ICAO - PAVEMENT RATING SYSTEM

INTERNATIONAL CIVIL AVIATION ORGANIZATION
Western and Central African (WACAF) Office

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PAVEMENT CLASSIFICATION RATING

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PCR concept

- Similarly to the PCN, the PCR represents the pavement bearing strength (on the ACR scale) for unrestricted operations
- A PCR SHALL be determined by the airport operator for all the pavements intended for aircraft of mass greater than 5.7 tons
- The PCR should be published in the Aeronautical Information Publication (AIP) according to the format defined in ICAO Annex 14 (§ 2.6.6)

PCR 560 / F / B / W / T

PCR number

Pavement type
F: Flexible
R: Rigid

Subgrade strength category
A: High
B: Medium
C: Low
D: Ultra low

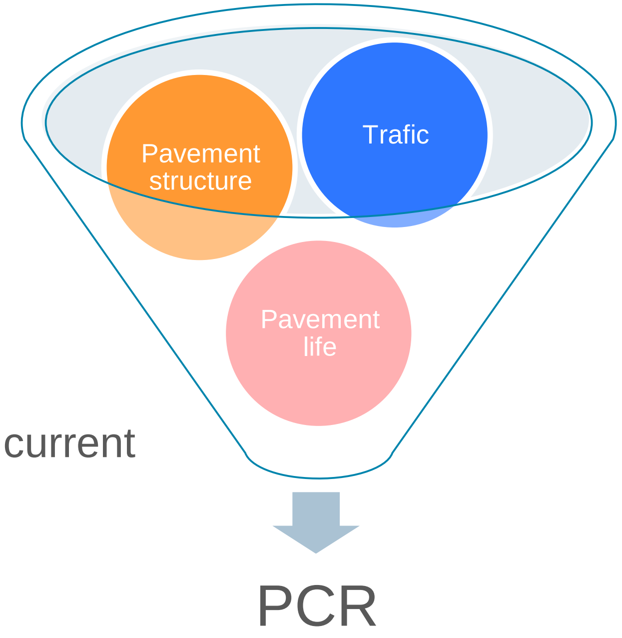
Maximum allowable tire pressure
W: No pressure limit
X: 1.75 MPa
Y: 1.25 MPa
Z: 0.5 MPa

Evaluation method
U: Using aircraft experience
T: Technical evaluation

PCR concept

- The PCR is the result of **balance** between:
  - The mechanical characteristics of the pavement
  - The traffic it is intended to serve
  - The expected pavement design life (or remaining life)

- The PCR to be reported is such that the pavement strength is sufficient for the current and future traffic until the (planned) end of the pavement life



⚠ With the exception of massive overloading, there is generally no risk of sudden pavement failure associated with the operations of an aircraft with ACR > PCR
For rigid pavements however, an overload combined with a thermal gradient may initiate the slab cracking

- The decision to allow operations of an aircraft with ACR > PCR (overload operations) falls to the airport operator depending on its pavement management policy

General principles

- The PCR determination process entails the following steps:
  - ➢ Determination of the pavement type (F/R)
  - ➢ Determination of the subgrade strength category (A/B/C/D)
  - ➢ Determination of the tire pressure category (W/X/Y/Z)
  - ➢ Determination of the PCR number
    - – Either with a technical evaluation (recommended)
    - – Or “using aircraft” experience

General principles

Determination of pavement type (F/R)

- For the PCR determination, pavements must be classified as either flexible or rigid

- A **rigid pavement** is that employing a PCC slab (plain, reinforced, or pre-stressed and with or without intermediate layers between the slab and subgrade)

- A **flexible pavement** is that consisting of a series of layers increasing in strength from the subgrade to the wearing surface

- Composite pavements (PCC overlay on a flexible pavement or flexible overlay on a rigid pavement) require care in classification:
  - If the rigid element remains the predominant structural element and is not severely distressed, the pavement should be classified as **rigid**
  - Otherwise, the pavement should be classified as **flexible**

- Where classification remains doubtful, designation as flexible pavement is generally conservative

General principles

Determination of subgrade strength category (A/B/C/D)

- The subgrade strength is now characterized by its elastic modulus (Young's modulus) for both flexible and rigid pavements
- There is now a **unified subgrade strength characterization** for both pavement types

	CAT A High	**CAT B Medium**	**CAT C Low**	**CAT D Ultra-low**
PCR (flexible and rigid)	$E \geq 150$ MPa	$100 \leq E < 150$ MPa	$60 \leq E < 100$ MPa	$E < 60$ MPa
PCN (flexible	$CBR > 13$	$8 < CBR \leq 13$	$4 < CBR \leq 8$	$CBR \leq 4$
PCN (rigid)	$K > 120$ MN/m3	$60 < K \leq 120$ MN/m3	$25 < K \leq 60$ MN/m3	$K \leq 25$ MN/m3

- The Young's modulus E may be obtained by the following means:
  - In-situ tests (plate load test)
  - Laboratory tests
  - Conversion from CBR or K value

Example of conversions: $E = 10\ CBR$ (E in MPa) $E = 20.15\ K^{1.284}$ (E in psi, K in pci)

General principles

Determination of tire pressure category (W/X/Y/Z)

- The tire pressure categories remain unchanged compared to the PCN

	Code W Unlimited	Code X High	Code Y Medium	Code Z Low
PCR (and PCN)	No pressure limit	P ≤ 1.75 MPa	P ≤ 1.25 MPa	P ≤ 0.50 MPa

- The results of pavement research and reevaluation of old test results reaffirm that except for unusual pavement construction (i.e. flexible pavements with a thin asphaltic concrete cover or weak upper layers), tire pressure effects are secondary to wheel load and wheel spacing

- **Rigid pavements** generally do not require tire pressure restrictions (except cases of spalling joints or unusual surface defects)

- For **flexible pavements** (or rigid pavements with flexible overlays), it is usually acceptable to establish category limits only when experience with high tire pressures indicates pavement distress

PCR determination – Using aircraft experience (U) / TEMPORARY

- When, for economic or other reasons a technical evaluation is not feasible, evaluation can be based on experience with "using aircraft"

- A pavement **satisfactorily sustaining its using traffic** can be considered capable of supporting the heaviest aircraft **regularly using it** and any other aircraft that has no greater pavement strength requirements

- The condition of the pavement (cracking, distortion) is of first importance
  - In general, a pavement in good condition can be considered to be satisfactorily sustaining the using traffic
  - Indications of advancing distress show that the pavement is being overloaded

- A PCI below the critical Threshold (65 for Runway, 60 for all other mvt areas) are not eligible to a code U PCR

PCR determination – Using aircraft experience (U) / TEMPORARY

- The PCR determination using aircraft experience relies on the following steps:

  1. Identify the aircraft using the pavement, with operating weights and frequency of operations
  2. Determine the corresponding ACR for the identified pavement type and subgrade strength category
  3. Report the PCR as the ACR of the most critical aircraft

⚠ Only aircraft using the pavement on a continuing basis without unacceptable pavement distress should be considered

- When a significant increase in use of the pavement is expected, the PCR should be adjusted downward to accommodate the increase

PCR determination – Using aircraft experience (U) / TEMPORARY

- Example: An airport operator wants to assess the PCR of its runway, however due to financial constraints a technical evaluation is not deemed feasible:
  - The runway is a flexible pavement
  - The subgrade modulus can be estimated from the historical CBR of 9: $E \approx 10\ CBR = 90\ MPa$ ⇨ subgrade category C
  - There is no evidence of pavement distress attributable to high tire pressures ⇨ tire pressure category W
  - The runway has been accommodating the following traffic without any significant damage

    Note: The most demanding aircraft only are considered, other aircraft can be dismissed as they will not lead to the most critical ACR

    Note 2: For such types of traffic, a technical evaluation is obviously preferable

Aircraft type	Operating weight	Annual departures	ACR @ operating weight
A330-300	233.9 t	104	650 F/C
A350-900	268.9 t	52	720 F/C
777-300ER	352.4 t	6	790 F/C
787-9	254.7 t	52	750 F/C

- The number of annual departures for the 777-300ER is very low as compared to other aircraft, hence it should be dismissed from the PCR assignment
- The PCR should be reported as **750 F/C/W/U**
- The 777-300ER would then be accepted based on the ICAO overload allowance (10% of PCR)

PCR determination – Technical evaluation (T)

Overview of generic procedure

CDF: See next section

- The ACR/PCR method does permit States to use the design/evaluation procedure of their choice when determining the PCR rating for their pavements, provided it remains consistent with the overall parameters of the ACR-PCR method

- Unlike the PCN, the ICAO developed a *generic procedure* for the PCR technical evaluation in order to fill the gap for states that may lack the expertise in the area

- The PCR determination should be based on the concept of Cumulated Damage Factor (CDF) implementing Miner's rule:

  $CDF = CDF_1 + CDF_2 \ldots + CDF_N$ where $i = 1..N$ denotes the different aircraft in the mix

- A valid PCR procedure must ensure that:
  - If the pavement CDF is lower than or equal to 1.0 (well or over-designed), no weight restriction should occur for aircraft in the evaluated traffic
  - If the pavement CDF is higher than 1.0 (under-designed), at least one aircraft from the evaluated traffic will be weight-restricted

- As the PCR is related to the *structural* pavement life, the CDF for flexible pavements should be based on the subgrade failure mode

PCR determination – Technical evaluation (T)

Mechanical model selection

- The PCR calculation procedure requires a mechanical model for the calculation of pavement mechanical responses
- The basic recommendation is to use Layered Elastic Analysis (LEA) as the mechanical model for PCR determination, similar to what is used for the ACR calculation
- However states may decide to adapt the mechanical model or use a more complex modelling (e.g. Finite Element Model)

PCR determination – Technical evaluation (T)

Damage model selection

See “Damage model” after

- Although a full damage model is prescribed for the ACR calculation, the **generic PCR procedure does not dictate the use of a preferred damage model**

- The following elements can therefore be customized for the PCR calculation (see Module 2 for details):
  - Elementary (subgrade damage) law
  - Consideration of multi-axle loads (tandem wheels)
  - Handling of aircraft lateral wander

- Using **the same damage model as for pavement design** will ensure consistency between what the actual pavement is able to withstand and the PCR assignment

⚠ Inconsistency between the damage models used for pavement design and PCR determination may result in:

- PCR underestimation (hence unoptimized use of pavement, potential denial of aircraft operations, loss of revenue)
- PCR overestimation (hence accelerated pavement deterioration and reduced pavement life)

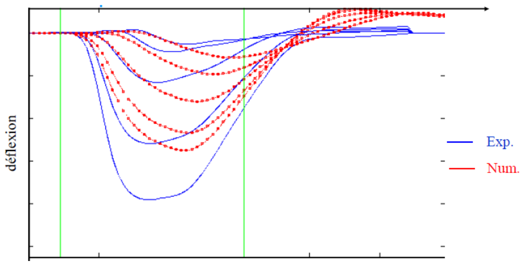
- Understanding and selecting the appropriate damage model for PCR calculation is of **paramount importance**

PCR determination – Technical evaluation (T)

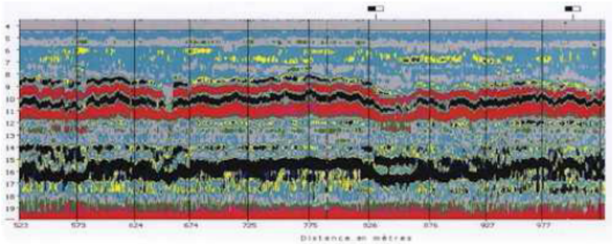
Inputs determination: Pavement structure

- The proper determination of **inputs** is a key step for a reliable PCR determination

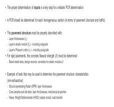
- A PCR should be determined for each homogeneous section (in terms of pavement structure and traffic)



- The **pavement structure** must be properly described with:
  - Layer thicknesses (t_i)
  - Layer's elastic moduli (E_i) – including subgrade
  - Layer's Poisson's ratio (ν_i) – including subgrade
- For rigid pavements, the concrete flexural strength (R) must be determined
  - Beam break tests, design records, correlation to elastic modulus E



- Example of tools that may be used to determine the pavement structure characteristics (non-exhaustive):
  - Ground-penetrating Radar (GPR): layer thicknesses
  - Core samples and lab tests: layer thicknesses, mechanical properties
  - Heavy Weight Deflectometer (HWD): elastic moduli, load transfer

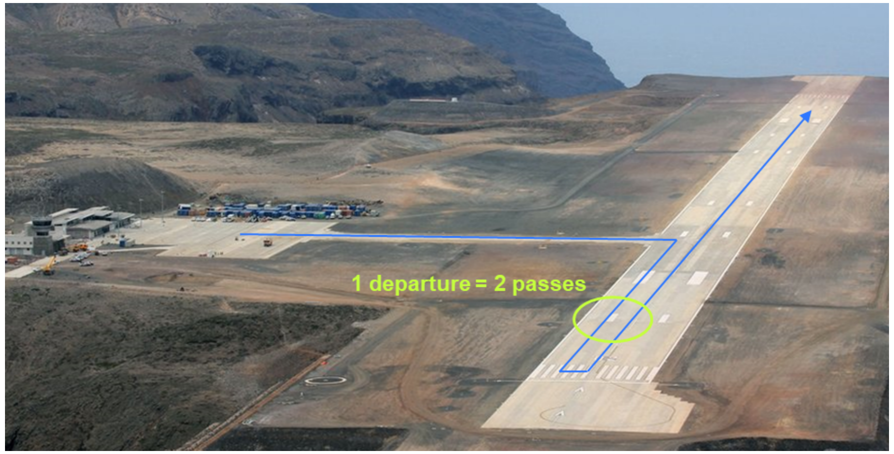


The data required for PCR technical evaluation is similar to that required for an accurate PCN technical evaluation

PCR determination – Technical evaluation (T)

Inputs determination: Aircraft traffic

- The **aircraft traffic** must be described in terms of:
  - Aircraft types (defining landing gear type and geometry, tire pressure)
  - Operating weights
  - Total number of passes forecasted over the expected (remaining) pavement life
  - Quantification of aircraft wander



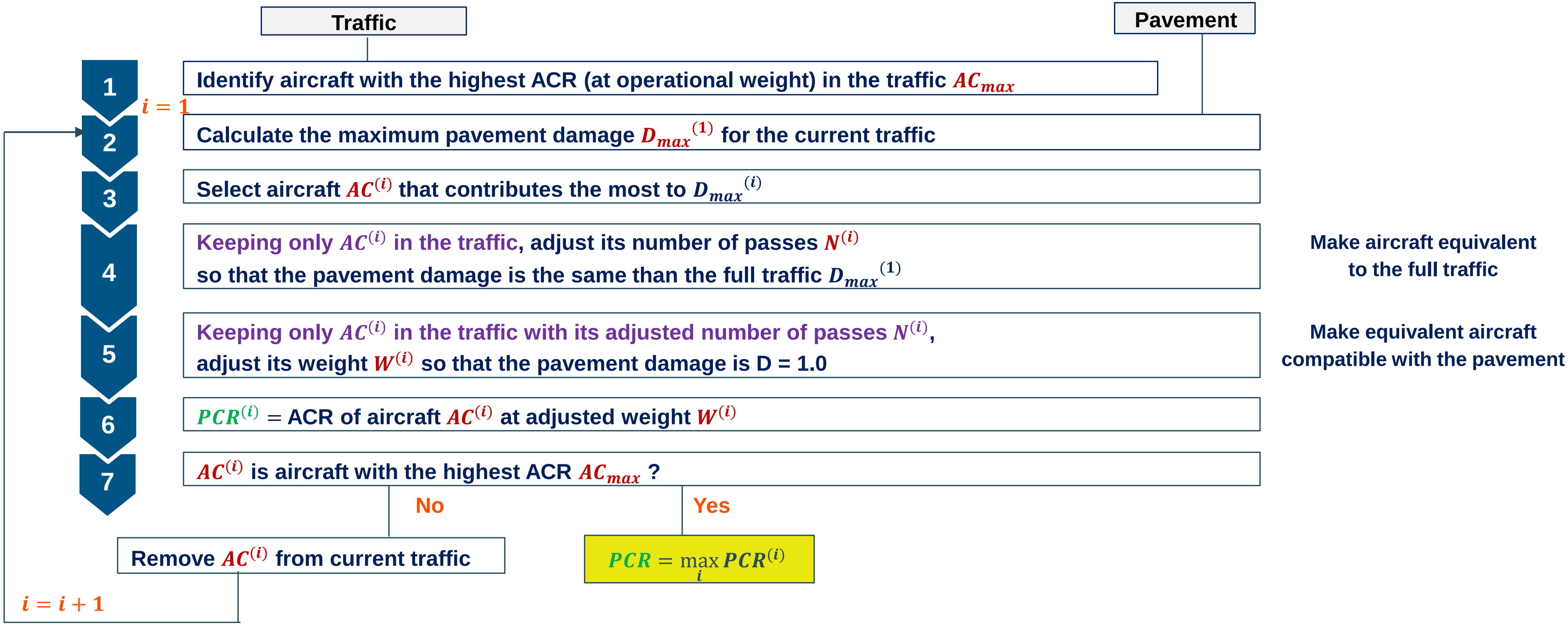
- When a pavement is subject to both departures and arrivals, the maximum anticipated take-off weight and landing weight should be considered. One movement = One Landing + One Takeoff
- Otherwise, the traffic should reflect as closely as possible the actual operating weights and associated number of passes

- The number of passes must reflect the actual number of times the pavement is loaded, hence it may be different from the number of departures or arrivals depending on the airport layout
  - E.g.: For a runway with a central taxiway only, 1 departure = 2 passes (Passes per Traffic Cycle ratio P/TC = 2)

- Aircraft wander depends on the pavement function (runway, taxiway, taxilane, apron), typical values can be found in the ICAO ADM Part 3, Pavements, 3rd Edition – July 2022

PCR determination – Technical evaluation (T)

Procedure flowchart



Traffic

Pavement

1 Identify aircraft with the highest ACR (at operational weight) in the traffic AC_{max}

$i = 1$

2 Calculate the maximum pavement damage ${D_{max}}^{(1)}$ for the current traffic

3 Select aircraft $AC^{(i)}$ that contributes the most to ${D_{max}}^{(i)}$

4 Keeping only $AC^{(i)}$ in the traffic, adjust its number of passes $N^{(i)}$ so that the pavement damage is the same than the full traffic ${D_{max}}^{(1)}$

Make aircraft equivalent to the full traffic

5 Keeping only $AC^{(i)}$ in the traffic with its adjusted number of passes $N^{(i)}$, adjust its weight $W^{(i)}$ so that the pavement damage is D = 1.0

Make equivalent aircraft compatible with the pavement

6 $PCR^{(i)} =$ ACR of aircraft $AC^{(i)}$ at adjusted weight $W^{(i)}$

7 $AC^{(i)}$ is aircraft with the highest ACR AC_{max} ?

