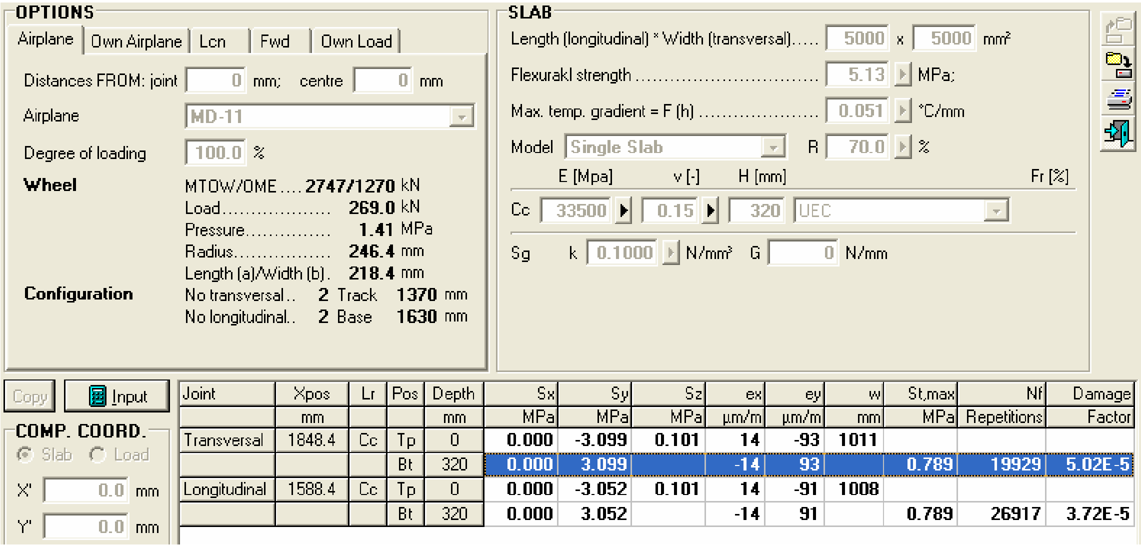


Figure 8 Calculating the allowable number of load repetitions of a MD 11.

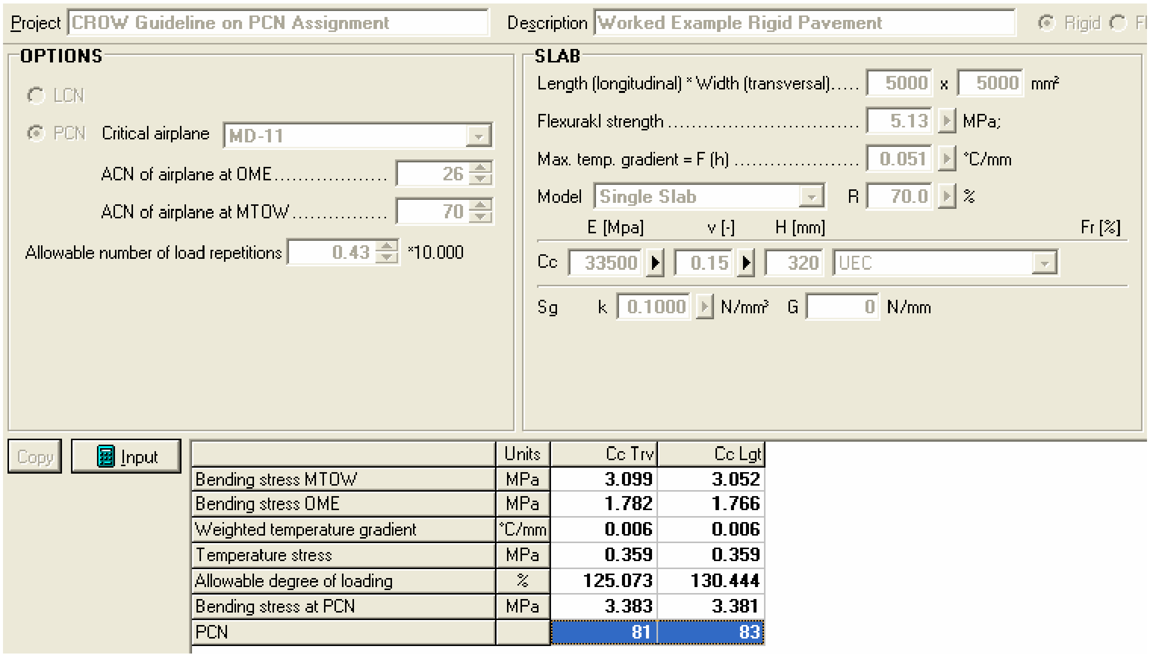


Figure 9 Calculating PCN

- Calculate the allowable ACN-load by varying the gross weight of the critical aircraft until the same Miner damage is gained during the PCN life course.
- Calculate the corresponding ACN that refers to the allowable mass using the published ACN data of the critical aircraft;
- Assign this ACN as being equal to the pavements PCN. Should the PCN be higher than the ACN of the critical aircraft, the PCN-life course can either be prolonged or limited to this ACN-value. Should the PCN be smaller than the required ACN of the critical aircraft, either a smaller PCN life course should be selected or the pavement must be strengthened to meet the requirements.