No

Remove $AC^{(i)}$ from current traffic

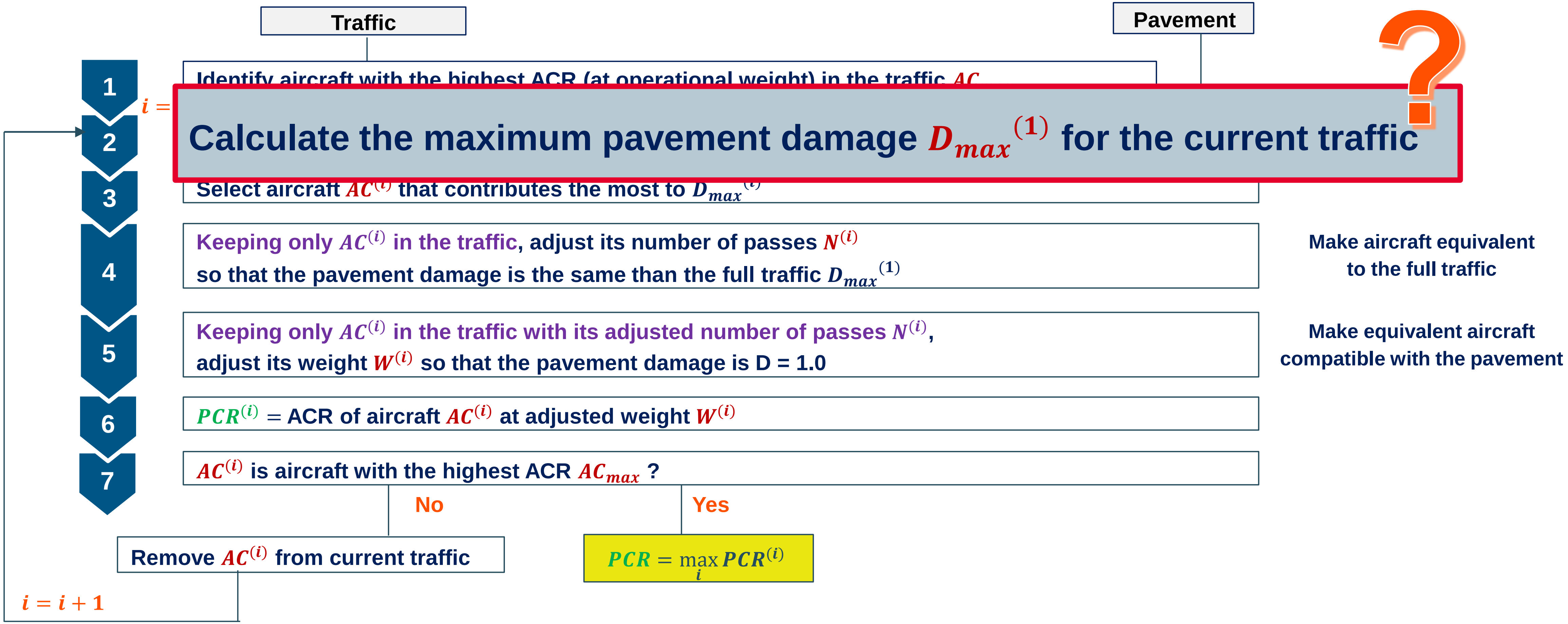
$i = i + 1$

Yes

$PCR = \max_i PCR^{(i)}$

PCR determination – Technical evaluation (T)

Procedure flowchart



Traffic

Pavement

1 Identify aircraft with the highest ACR (at operational weight) in the traffic AC

$i =$

Calculate the maximum pavement damage $D_{max}^{(1)}$ for the current traffic

2

3 Select aircraft $AC^{(i)}$ that contributes the most to $D_{max}^{(i)}$

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No

Remove $AC^{(i)}$ from current traffic

$i = i + 1$

Yes

$PCR = \max_{i} PCR^{(i)}$

CUMULATIVE DAMAGE FACTOR

CUMULATIVE DAMAGE FACTOR - DEFINITION

- The cumulative damage factor (CDF) is the amount of the structural fatigue life of a pavement which has been used up. It is expressed as the ratio of applied load repetitions to allowable load repetitions to failure, or, for one airplane and constant annual departures:

- $CDF = \frac{Applied\ coverages}{Coverages\ to\ failure}$

- where a coverage is one application of the maximum strain or stress due to load on a given point in the pavement structure.

- When CDF = 1, the pavement subgrade will have used all of its fatigue life;
- When CDF < 1, the pavement subgrade will have some remaining life and the value of CDF will give the fraction of the life used;
- When CDF > 1, all of the fatigue life will have been used and the pavement subgrade will have failed.

- For multiple aircraft (Miner's Rule):
- $CDF = CDF_1 + CDF_2 + \cdots + CDF_N$ (Where CDF_i is the CDF for each airplane in the traffic mix and N is the number of airplanes in the mix.

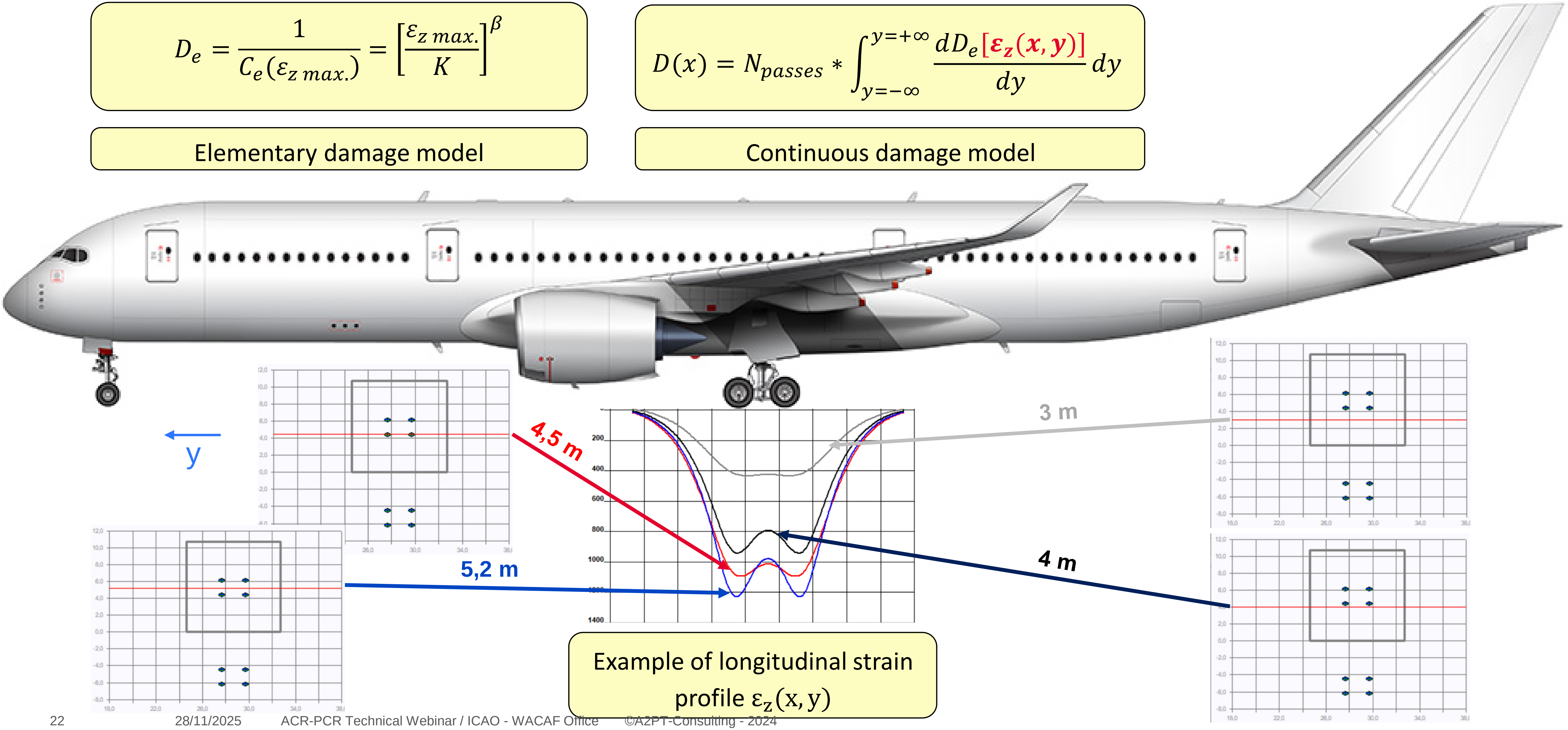
DAMAGE MODEL (EXAMPLE: WÖHLER)

$$D_e = \frac{1}{C_e(\varepsilon_{z\,max.})} = \left[\frac{\varepsilon_{z\,max.}}{K}\right]^{\beta}$$

Elementary damage model

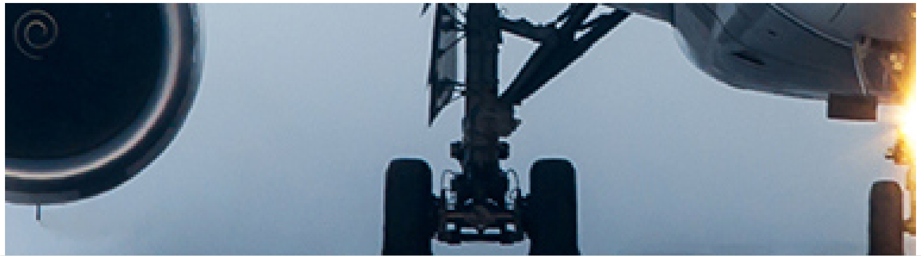
$$D(x) = N_{passes} * \int_{y=-\infty}^{y=+\infty} \frac{dD_e[\boldsymbol{\varepsilon_z(x,y)}]}{dy}\, dy$$

Continuous damage model

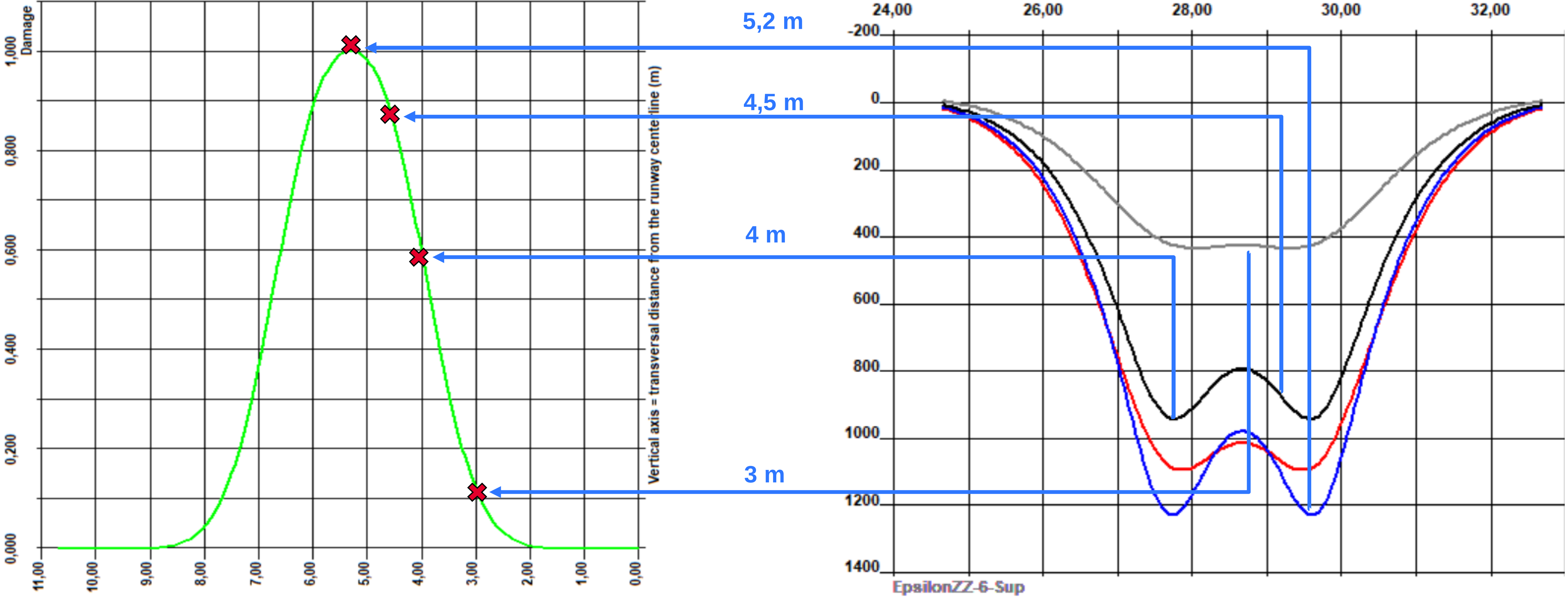


Example of longitudinal strain profile $\varepsilon_z(x, y)$

HOW IS CDF CURVE CALCULATED?

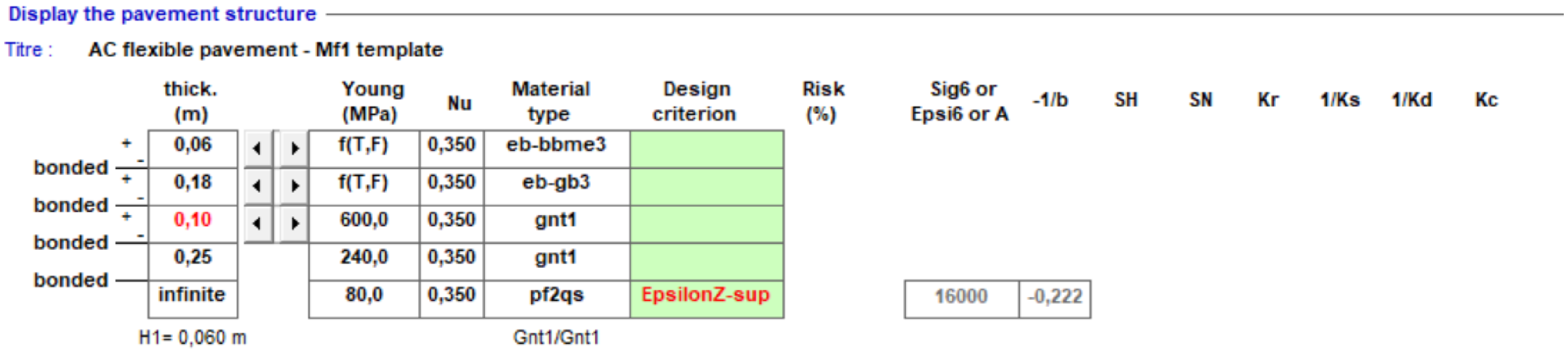


$$D(y,z_k) = \frac{\beta}{K^\beta}\int_{-\infty}^{+\infty} < \varepsilon(x,y,z_k) >^{\beta-1} < \frac{d\varepsilon}{dx}(x,y,z_k) > dx$$



EXAMPLE: CDF OF A MIX

PAVEMENT CROSS SECTION STRUCTURE



Display the pavement structure

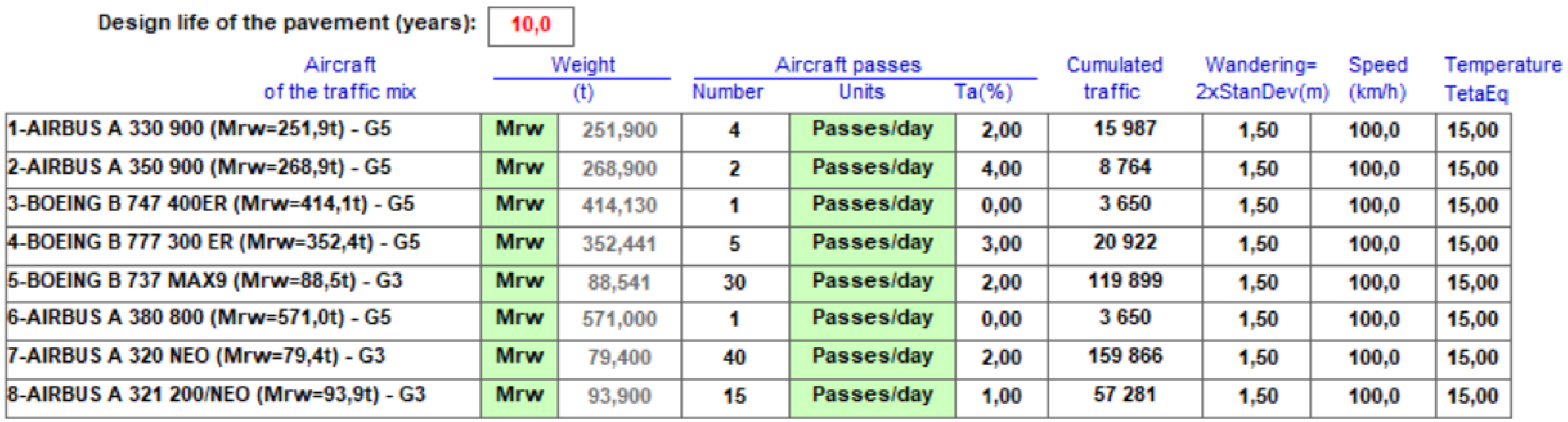
Titre : **AC flexible pavement - Mf1 template**

Interface	thick. (m)	Young (MPa)	Nu	Material type	Design criterion	Risk (%)	Sig6 or Epsi6 or A	-1/b	SH	SN	Kr	1/Ks	1/Kd	Kc
bonded	0,06	f(T,F)	0,350	eb-bbme3										
bonded	0,18	f(T,F)	0,350	eb-gb3										
bonded	0,10	600,0	0,350	gnt1										
bonded	0,25	240,0	0,350	gnt1										
	infinite	80,0	0,350	pf2qs	EpsilonZ-sup		16000	-0,222						

H1= 0,060 m

Gnt1/Gnt1

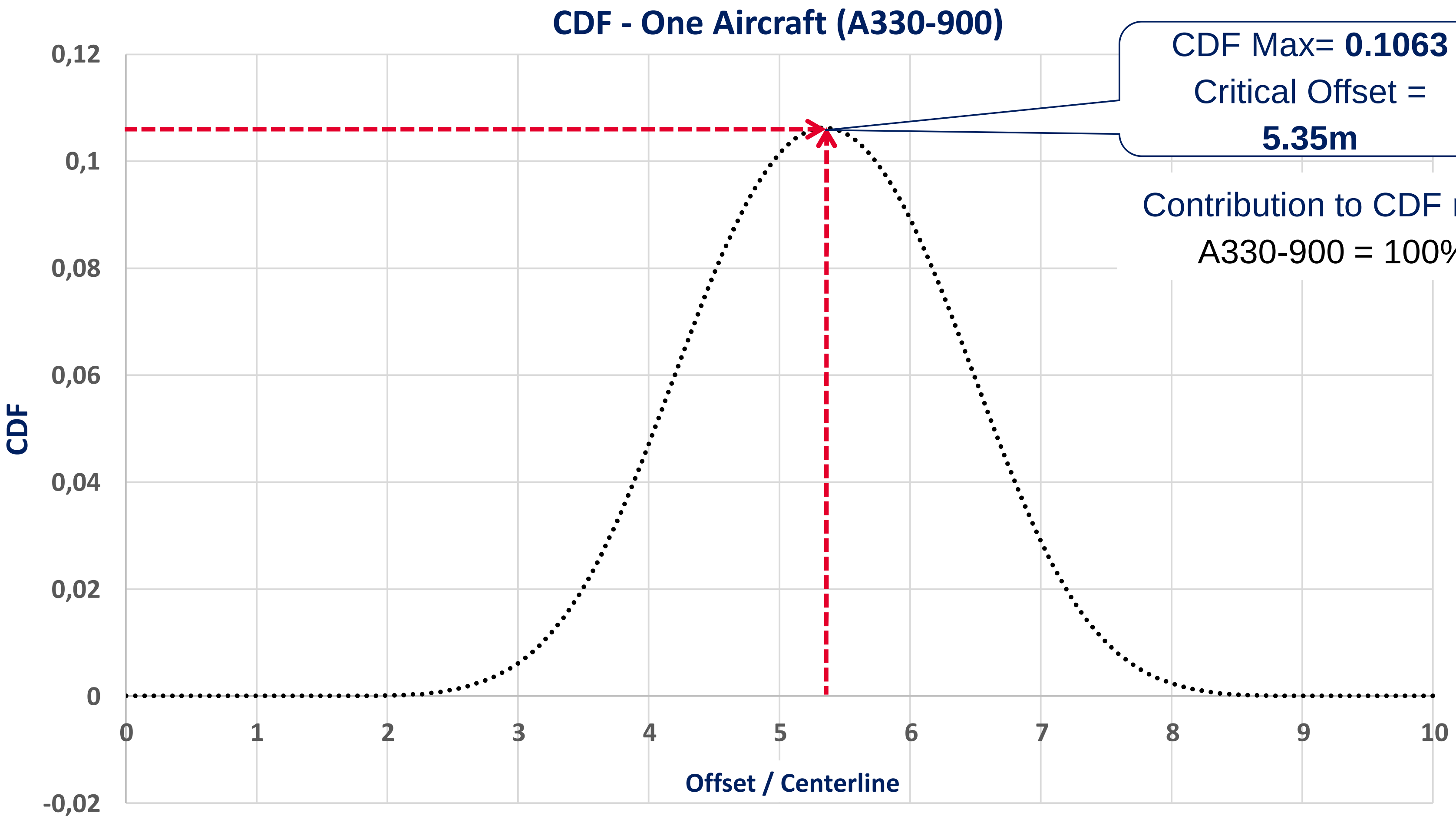
AIRCRAFT MIX



Design life of the pavement (years): 10,0

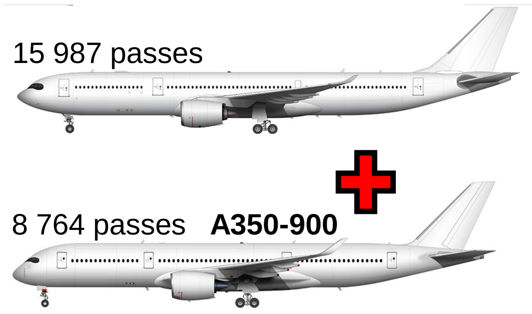
Aircraft of the traffic mix	Weight	(t)	Aircraft passes Number	Units	Ta(%)	Cumulated traffic	Wandering= 2xStanDev(m)	Speed (km/h)	Temperature TetaEq
1-AIRBUS A 330 900 (Mrw=251,9t) - G5	Mrw	251,900	4	Passes/day	2,00	15 987	1,50	100,0	15,00
2-AIRBUS A 350 900 (Mrw=268,9t) - G5	Mrw	268,900	2	Passes/day	4,00	8 764	1,50	100,0	15,00
3-BOEING B 747 400ER (Mrw=414,1t) - G5	Mrw	414,130	1	Passes/day	0,00	3 650	1,50	100,0	15,00
4-BOEING B 777 300 ER (Mrw=352,4t) - G5	Mrw	352,441	5	Passes/day	3,00	20 922	1,50	100,0	15,00
5-BOEING B 737 MAX9 (Mrw=88,5t) - G3	Mrw	88,541	30	Passes/day	2,00	119 899	1,50	100,0	15,00
6-AIRBUS A 380 800 (Mrw=571,0t) - G5	Mrw	571,000	1	Passes/day	0,00	3 650	1,50	100,0	15,00
7-AIRBUS A 320 NEO (Mrw=79,4t) - G3	Mrw	79,400	40	Passes/day	2,00	159 866	1,50	100,0	15,00
8-AIRBUS A 321 200/NEO (Mrw=93,9t) - G3	Mrw	93,900	15	Passes/day	1,00	57 281	1,50	100,0	15,00

15 987 passes **A330-900**



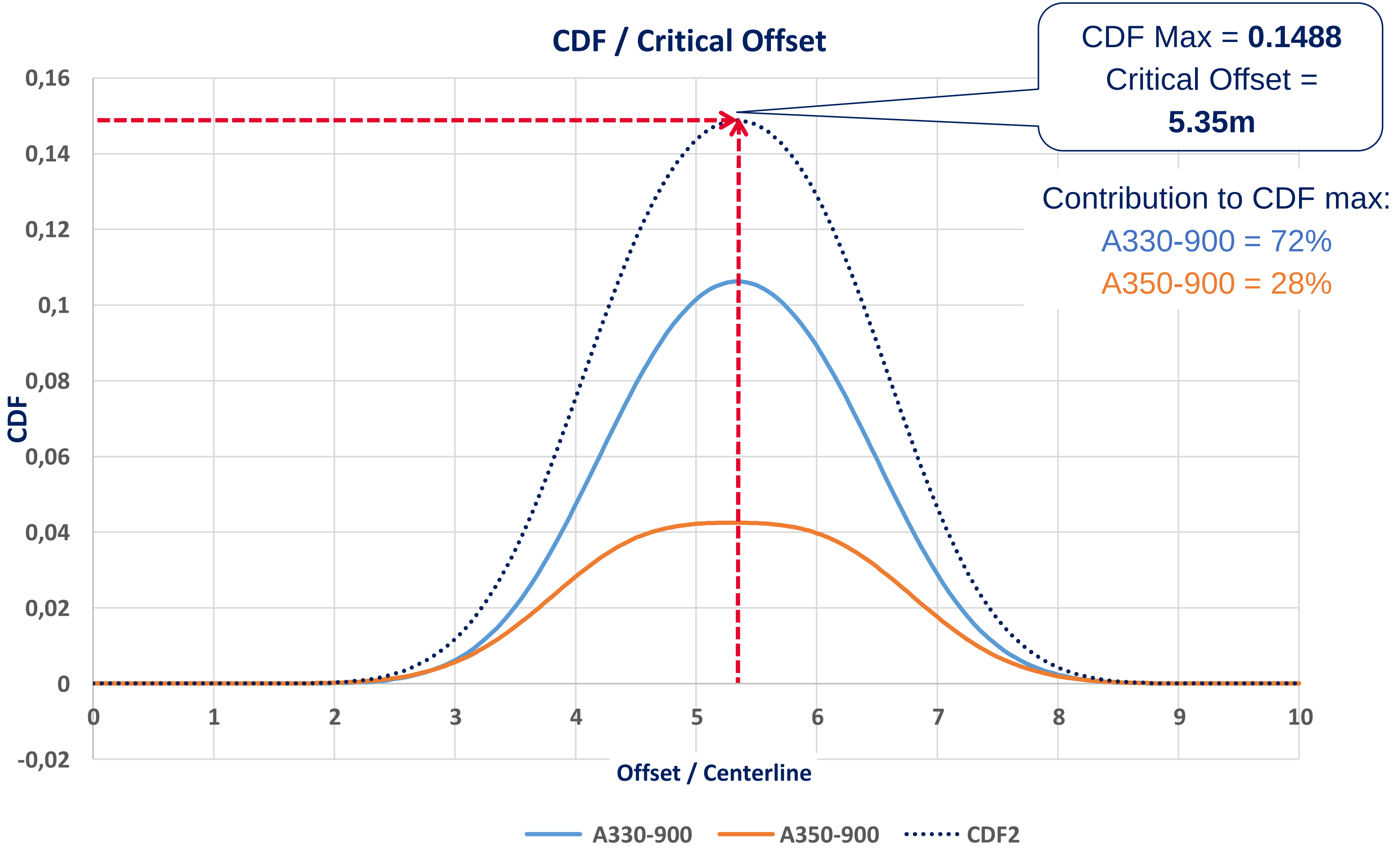
CDF Max= **0.1063**
Critical Offset =
5.35m

Contribution to CDF max:
A330-900 = 100%



15 987 passes

8 764 passes **A350-900**



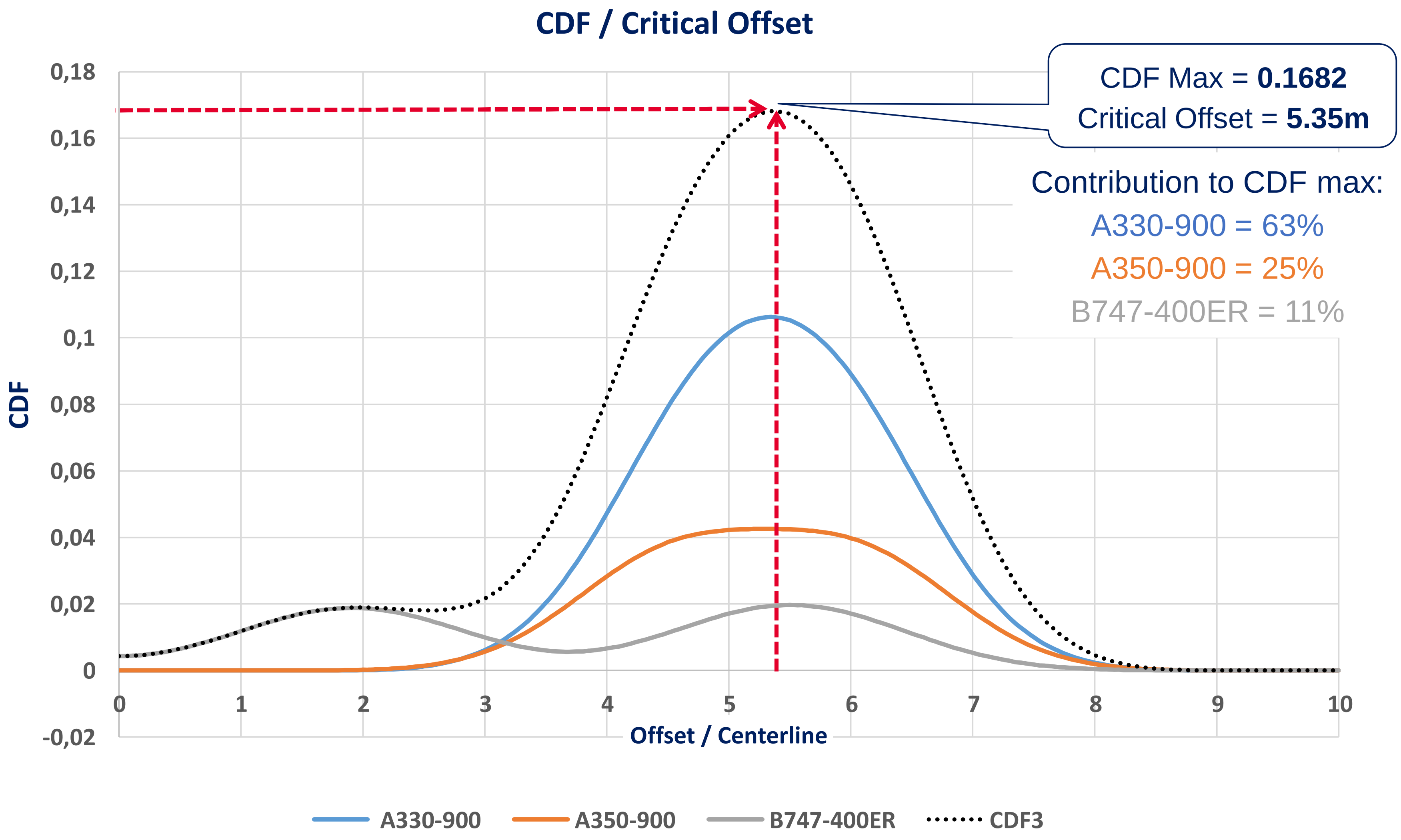
CDF Max = **0.1488**
Critical Offset =
5.35m

Contribution to CDF max:
A330-900 = 72%
A350-900 = 28%


15 987 passes

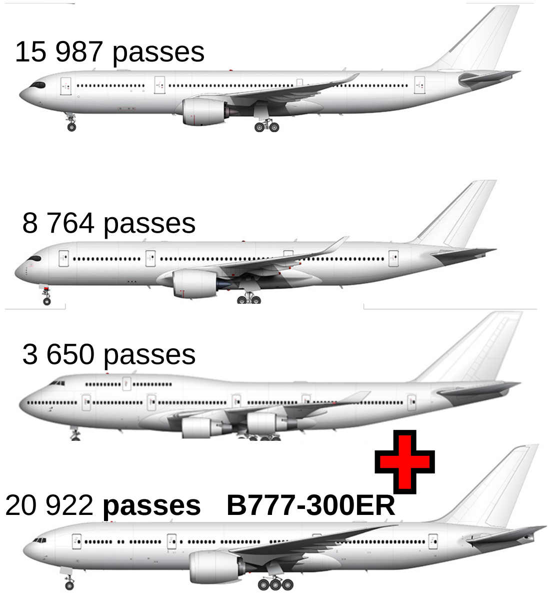

8 764 passes


3 650 passes **B747-400**

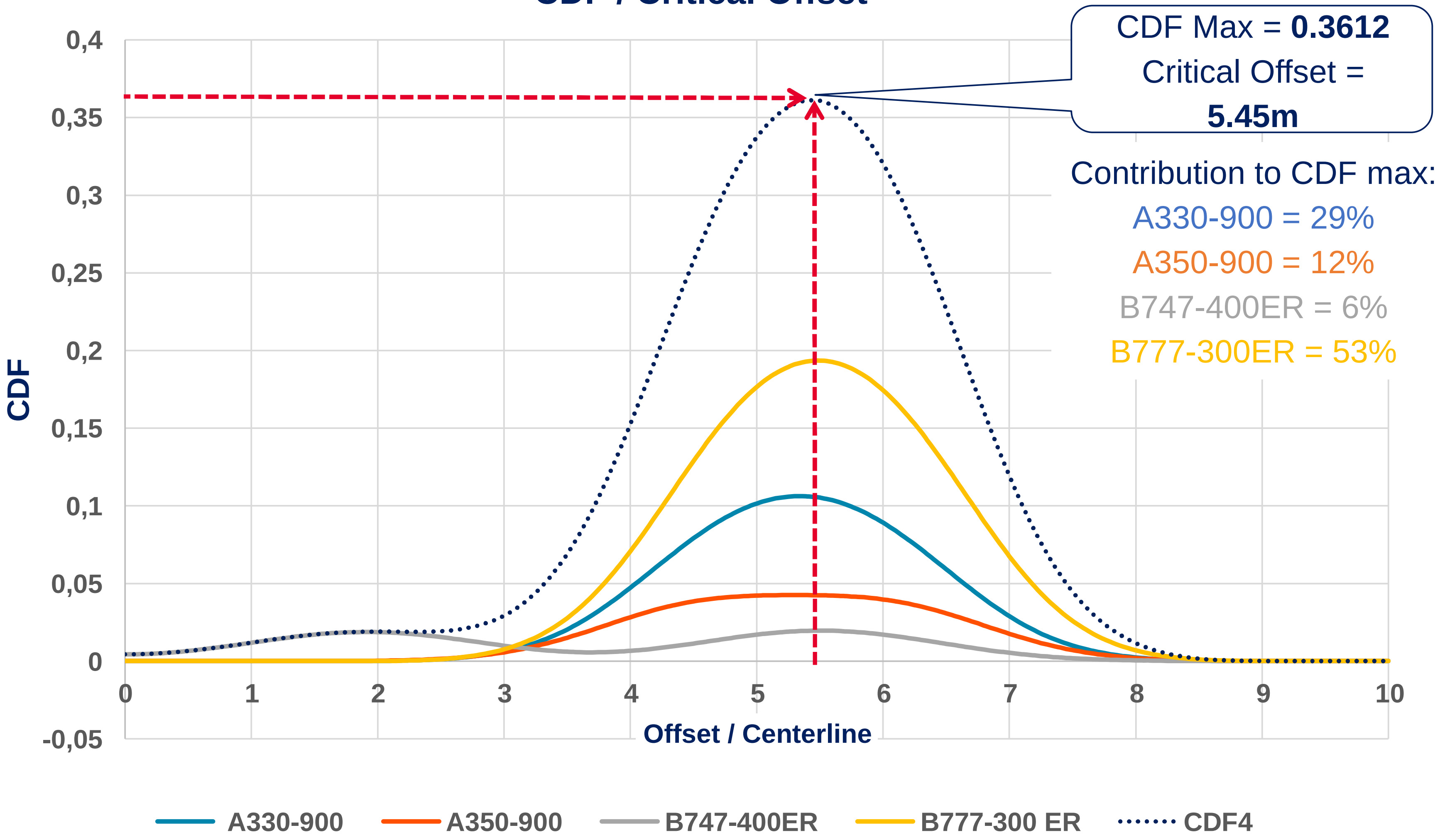


CDF Max = **0.1682**
Critical Offset = **5.35m**

Contribution to CDF max:
A330-900 = 63%
A350-900 = 25%
B747-400ER = 11%

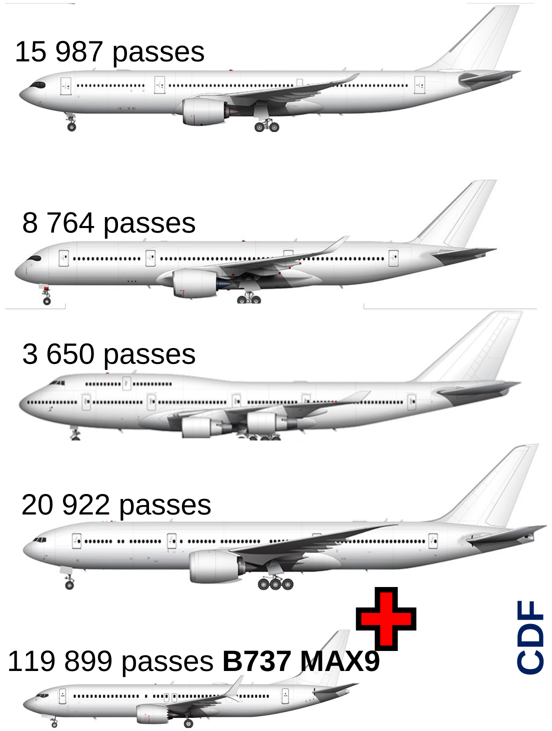


CDF / Critical Offset



CDF Max = **0.3612**
Critical Offset =
5.45m

Contribution to CDF max:
A330-900 = 29%
A350-900 = 12%
B747-400ER = 6%
B777-300ER = 53%