The PCN reporting format is 81 F/R/W/T.

Note that the transverse edge is critical. To report the results of the PCN evaluation to the CAA., the reporting form in Appendix 4 must be filled in. Note that the airport authorities may decide to report a PCN of 66 only, being equal to the maximum ACN of the aircraft using the pavement.

Note that the MD11 has an ACN at MTOW of 66, not exceeding the calculated PCN.
However, should the technical PCN have been lower the aircraft's ACN, an airport authority has several options:

- First one may use clause 19.1 'Overload Operation' of ICAO Annex 14 to allow MD11 aircraft as occasional movements on rigid pavement by 5 percent above the reported PCN.
- The second option is to download the aircraft to meet the desired ACN. Decreasing the pavement PCN-evaluation life has limited effect because of the nature of the cement concrete.
- Therefore, the last option is to rehabilitate the pavement and to construct a thicker slab.

It is mentioned, that if a rigid base layer is incorporated in the concrete pavement, this layer may become critical. Therefore, use of a multi-slab model is mandatory (see Figure 10).

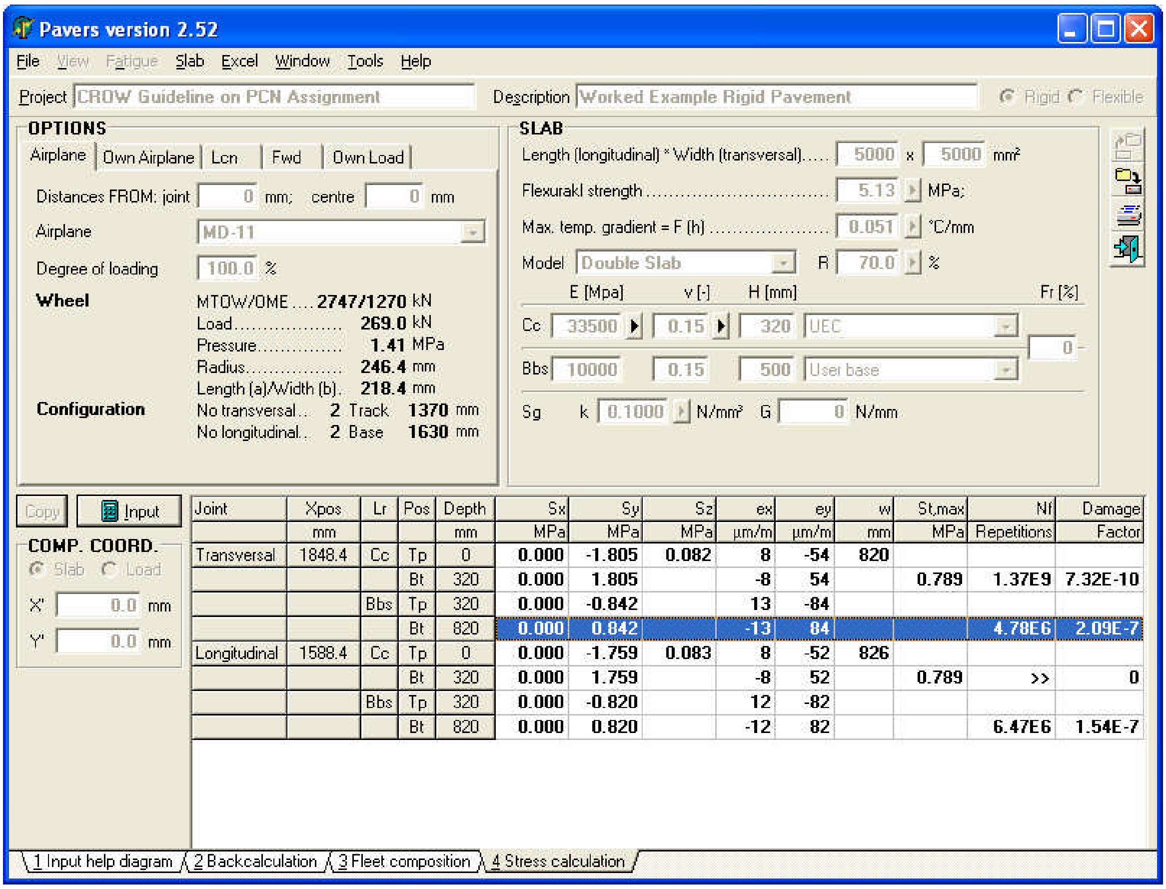


Figure 10 The critical layer in this concrete pavement is the Cement Treated Base (CTB)