15 987 passes

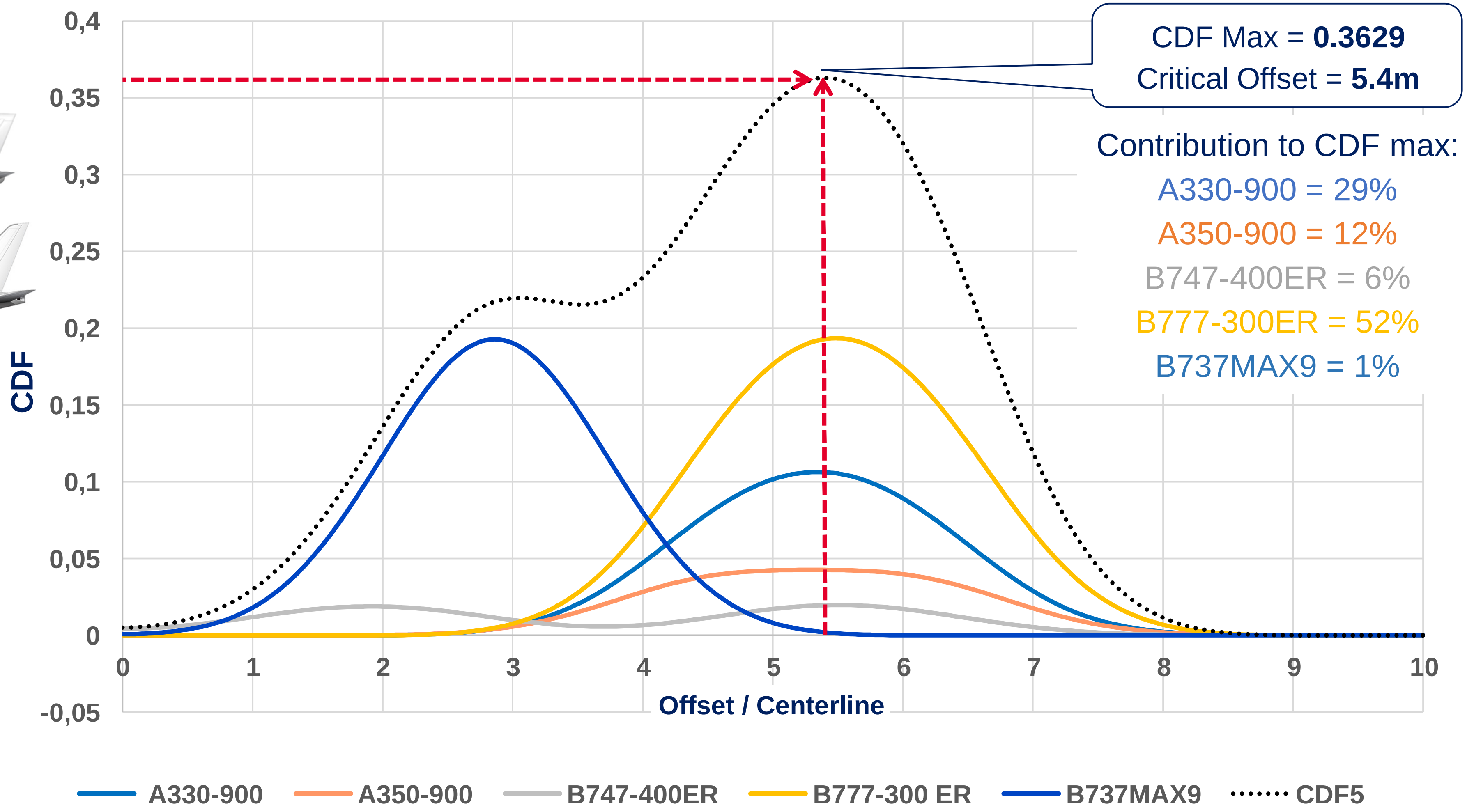
8 764 passes

3 650 passes

20 922 passes

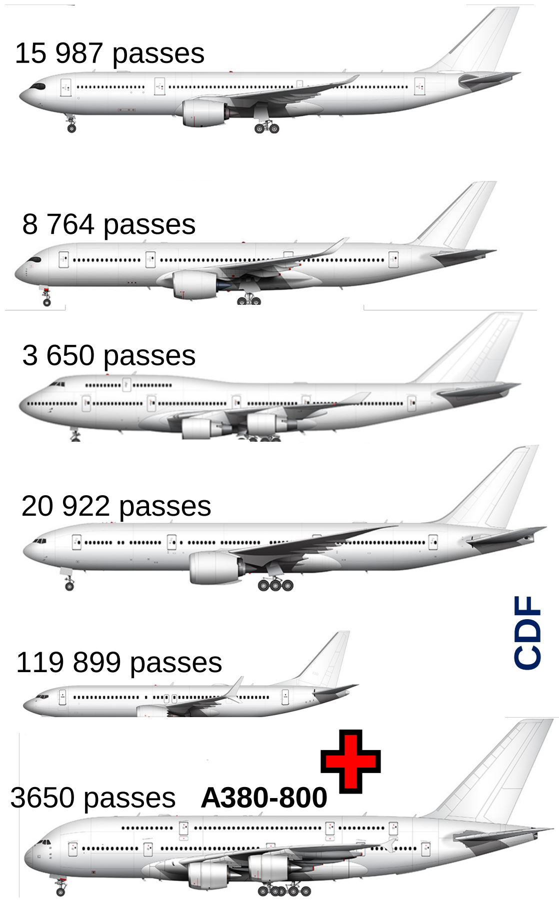
119 899 passes **B737 MAX9**

CDF / Critical Offset

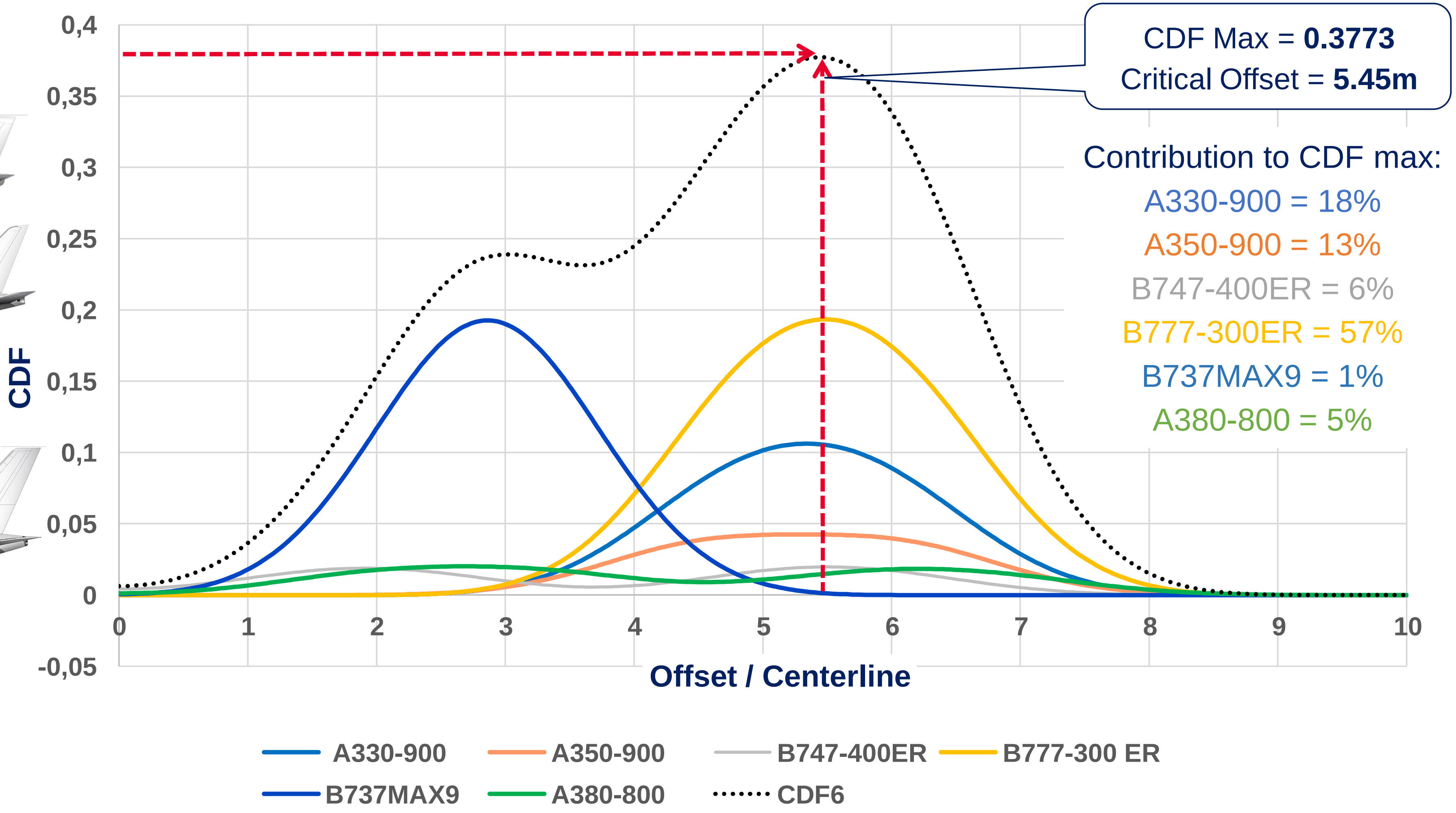


CDF Max = **0.3629**
Critical Offset = **5.4m**

Contribution to CDF max:
A330-900 = 29%
A350-900 = 12%
B747-400ER = 6%
B777-300ER = 52%
B737MAX9 = 1%

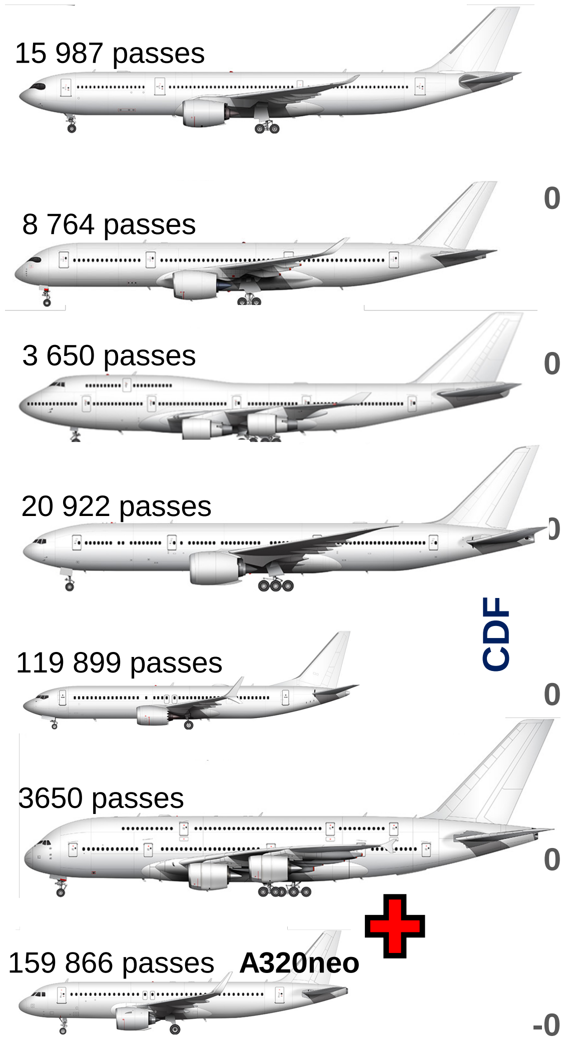


CDF / Critical Offset

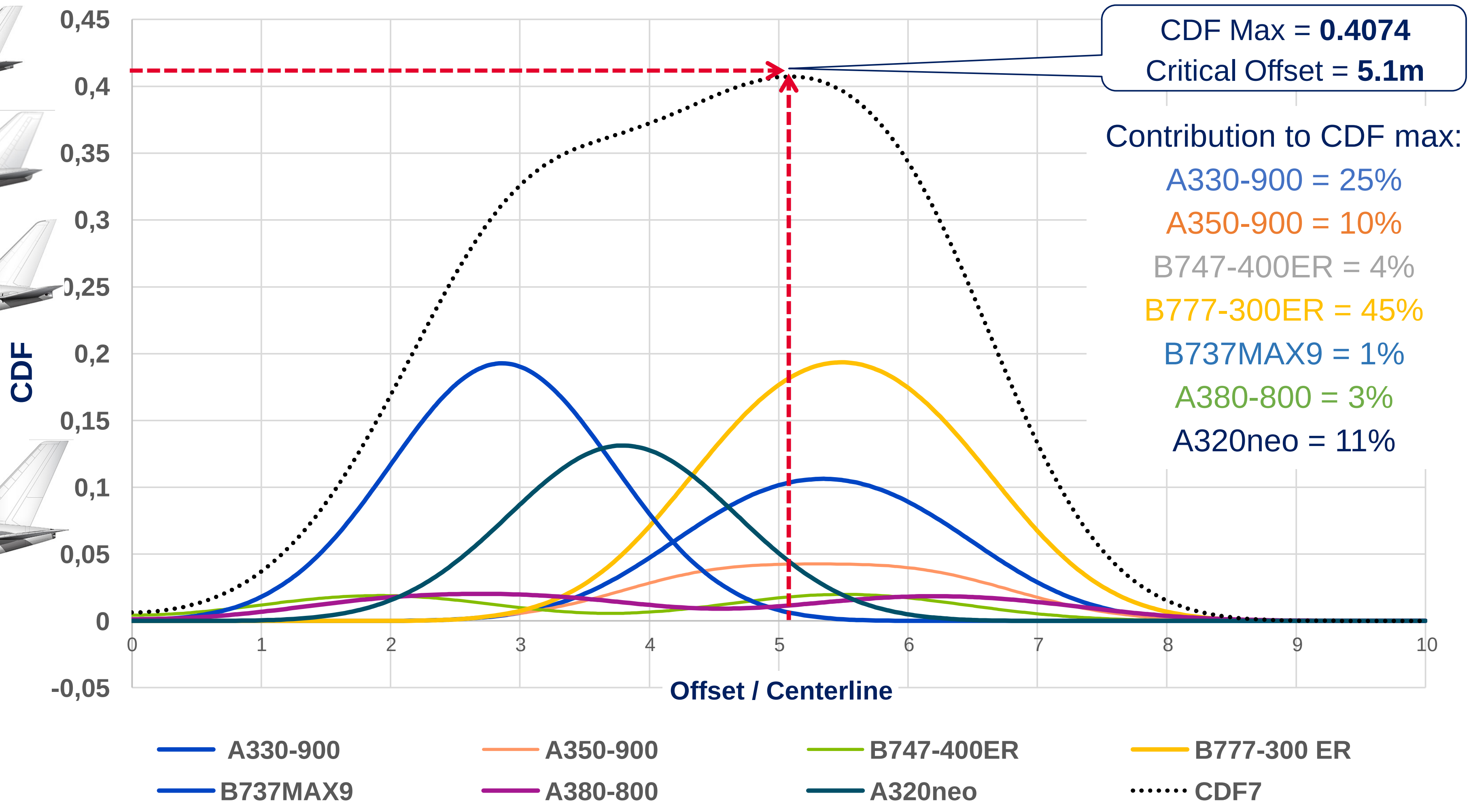


CDF Max = **0.3773**
Critical Offset = **5.45m**

Contribution to CDF max:
A330-900 = 18%
A350-900 = 13%
B747-400ER = 6%
B777-300ER = 57%
B737MAX9 = 1%
A380-800 = 5%



CDF / Critical Offset



CDF Max = **0.4074**
Critical Offset = **5.1m**

Contribution to CDF max:
A330-900 = 25%
A350-900 = 10%
B747-400ER = 4%
B777-300ER = 45%
B737MAX9 = 1%
A380-800 = 3%
A320neo = 11%


15 987 passes


8 764 passes


3 650 passes


20 922 passes

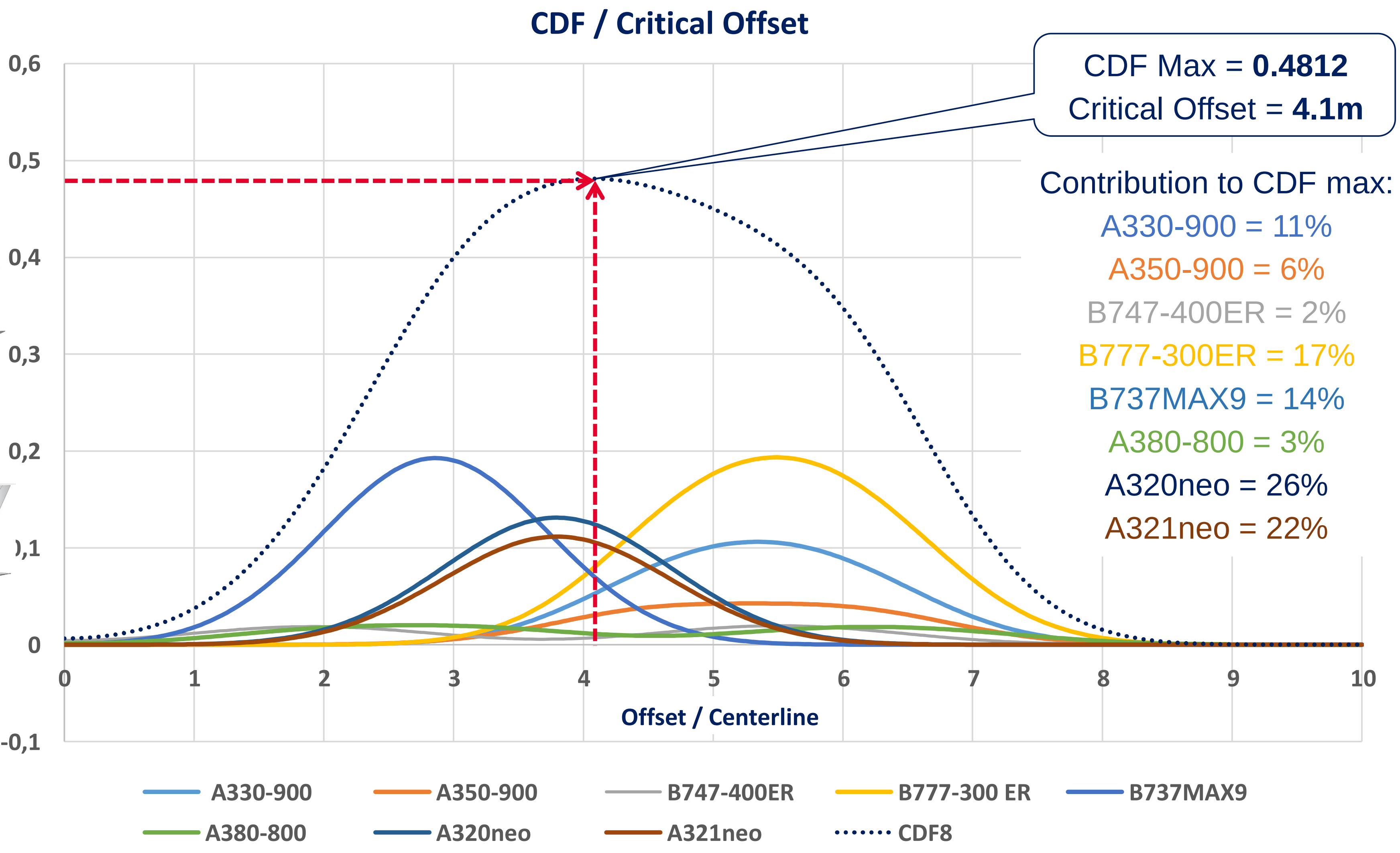

119 899 passes


3650 passes


159 866 passes

+


57 281 passes **A321neo**



CDF Max = **0.4812**
Critical Offset = **4.1m**

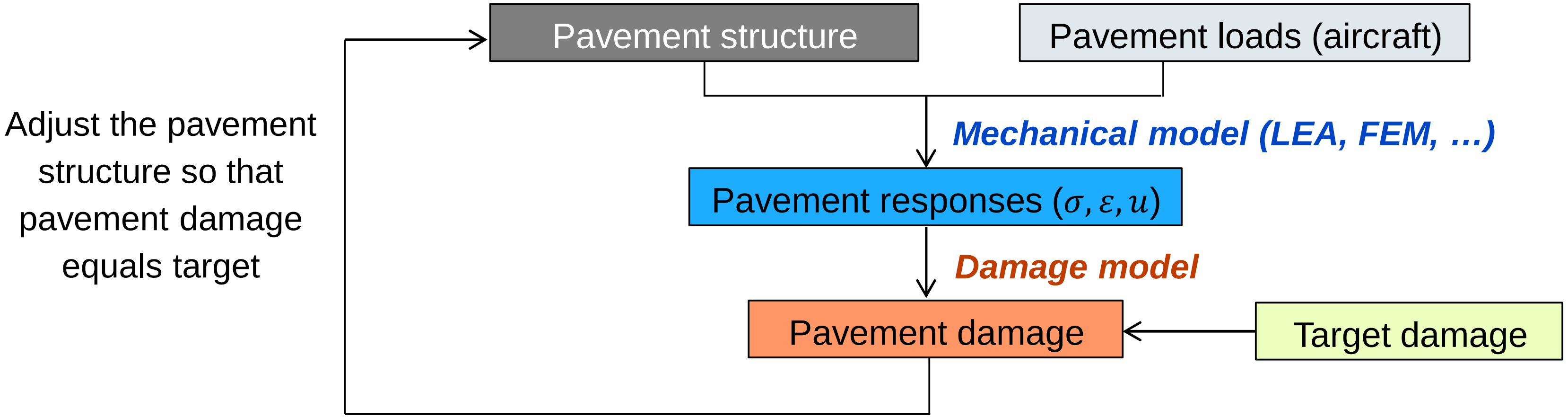
Contribution to CDF max:
A330-900 = 11%
A350-900 = 6%
B747-400ER = 2%
B777-300ER = 17%
B737MAX9 = 14%
A380-800 = 3%
A320neo = 26%
A321neo = 22%

CALCULATION & DAMAGE MODEL

Introduction to rational pavement design methods

General principle

- Rational pavement design procedures involve the following steps:
  - Determine the pavement mechanical responses, i.e. compute the displacements u, internal stresses σ and strains ε created by the aircraft surface loads
    ⇨ this relies on a **mechanical model** (e.g. Layered Elastic Analysis LEA, Finite Element Model FEM, …)
  - Determine the pavement damage induced by the aircraft surface loads
    ⇨ this relies on a **damage model** that relates pavement mechanical responses to pavement damage
  - Adjust the pavement structure until a target damage (conventionally D = 1) is reached



Introduction to rational pavement design methods

Mechanical model

- The **mechanical model** aims at modelling the physical responses of the pavement structure subject to aircraft loads
- Its choice is generally the result of a trade-off between modelling complexity (and computation time) and accuracy against the physical reality
- The most commons calculation models for pavement design can be grouped into 2 families

	Layered Elastic Analysis (LEA) – "Burmister model"	**Finite Element Model (FEM)**
Pavement modelling	- Layers extending infinitely horizontally - 3-dimensional	- Layers with boundaries, divided into elements - 2-dimensional or 3-dimensional
Material properties	- Linear elastic - Isotropic - Homogeneous	- Linear elastic, non-linear elastic, viscoelastic, plastic - May be anisotropic - May be heterogeneous
Type of loads	- Usually circular - Uniformly distributed - Static	- Circular, rectangular or other shape - May be non-uniform - May be dynamic
Advantages	- Simple - Short run times	- Flexibility and customization - Possibility to implement advanced local crack expansion modeling
Disadvantages	- Lack of flexibility and customization - No advanced local crack modeling available	- Complex to very complex, input data may be difficult to get depending on the problem modelling - Longer run times
Applicability	- Mostly flexible pavements	- Mostly rigid pavements

Introduction to rational pavement design methods

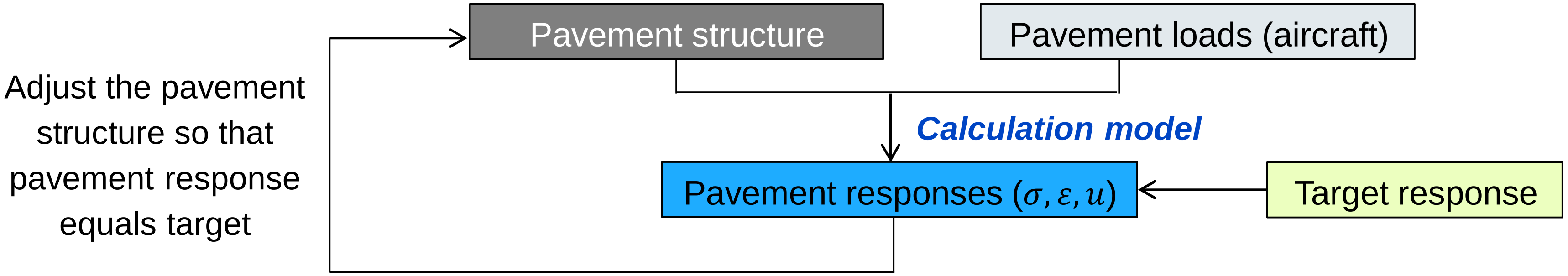
Damage model 1/2

- The **damage model** relates the pavement responses (stresses, strains, displacements) to pavement damage

- The most simple damage model consists in defining pavement damage as the ratio between the pavement response and the target (or maximum admissible) pavement response:

$$D = \frac{\text{Actual response}}{\text{Maximum admissible response}}$$

- Such approach is equivalent to designing the pavement structure directly for a target response



Introduction to rational pavement design methods

Damage model 2/2

- The damage models are usually more complex and involve several steps for transforming pavement responses into pavement damage

- There is no single, universal pavement damage model because of:
  - Different mechanical pavement behaviors (e.g. flexible vs. rigid pavements)
  - Different pavement materials around the world
  - Different modelling of pavement damage mechanisms (and research still underway)

- A damage model can be characterized by 4 key elements:

  1. The damage **criterion**
  2. The **elementary damage law** associated with the criterion
  3. The consideration of **multi-axle loads** (tandem wheels)
  4. The handling of **aircraft lateral wander**

Damage criterion

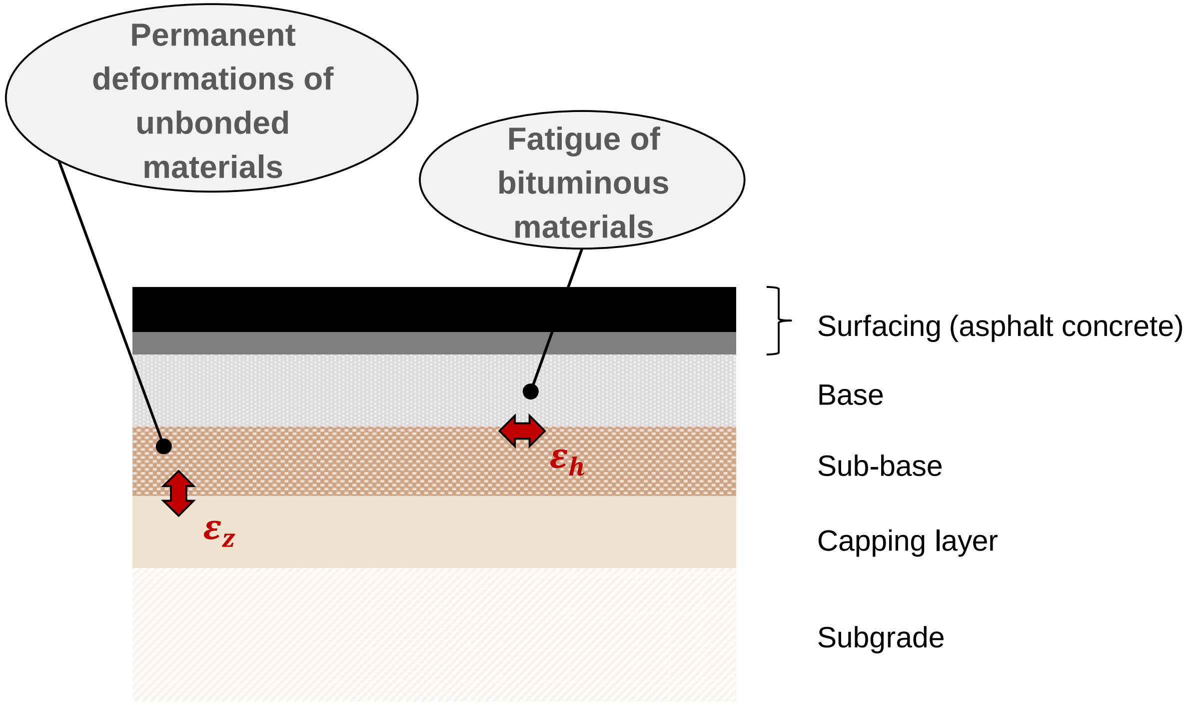
Flexible pavements

- The choice of the damage criterion depends on the **modes of damage** of the pavement structure

- For **flexible pavements** two types of damages are usually considered:

  - By fatigue, for bituminous materials (resulting in gradual bottom-up cracking of the material)
    ⇨ Damage is generally computed based on the values of horizontal strains ε_h at the base of the lower layer of bituminous materials

  - By permanent deformations for granular materials
    ⇨ Damage is generally computed based on the values of vertical strains ε_z at the top of the subgrade

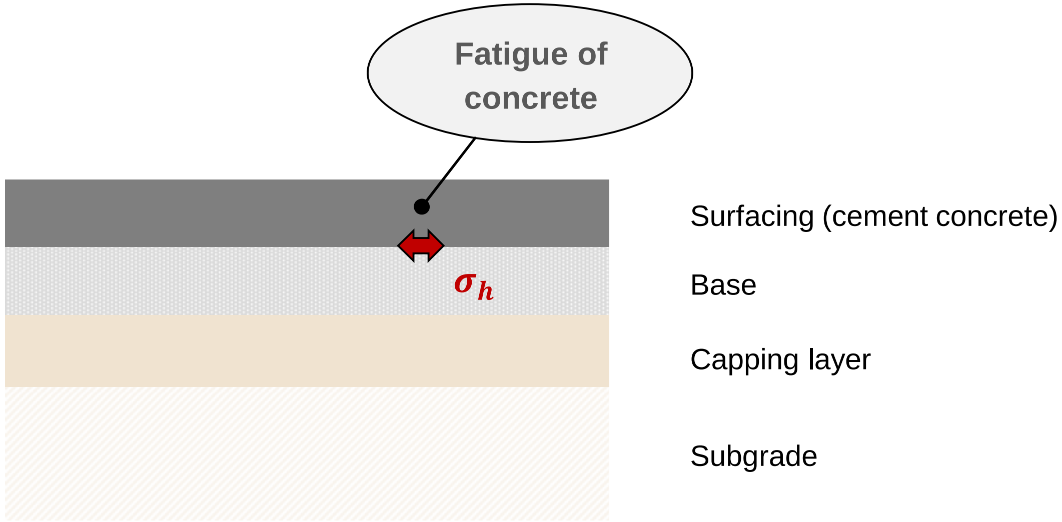


Damage criterion

Rigid pavements

- For **rigid pavements** the damage originates from fatigue of the concrete

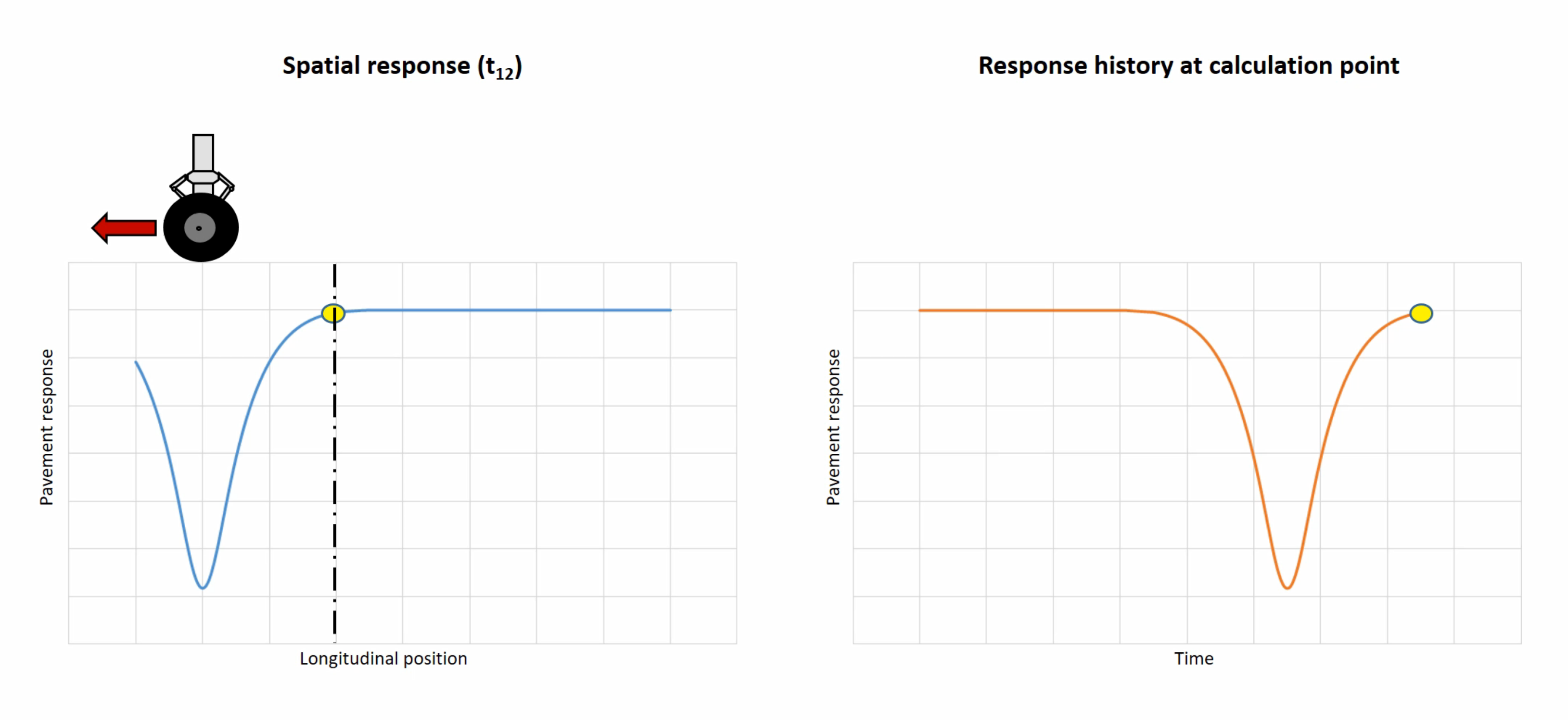
  ⇨ Damage is generally computed based on the values of horizontal tensile stresses σ_h at the base of cement concrete layer



Elementary damage law

Elementary response cycle

- An elementary pavement response cycle features a single response peak, starting from and returning to zero
- This is typically the kind of pavement response cycle that is seen by a given point in the pavement structure as a single-wheel load approaches, passes near the point, then moves away



Elementary damage law

Definition

- The elementary damage ΔD_{elem} is the (incremental) pavement damage produced by an elementary pavement response cycle
- This is also (by definition of pavement damage) the inverse of the number N of elementary cycles with peak response value s_{max} that results in pavement failure:

$$\Delta D_{elem} \stackrel{\text{def}}{=} \frac{1}{N(s_{max})}$$

- The elementary damage law (or failure model) is the function that relates s_{max} and ΔD_{elem}:

$$\Delta D_{elem} = f(s_{max})$$

- The type of response (stress or strain) considered in the elementary damage law depends on the chosen damage criterion

Elementary damage law

Examples 1/2

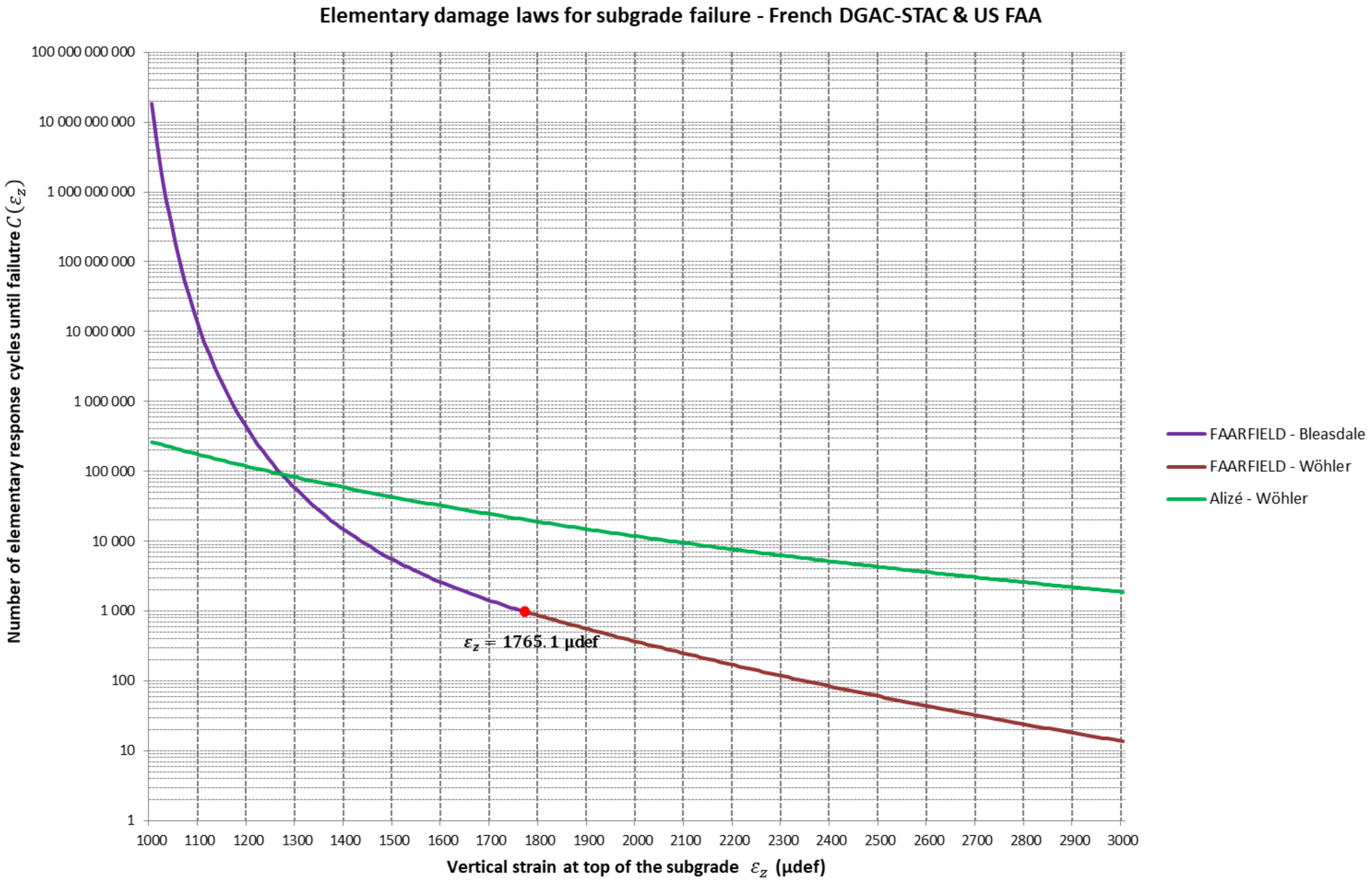
Model origin	Pavement type	Considered response s_{max}	Elementary damage law f	Parameters
French DGAC-STAC (Alizé-Lcpc)	Flexible	Horizontal strain at the base of bituminous materials ε_h	$\Delta D_{elem} = \left[\frac{\varepsilon_{h\,max}}{K}\right]^{\beta}$	• K depends on mechanical characteristics of the structure, temperature, and risk • $\beta = 5$
		Vertical strain at the top of the subgrade ε_z	$\Delta D_{elem} = \left[\frac{\varepsilon_{z\,max}}{K}\right]^{\beta}$	• $K = 16000$ • $\beta = 4.505$
US FAA (FAARFIELD)	Flexible	Horizontal strain at the base of bituminous materials ε_h	$\Delta D_{elem} = \left[\frac{\varepsilon_{h\,max}}{K}\right]^{\beta}$	• K depends on asphalt characteristics • $\beta = 4.630$
		Vertical strain at the top of the subgrade ε_z	$\Delta D_{elem} = 10^{-(a+b\varepsilon_{z\,max})^{-1/c}}$ ($\varepsilon_z \leq$ 1765 µdef)	• $a = -0.1638$ • $b = 185.19 \cdot 10^{-6}$ • $c = 1.6505$
			$\Delta D_{elem} = \left[\frac{\varepsilon_{z\,max}}{K}\right]^{\beta}$ ($\varepsilon_z \geq$ 1765 µdef)	• $K = 4141.31$ • $\beta = 8.1$
	Rigid	Horizontal stress at the base of the concrete σ_h	$\Delta D_{elem} = f(\sigma_h)$	• f is not analytical

- Elementary damage laws of the form $\Delta D_{elem} = \left[\frac{s_{max}}{K}\right]^{\beta}$ are known as “Wöhler” model

Elementary damage law

Examples 2/2

- For a same damage criterion, several elementary damage laws may exist, with significant differences
- Exemple with subgrade failure models from French DGAC-STAC & US FAA



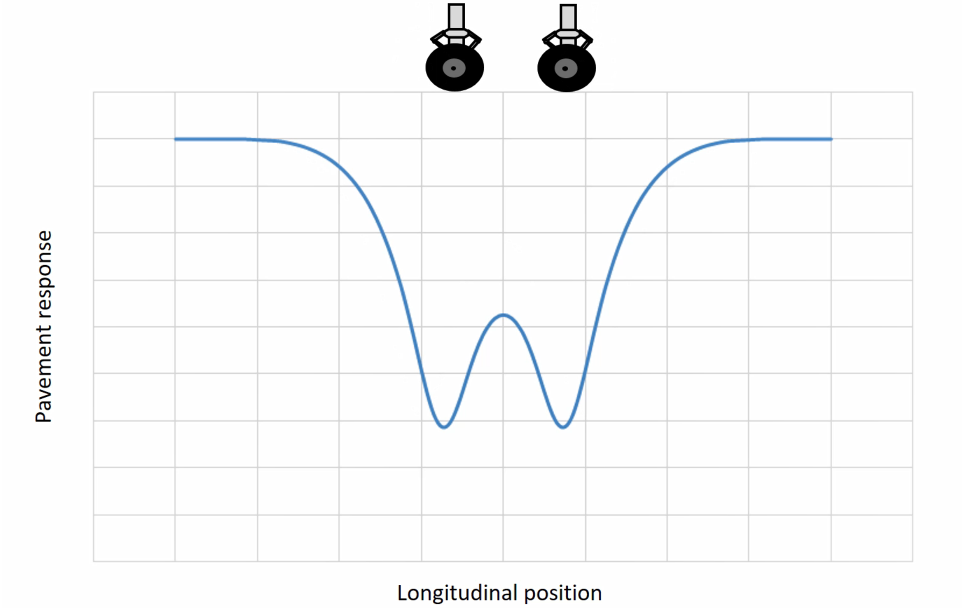
Consideration of multi-axle loads

Complex response cycle 1/3

- The elementary damage law are defined for elementary response cycles with a single peak and start/return to zero

- For landing gears with tandem wheels (bogies), the pavement response cycle is more complex and may feature multiple peaks, possibly with no return to zero between peaks

- The shape of the response profile depends on the mechanical characteristics of the pavement, the calculation depth within the structure, and the **axle distance**

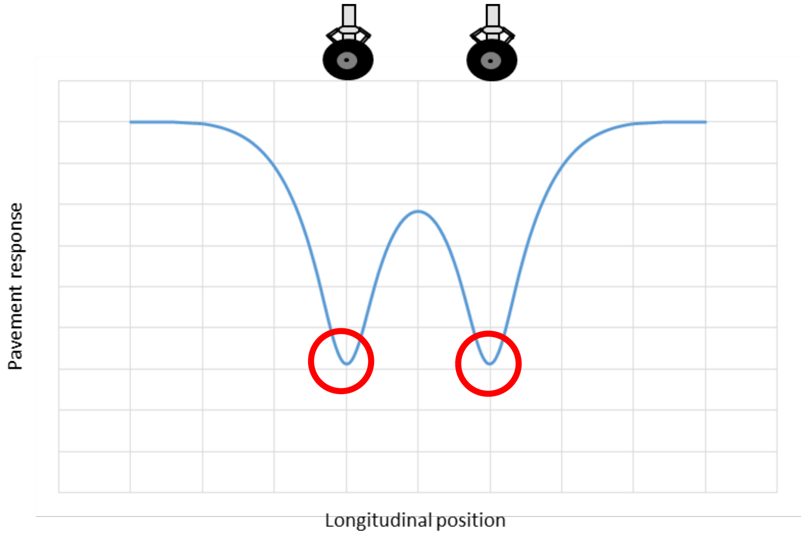


Consideration of multi-axle loads

Complex response cycle 2/3

- Let’s consider a sample complex response cycle
- This cycle features two peaks, hence it **produces more pavement damage** than an elementary cycle with the same peak value

Complex response cycle



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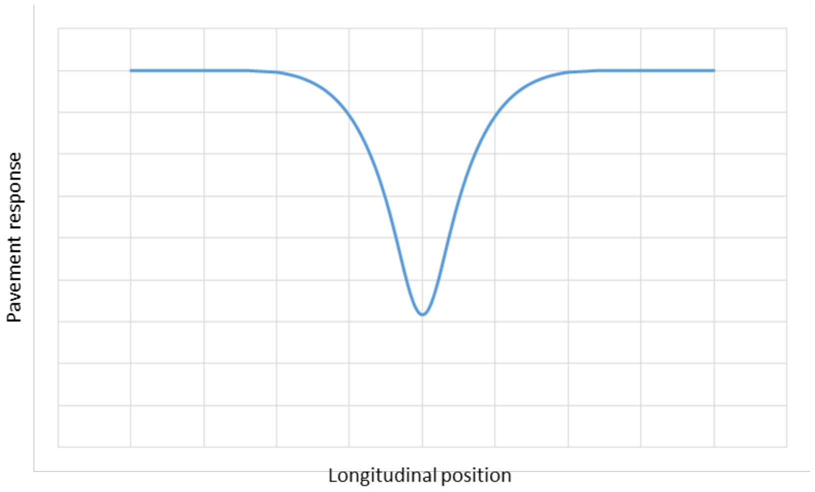
More damage

Elementary response cycle

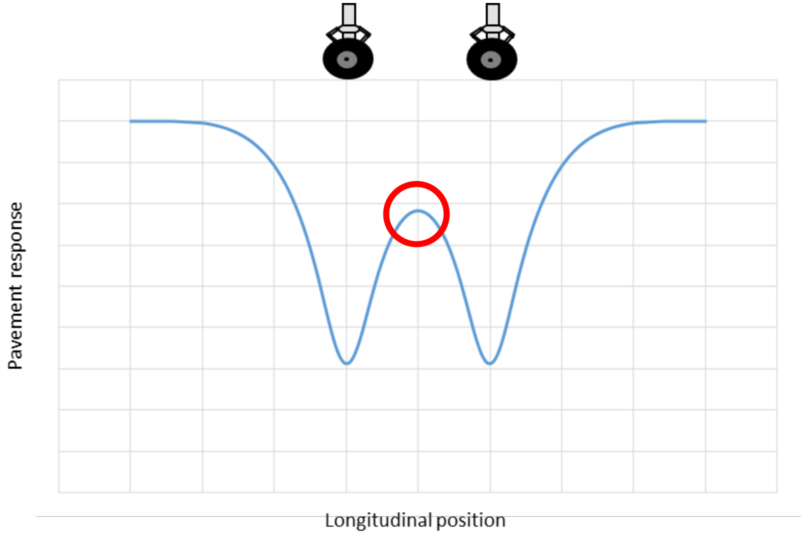


Consideration of multi-axle loads

Complex response cycle 3/3

- However there is no full unloading between the peaks (no return to zero), hence it **produces less pavement damage** than 2 elementary cycles with the same peak value

Complex response cycle



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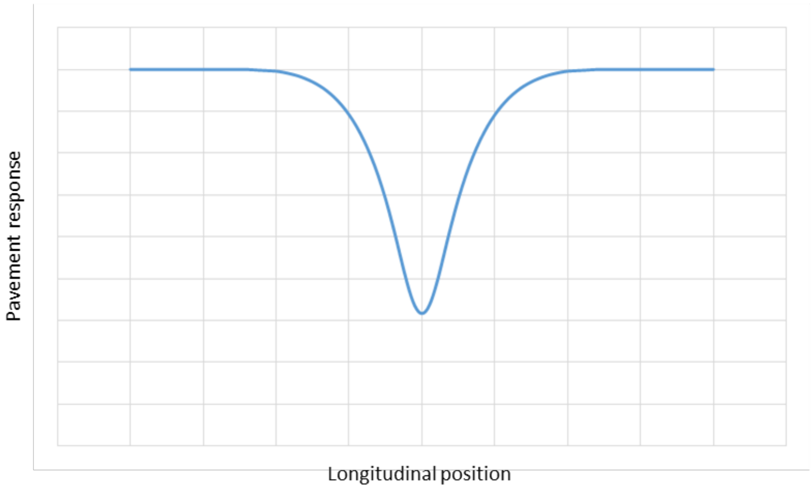
Less damage

2 x

Elementary response cycle



- The elementary damage law cannot be used as such for complex response cycles (multi-axle loads)
- There is a need to define a **procedure to compute the pavement damage for multi-axle loads**

Consideration of multi-axle loads

Tandem Factor 1/4

- One possible procedure to compute the pavement damage for multi-axle loads consists in the following steps:
  - Retain only the peak response s_{max} of the full complex cycle
  - Compute the elementary damage for the corresponding elementary response cycle $\Delta D_{elem} = f(s_{max})$
  - Apply a multiplication factor to get the damage corresponding to the complex cycle $\Delta D = \alpha\ \Delta D_{elem}$

- The multiplication factor is generally referred to as the **Tandem Factor** as it accounts for the effect of wheels in tandem

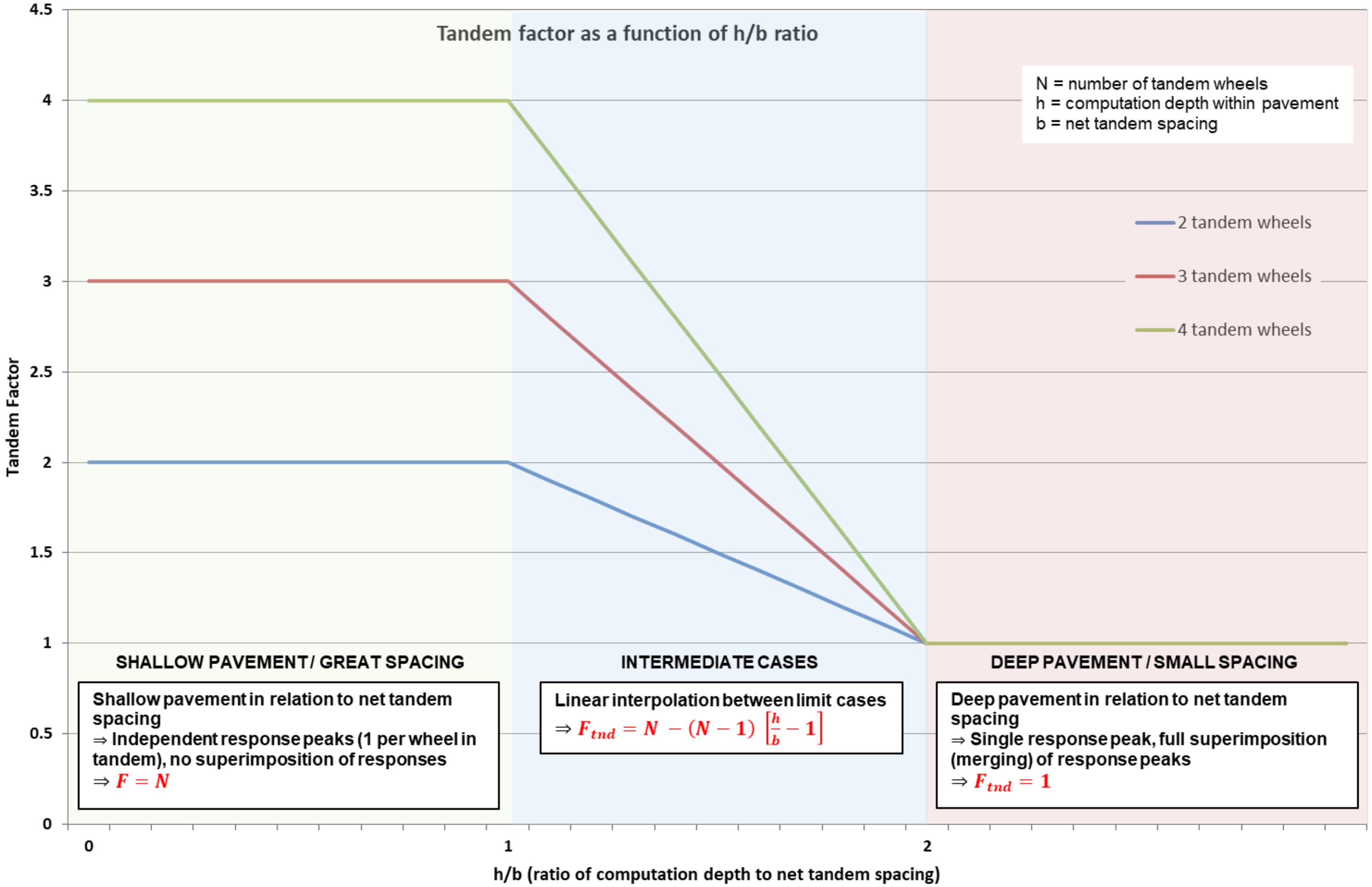
- This approach was the historical US FAA flexible pavement design procedure (the Tandem Factor being one of the two components of the Pass-to-Coverage ratio)

Consideration of multi-axle loads

Tandem Factor 2/4

- The Tandem Factor F_{tnd} is computed based on **geometrical parameters** only:
  - Net tandem spacing (i.e. tandem spacing minus length of tire contact patch) b
  - Computation depth within the pavement structure h

- The Tandem Factor procedure does not consider the full shape of the response cycle, but only the peak response value and geometrical parameters



N = number of tandem wheels
h = computation depth within pavement
b = net tandem spacing

Shallow pavement in relation to net tandem spacing
⇒ Independent response peaks (1 per wheel in tandem), no superimposition of responses
⇒ $F = N$

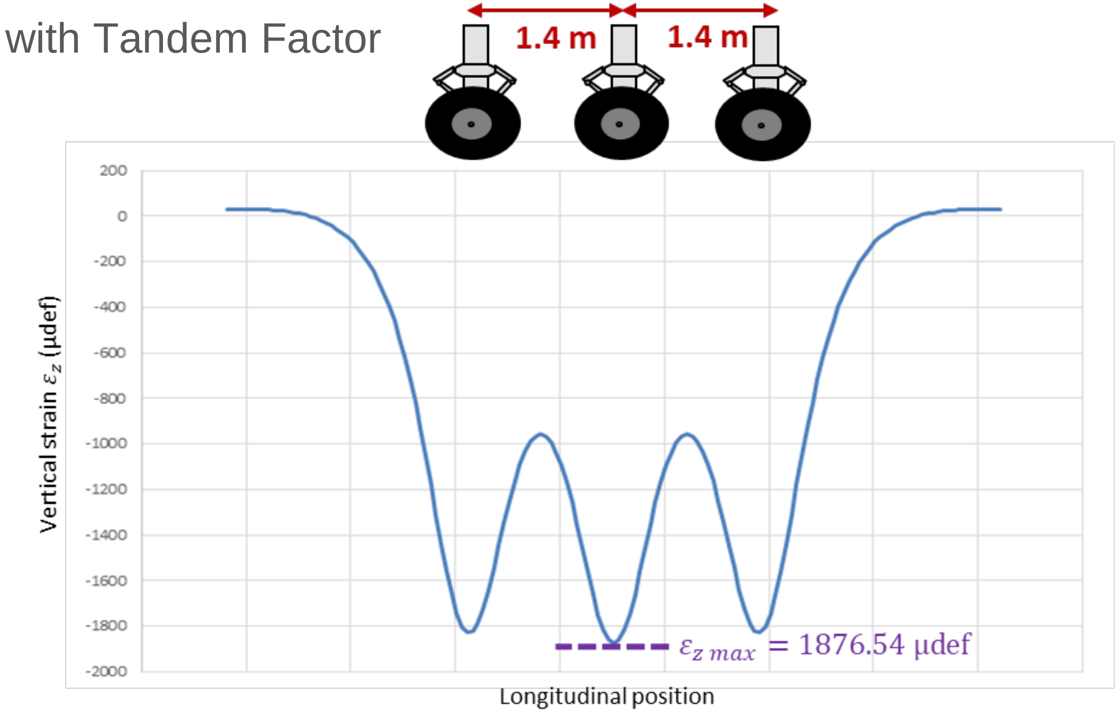
Linear interpolation between limit cases
⇒ $F_{tnd} = N - (N-1)\left[\frac{h}{b} - 1\right]$

Deep pavement in relation to net tandem spacing
⇒ Single response peak, full superimposition (merging) of response peaks
⇒ $F_{tnd} = 1$

Consideration of multi-axle loads

Tandem Factor 3/4

- Example 1: Calculation of pavement damage for multi-axle loads with Tandem Factor
- Data:
  - Vertical subgrade strain computed at $h = 45\ cm$
  - Aircraft: A350-1000
    - Tandem spacing = 140 cm
    - Tire contact length = 56.9 cm
    - Net tandem spacing $b = 140 - 56.9 = 83.1\ cm$
  - Elementary damage law: $\Delta D_{elem} = \left[\frac{\varepsilon_{z\,max}}{K}\right]^{\beta}$ $\quad K = 16000, \beta = 4.505$



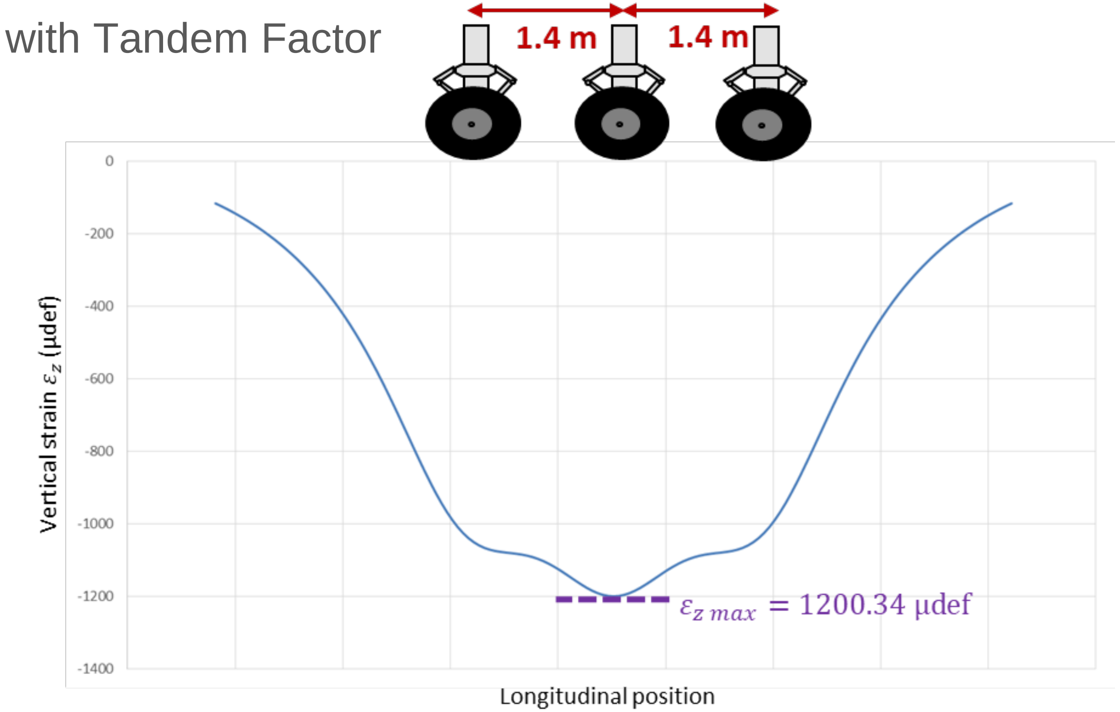
- Damage computation:
  - $\Delta D_{elem} = \left[\frac{1876.54}{16000}\right]^{4.505} = 6.42 \cdot 10^{-5}$
  - $h/b < 1 \Rightarrow F_{tnd} = 3$
  - $\boldsymbol{\Delta D = F_{tnd}\, \Delta D_{elem} = 19.26 \cdot 10^{-5}}$

- The damage is computed as three times the elementary damage, whereas there is no three full loading cycles (and the first and third peak are of lower extent)

Consideration of multi-axle loads

Tandem Factor 4/4

- Example 2: Calculation of pavement damage for multi-axle loads with Tandem Factor



- Data:
  - Vertical subgrade strain computed at $h = 100\ cm$
  - Aircraft: A350-1000
    - Tandem spacing = 140 cm
    - Tire contact length = 56.9 cm
    - Net tandem spacing $b = 140 - 56.9 = 83.1\ cm$
  - Elementary damage law: $\Delta D_{elem} = \left[\frac{\varepsilon_{z\,max}}{K}\right]^{\beta}$ $\quad K = 16000, \beta = 4.505$

- Damage computation:
  - $\Delta D_{elem} = \left[\frac{1200.34}{16000}\right]^{4.505} = 8.56 \cdot 10^{-6}$
  - $h/b = 1.20 \Rightarrow F_{tnd} = 3 - 2 * (1.20 - 1) = 2.6$
  - $\boldsymbol{\Delta D = F_{tnd}\, \Delta D_{elem} = 22.26 \cdot 10^{-6}}$

- The damage is computed as 2.6 times the elementary damage, whereas there is a single full loading cycle (elementary cycle)

Consideration of multi-axle loads

Integration of elementary damage 1/5

- Another approach consists in **integrating the elementary damage along the full complex response cycle**

- This is a **mechanistic approach** that considers the full response cycle, i.e. peak response values, and unloading between peaks

- This is the French DGAC-STAC procedure for flexible pavement design, now adopted as well in the US FAA flexible pavement design procedure

Consideration of multi-axle loads

Integration of elementary damage 2/5

- The integration of elementary damage along the full response cycle is written as:

$$\Delta D = \int_{-\infty}^{+\infty} \frac{dD_{elem}[s(x)]}{dx} \mathcal{H}\left[\frac{ds(x)}{dx}\right] dx = \int_{-\infty}^{+\infty} \frac{dD_{elem}(s)}{ds} \frac{ds(x)}{dx} \mathcal{H}\left[\frac{ds(x)}{dx}\right] dx$$

where:

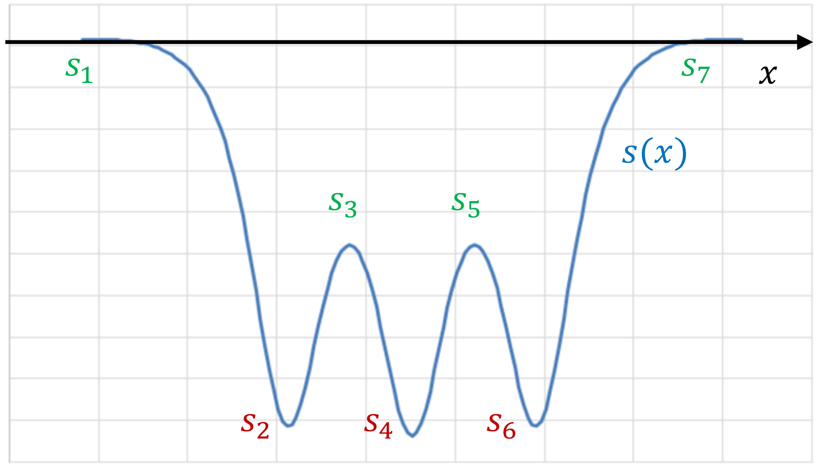
  - D_{elem} is the elementary damage law
  - s denotes the pavement response
  - x is the longitudinal location (or any other monotonous increasing parameterization of time)
  - $\mathcal{H}$is the Heaviside function, $\mathcal{H}(x) = 1$ for x > 0 , $\mathcal{H}(x) = 0$ else

- It can be demonstrated that this damage can also be expressed in function of the elementary damage at responses' maxima and minima:

$$\Delta D = \sum_{k=1}^{N} \delta_k D_{elem}(s_k) = + \sum_{i=1}^{N_{maximum}} D_{elem}(s_{\max i}) - \sum_{j=1}^{N_{minimum}} D_{elem}(s_{\min j})$$

where:

  - N is the number of response extremum
  - D_{elem} is the elementary damage law
  - s_k denotes the pavement kth response extremum
  - $\delta_k = 1$ if s_k is a maximum, $\delta_k = -1$ if s_k is a minimum



Consideration of multi-axle loads

Integration of elementary damage 3/5

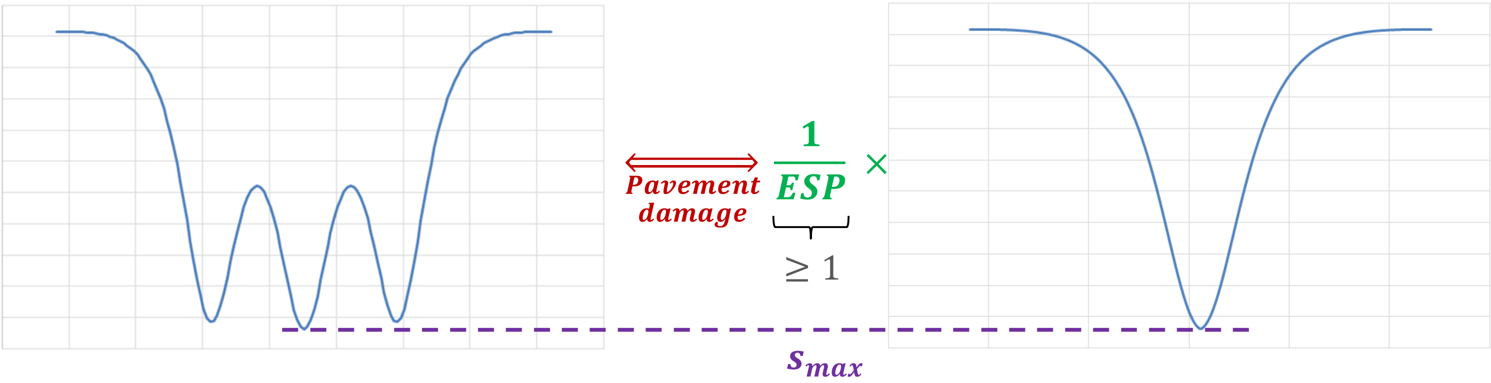
- If the response cycle features a single peak s_{max}, the integration procedure logically gives:

$$\Delta D = \mathrm{D_{elem}}(\mathrm{s_{max}}) = \Delta D_{elem}$$

- For any response cycle (with maximum value s_{max}), the **Equivalent Single Peak** (ESP) ratio is defined as the ratio of the pavement damage induced by an elementary cycle with maximum value s_{max} to the pavement damage induced by the full cycle:

$$ESP \stackrel{\text{def}}{=} \frac{D_{elem}(s_{max})}{\Delta D} \leq 1 \qquad \text{(1 for an elementary cycle)}$$

- 1/ESP represents the number of repetitions of the elementary cycle that are required to produce a pavement damage equivalent to the full cycle
- 1/ESP is therefore functionally equivalent to the Tandem Factor, but their computations are different



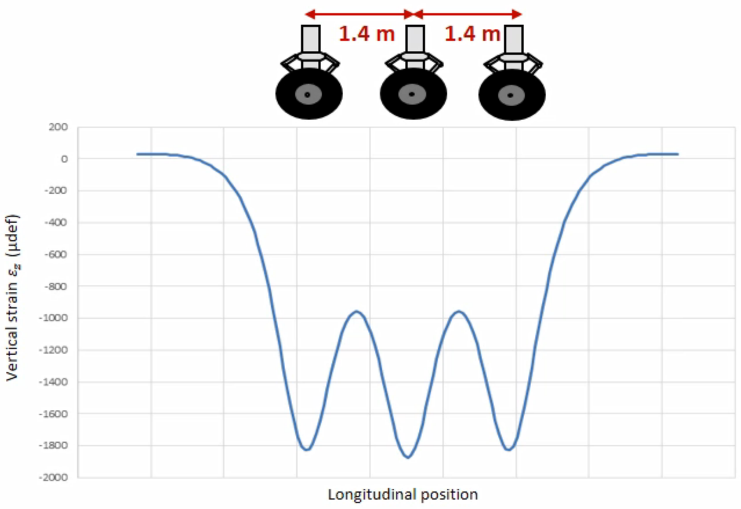
Consideration of multi-axle loads

Integration of elementary damage 4/5

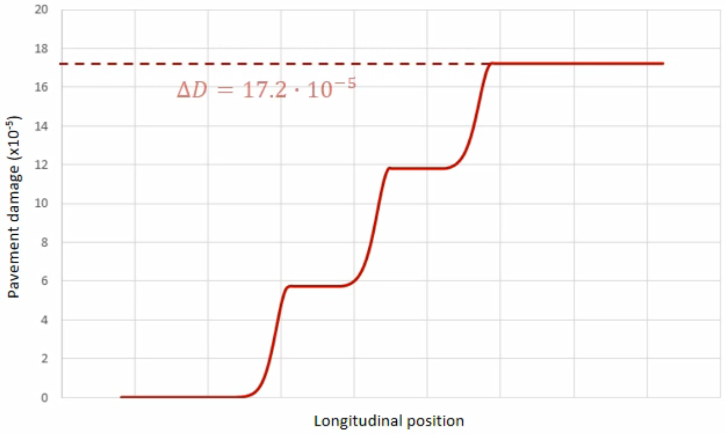
- Example 1: Calculation of pavement damage for multi-axle loads with integration of elementary damage
- Data:
  - Vertical subgrade strain computed at $h = 45\ cm$
  - Aircraft: A350-1000
  - Elementary damage law: $\Delta D_{elem} = \left[\frac{\varepsilon_{z\,max}}{K}\right]^{\beta}$ $\quad K = 16000, \beta = 4.505$
- Damage computation:
  - $\boldsymbol{\Delta D = 17.2\ \cdot 10^{-5}}$
- ESP computation:
  - $\Delta D_{elem} = \left[\frac{1876.54}{16000}\right]^{4.505} = 6.42\ \cdot 10^{-5}$
  - $1/ESP = 17.2/6.42 = 2.68$

Reminder: $F_{tnd} = 3$

- The damage is computed as less than three times the elementary damage, because of partial loading cycles



$$\Delta D = \int_{-\infty}^{+\infty} \frac{dD_e(\varepsilon_z)}{d\varepsilon_z} \frac{d\varepsilon_z(x)}{dx} H\left[\frac{d\varepsilon_z(x)}{dx}\right] dx$$



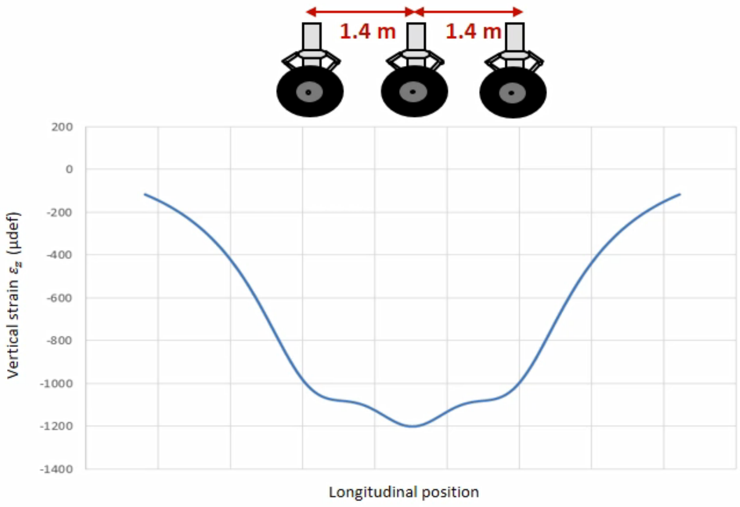
Consideration of multi-axle loads

Integration of elementary damage 5/5

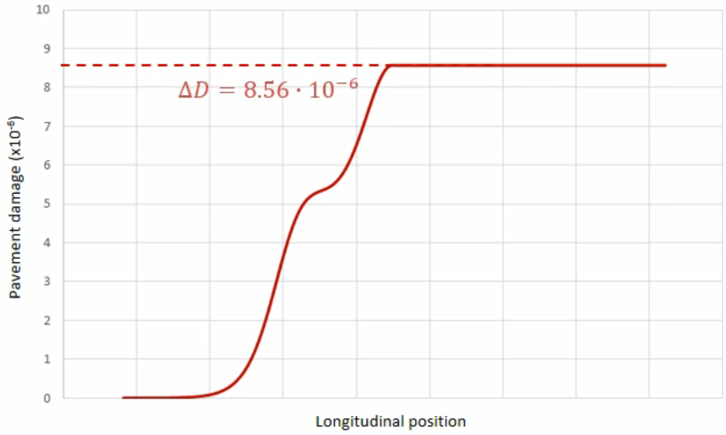
- Example 2: Calculation of pavement damage for multi-axle loads with integration of elementary damage
- Data:
  - Vertical subgrade strain computed at $h = 100\ cm$
  - Aircraft: A350-1000
  - Elementary damage law: $\Delta D_{elem} = \left[\frac{\varepsilon_{z\,max}}{K}\right]^{\beta}$ $\quad K = 16000, \beta = 4.505$
- Damage computation:
  - $\boldsymbol{\Delta D = 8.56\ \cdot 10^{-6}}$
- ESP computation:
  - $\Delta D_{elem} = \left[\frac{1200.34}{16000}\right]^{4.505} = 8.56\ \cdot 10^{-6}$
  - $1/ESP = 8.56/8.56 = 1$

Reminder: F_{tnd} = 2.6

- The damage is computed as the elementary damage, because the cycle features a single peak



$$\Downarrow \quad \Delta D = \int_{-\infty}^{+\infty} \frac{dD_e(\varepsilon_z)}{d\varepsilon_z} \frac{d\varepsilon_z(x)}{dx} H\left[\frac{d\varepsilon_z(x)}{dx}\right] dx$$



Handling of aircraft wander

Aircraft wander

- In real life, airplanes do not always travel along the theoretical path that is centered on the longitudinal axis of the pavement (pavement centerline), this phenomenon is known as **lateral wander**

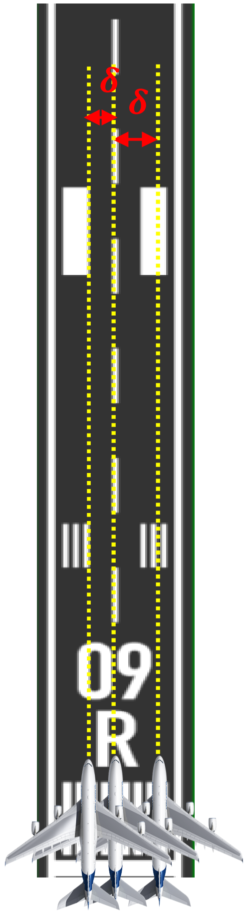
- Field surveys conducted in the past concluded that the distribution of theses misalignments throughout the pavement life can be adequately represented by a normal distribution centered on the pavement centerline, with a standard deviation σ_{wander}

- The value of σ_{wander} typically depends on the ground speed, therefore runways are generally associated with higher values than taxiways, while aprons are usually considered as zero-wander areas

- The presence of lateral wander reduces the pavement damage that would be caused if the traffic would be perfectly channelized:

$$\Delta D_{wander} \leq \Delta D_{no\ wander}$$

(equal if $\sigma_{wander} = 0$)



Handling of aircraft wander

Pass-to-Coverage ratio 1/4

- Historically, aircraft wander was considered through the use of a **Pass-to-Coverage** (P/C) ratio, representing the number of aircraft passes that are statistically required for a given point across the pavement width to receive a full load application (coverage)

- The procedure to compute the damage across the pavement width $\Delta D(y)$ is therefore as such:
  - Determine the maximum pavement damage without wander $\Delta \mathrm{D}_{max\ no\ wander}$
  - Compute P/C ratio as function of transverse location on the pavement $({}^{P}/_{C})(y)$
  - The pavement damage is calculated as $\Delta D(y) = ({}^{C}/_{P})(y) \cdot \Delta \mathrm{D}_{max\ no\ wander}$

- This approach is the one used by the US FAA flexible and rigid pavement design procedures

Handling of aircraft wander

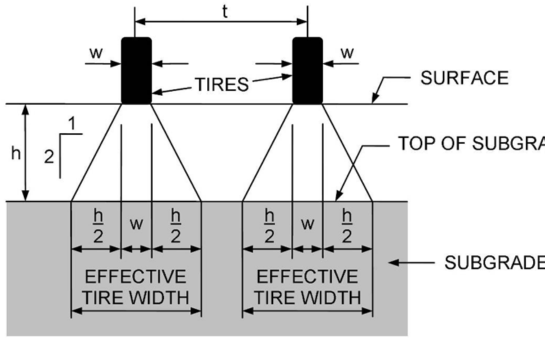
Pass-to-Coverage ratio 2/4

- Similarly to the Tandem Factor, the P/C ratio is computed based on **geometrical parameters** only:
  - Wheel track t
  - Width of tire contact patch w
  - Computation depth within the pavement structure h

- For the P/C computation, wheels in tandem are counted as one footprint moving along the pavement (i.e. wheels in tandem are ignored)

- The first step consists in projecting the landing gear footprint down to the computation depth and determining the corresponding effective tire footprint:

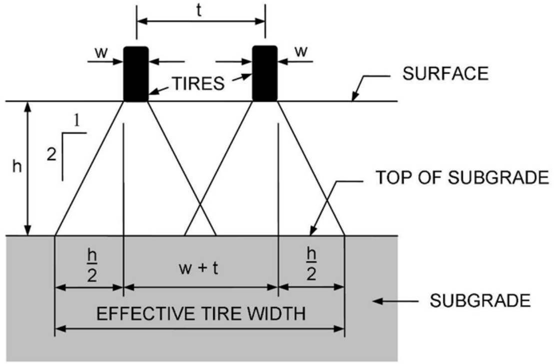
Computation depth	Number of effective tires n_{eff}	Effective tire width w_{eff}	Effective tire centers μ_{eff}
$h < t - w$	n_{tires}	$w + h$	Centers of each tire
$h \geq t - w$	1	$w + t + h$	Center of all tires



$h < t - w \Rightarrow$ No overlap

2 equivalent tires

$w_{eff} = w + h$



$h \geq t - w \Rightarrow$ Overlap

1 equivalent tire

$w_{eff} = w + t + h$

Handling of aircraft wander

Pass-to-Coverage ratio 3/4

- For a point at transverse location y the Coverage-per-Pass (C/P) is the probability that the point is covered by any of the effective tires:

$$\left({}^{C}/_{P}\right)(y) = \mathrm{Prob}(y \in \text{ one of the effective tires})$$

$$\left({}^{C}/_{P}\right)(y) = \sum_{i=1}^{n_{eff}} \mathrm{Prob}(y \in \text{ effective tire i})$$

- Assuming a normal model for the transverse location of the effective tires, this leads to:

$$\left({}^{C}/_{P}\right)(y) = \frac{1}{\sigma_{wander}\sqrt{2\pi}} \sum_{i=1}^{n_{eff}} \int_{y-\frac{w_{eff_i}}{2}}^{y+\frac{w_{eff_i}}{2}} \exp\left[-\frac{1}{2}\left(\frac{t-\mu_{eff_i}}{\sigma_{wander}}\right)^2\right] dt$$

- The Pass-to-Coverage (P/C) ratio is simply the inverse of the Coverage-per-Pass:

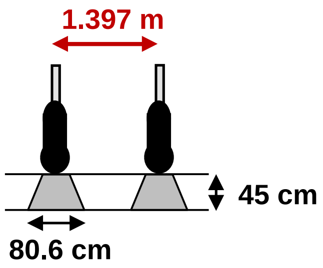
$$\left({}^{P}/_{C}\right)(y) = \frac{1}{({}^{C}/_{P})(y)}$$

Handling of aircraft wander

Pass-to-Coverage ratio 4/4

- Example: Calculation of transverse pavement damage with P/C ratio

- Data (same than previous example 1):
  - Vertical subgrade strain computed at $h = 45\ cm$
  - Aircraft: A350-1000
    - Wheel track t = 139.7 cm
    - Tire contact width w = 35.6 cm
    - $h < t - w \Rightarrow$ 2 effective tires, $w_{eff} = 35.6 + 45 = 80.6\ cm$



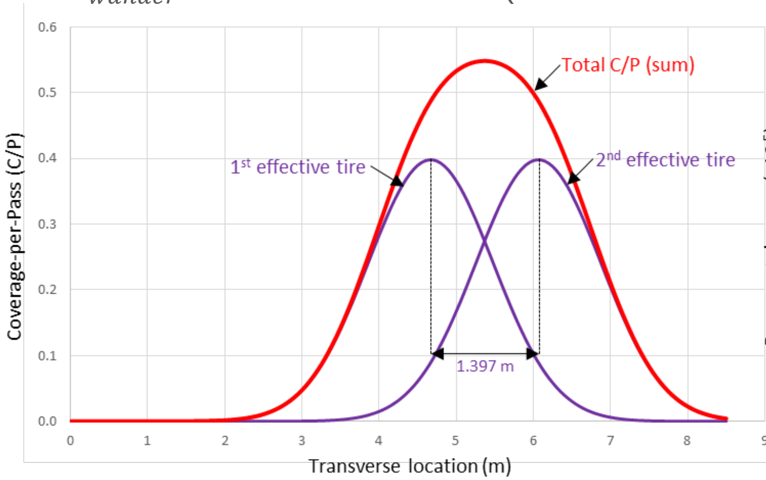
- From previous example 1 with integration of elementary damage we had:

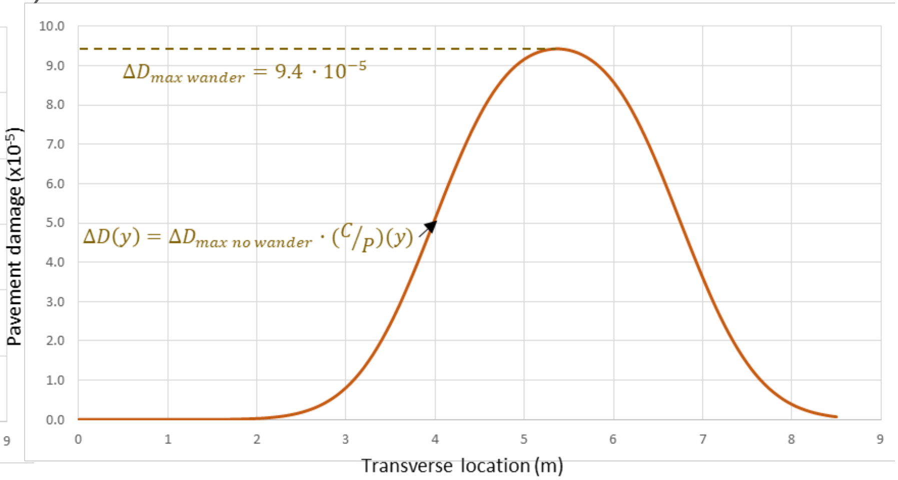
$$\Delta D_{max\ no\ wander} = 17.2 \cdot 10^{-5}$$

- Transverse damage computation:

$$\boldsymbol{\Delta D(y) = \left({}^{C}/_{P}\right)(y) \cdot \Delta D_{max\ no\ wander}}$$

$\sigma_{wander} = 30.435\ in = 77.3cm$ (standard FAA value)





Handling of aircraft wander

Probabilistic weighting of no-wander damage 1/4

- Another approach consists in the following steps:
  - Determine the full transverse damage profile without wander $\Delta D_{no\ wander}(y)$
  - Compute the probabilities of the different trajectories across the pavement width based on the chosen model (e.g. normal model)
  - Compute the pavement damage for each different trajectory, weighted by its probability of occurrence
  - Sum the damage for all the trajectories to get the total pavement damage $\Delta D(y)$

- This approach relies on **Miner's rule to perform a probabilistic-weighted sum of pavement damage without wander**

- This is a **mechanistic approach** that considers the full transverse damage profile without wander, while the P/C is applied to the maximum damage only

- This is the French DGAC-STAC procedure for flexible pavement design

Handling of aircraft wander

Probabilistic weighting of no-wander damage 3/4

- The total pavement damage with wander is therefore computed as:

$$\Delta D(y) = \int_{c=-\infty}^{c=+\infty} \underbrace{\Delta D_{no\ wander}(y-c)}_{\substack{\text{Damage at location } y \\ \text{when aircraft is centered on } c}} \; \underbrace{\frac{1}{\sigma_{wander}\sqrt{2\pi}} \exp\left[-\frac{c^2}{2{\sigma_{wander}}^2}\right] dc}_{\text{Probability that aircraft is centered on } c}$$

- The aircraft trajectories may also be discretized in $(c_k)_{k=1..n}$ trajectories separated by Δc:

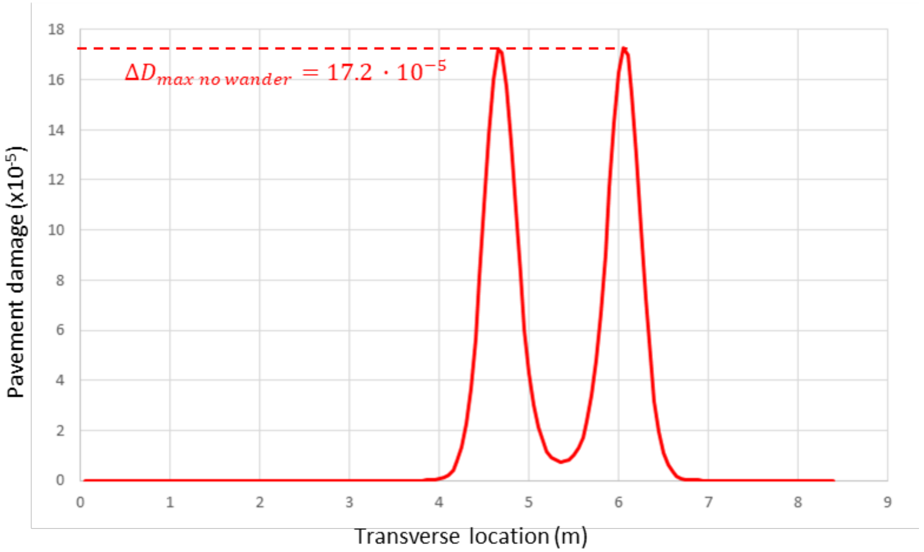
$$\Delta D(y) \cong \sum_{k=1}^{n} \Delta D_{no\ wander}(y-c_k) \; \underbrace{\text{Prob(aircraft centered on } c_k)}$$

$$= \frac{1}{\sigma_{wander}\sqrt{2\pi}} \int_{c_k-\frac{\Delta c}{2}}^{c_k+\frac{\Delta c}{2}} \exp\left[-\frac{c^2}{2{\sigma_{wander}}^2}\right]$$

Handling of aircraft wander

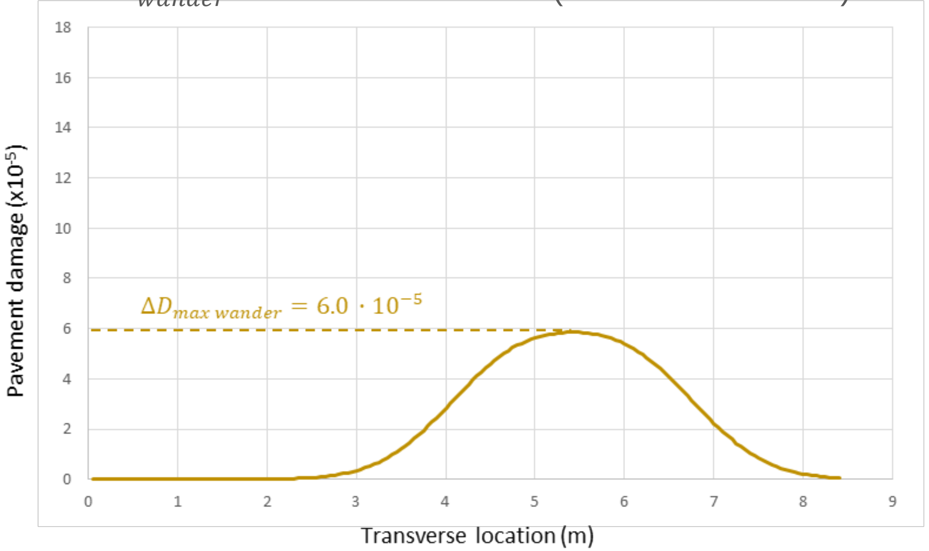
Probabilistic weighting of no-wander damage 4/4

- Example: Calculation of transverse pavement damage with probabilistic weighting of no-wander damage
- Data (same than previous example 1):
  - Vertical subgrade strain computed at $h = 45\ cm$
  - Aircraft: A350-1000
- A full transverse damage profile without wander is computed, then the probabilistic weighting procedure is applied to compute the full damage profile with wander



Probabilistic weighting

$\sigma_{wander} = 30.435\ in = 77.3cm$ (standard FAA value)



Summary

- There is no single, universal pavement damage model

- A damage model can be characterized by 4 key elements:
  1. The damage **criterion**
  2. The **elementary damage law** associated with the criterion
  3. The consideration of **multi-axle loads** (tandem wheels)
  4. The handling of **aircraft lateral wander**

- The parameterization of the damage model may have an impact on the number and locations of the response calculation points

Examples of PCR technical evaluation

Example 1 – Flexible pavement – Well-designed (CDF ~ 1.0)

- A (new) flexible runway is designed according to the French rational design method.
- The subgrade modulus is estimated as: $E = 80\ MPa$ ⇨ subgrade category C
- The surface layer is made of asphalt concrete able to withstand the highest tire pressures ⇨ tire pressure category W

- The damage model for the PCR evaluation is the same than used for pavement design (French DGAC-STAC damage model)

EB-BBA2 **Wearing course**	$E = 5500\ MPa$	$\nu = 0.35$	$t = 6\ cm$
EB-GB3 **Base course**	$E = 14000\ MPa$	$\nu = 0.35$	$t = 13\ cm$
GNT1 **Sub-base**	$E = 450\ MPa$	$\nu = 0.35$	$t = 25\ cm$
Subgrade	$E = 80\ MPa$	$\nu = 0.35$	$t = \infty$

Examples of PCR technical evaluation

Example 1 – Flexible pavement – Well-designed (CDF ~ 1.0)

- Traffic forecasted over the 10-year pavement life

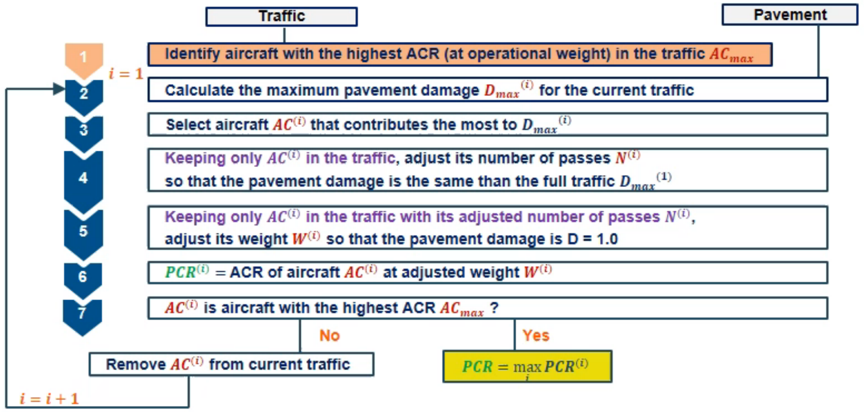
Aircraft	Operating weight (t)	Passes
A319neo	75.9	258 542
A320neo	79.4	232 094
A321neo	97.4	210 424
A330-200	233.9	51 405
A330-300	233.9	19 396
A350-900	268.9	8 971
A380-800	571.0	29 123

Aircraft	Operating weight (t)	Passes
737-800	79.2	98 433
757-200	116.1	4 352
767-300	163.8	17 094
767-400ER	204.6	3 415
787-8	228.4	10 885
787-9	254.7	16 045
777-200	248.1	40 378
777-300ER	352.4	37 842

- Aircraft wander is considered as per the French rational design method for flexible runways (Gaussian distribution, σ = 75 cm = 29.53 in)

Examples of PCR technical evaluation

Example 1 – Flexible pavement – Well-designed (CDF ~ 1.0)



Traffic

Pavement

1 Identify aircraft with the highest ACR (at operational weight) in the traffic AC_{max}

$i = 1$

2 Calculate the maximum pavement damage $D_{max}{}^{(i)}$ for the current traffic

3 Select aircraft $AC^{(i)}$ that contributes the most to $D_{max}{}^{(i)}$

4 Keeping only $AC^{(i)}$ in the traffic, adjust its number of passes $N^{(i)}$ so that the pavement damage is the same than the full traffic $D_{max}{}^{(1)}$

5 Keeping only $AC^{(i)}$ in the traffic with its adjusted number of passes $N^{(i)}$, adjust its weight $W^{(i)}$ so that the pavement damage is D = 1.0

6 $PCR^{(i)}$ = ACR of aircraft $AC^{(i)}$ at adjusted weight $W^{(i)}$

7 $AC^{(i)}$ is aircraft with the highest ACR AC_{max} ?

No

Remove $AC^{(i)}$ from current traffic

$i = i + 1$

Yes

$PCR = \max_i PCR^{(i)}$

Examples of PCR technical evaluation

Example 1 – Flexible pavement – Well-designed (CDF ~ 1.0)

- The PCR should be reported as **800 F/C/W/T**

⚠

- The PCR would have been reported as 590 /F/C/W/T based on the A321neo if only the most contributing aircraft is considered
- This would have lead to weight restrictions for most of the long-range aircraft, despite the pavement being properly designed for the entire traffic

Examples of PCR technical evaluation

Example 2 – Flexible pavement – Under-designed (CDF > 1.0)

- An existing flexible taxiway had been designed according to the US FAA design procedure.
- The subgrade modulus is estimated as: $E = 59\ MPa$ ⇨ subgrade category D
- There is no evidence of pavement distress attributable to excessive tire pressure ⇨ tire pressure category W

- The damage model for the PCR evaluation is the same than used for pavement design (FAA damage model for flexible pavements)

P401 HMA Wearing course	$E = 1378\ MPa$	$\nu = 0.35$	$t = 12.7\ cm\ (5\ in)$
P403 HMA Base course	$E = 2757\ MPa$	$\nu = 0.35$	$t = 13.97\ cm\ (5.5\ in)$
P209 Crushed agg. Sub-base	$E = 358.3\ MPa$	$\nu = 0.35$	$t = 17.78\ cm\ (7\ in)$
P209 Crushed agg. Sub-base	$E = 233.5\ MPa$	$\nu = 0.35$	$t = 25.4\ cm\ (10\ in)$
Subgrade	$E = 59\ MPa$	$\nu = 0.35$	$t = \infty$

Examples of PCR technical evaluation

Example 2 – Flexible pavement – Under-designed (CDF > 1.0)

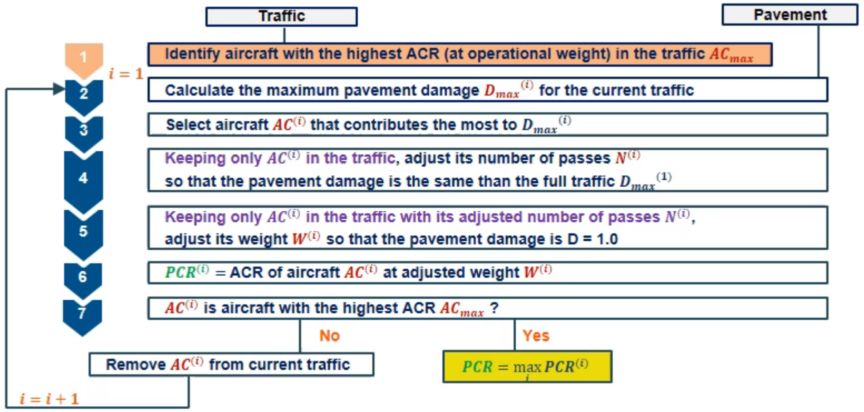
- Traffic forecasted over the expected remaining pavement life

Aircraft	Operating weight (t)	Passes
ATR 42	18.8	172 042
ATR 72	22.7	151 032
E195	49.0	132 042
A319neo	75.9	32 043
A320neo	79.4	35 674
737-700	70.3	40 059
737-800	79.2	30 784
737-900ER	85.4	20 842

- Aircraft wander is considered as per the FAA Pass-to-Coverage method (Gaussian distribution, σ = 30.54 in = 77.57 cm)

Examples of PCR technical evaluation

Example 2 – Flexible pavement – Under-designed (CDF > 1.0)



Examples of PCR technical evaluation

Example 2 – Flexible pavement – Under-designed (CDF > 1.0)

- The PCR should be reported as **550 F/D/W/T**

- The ACR of the 737-900ER (563 F/D) exceeds the PCR and would therefore be weight-limited (consistently with the pavement being under-designed for the traffic, CDF > 1.0)

⚠

- The PCR would be computed as 620 F/D/W/T if the French damage model is used
- The PCR would therefore be overestimated and no limitation would apply to the aircraft within the traffic, leading to reduced pavement life vs. expectations
- This highlights the importance of the **damage model selection for PCR calculation**

Consequences of PCR inaccuracies

Over-estimated PCR (underestimated CDF)

➔ More traffic acceptance (weight/volume) than what the pavement is able to withstand over its design life

➔ Premature pavement damage, increase of maintenance / repairs **COSTS**

Under-estimated PCR (overestimated CDF):

➔ Aircraft weight / annual departure restriction or operations not granted,

➔ Pavement usage not optimized, **Loss of airport revenues**,

Accurate PCR = A virtuous circle

Optimized PCR (CDF consistent with the initial pavement design parameters)

- ✓ **Maximize the use of pavement, reduced maintenance needs and cost, increase airport revenues through airport charges (Landing charges, parking charges etc.)**

- ✓ **All of that contributes to GHG* emissions reduction through a well mastered pavement life cycle (from raw material to end-life…)**

- ✓ **ACR-PCR is a powerful tool allowing end users to better manage aircraft allowable weights while preserving airport pavement assets**

Overload operations

- Overloading of pavements can result from:
  - Loads larger than the design or evaluation load
  - A substantially increased application rate

- With the exception of massive overloading, pavements in their structural behavior are not subject to a particular limiting load above which they suddenly fail

- ICAO provides general pavement overload evaluation guidance for minor overloading, sometimes referred to as “ICAO allowance”

- Larger overloads may be assessed thanks to a detailed technical analysis, consistent with the PCR technical evaluation philosophy

- Specific state practices for overload operations may be developed (as for the ACN-PCN method)

Overload operations

ICAO allowance

- 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:
  - For flexible and rigid pavements, occasional movements by aircraft with ACR not exceeding **10 per cent above the reported PCR** should not adversely affect the pavement
  - The annual number of overload movements should not exceed approximately **5 per cent of the total annual movements excluding light aircraft**.

Note: ICAO allowance was previously 10 % of PCN for flexible pavements and 5 % of PCN for rigid pavements.

- Overloads should not be permitted:
  - On pavements exhibiting signs of distress
  - During periods of thaw following frost penetration
  - When the strength of the pavement (or subgrade) could be weakened by water

- The pavement condition should be regularly monitored when overload operations are conducted
- Excessive overloads may significantly reduce the pavement life

Overload operations

Technical analysis

- Overloads in excess of 10% can be considered on a case by case basis if supported by a technical analysis

- The ACR, even if exceeding the reported PCR, cannot predict accurately how the overload will affect the pavement damage (hence pavement life) since it is strongly dependant on its offset to the location of the maximum pavement damage

- The technical analysis should therefore determine how the overload operations **contribute to the maximum pavement damage** (maximum CDF) when mixed with the other traffic

- The inputs required to perform such analysis are the same than for the PCR technical evaluation:
  - Pavement structure
  - Aircraft traffic (including overload operations)
  - Damage model (consistent with the PCR calculation and pavement design)

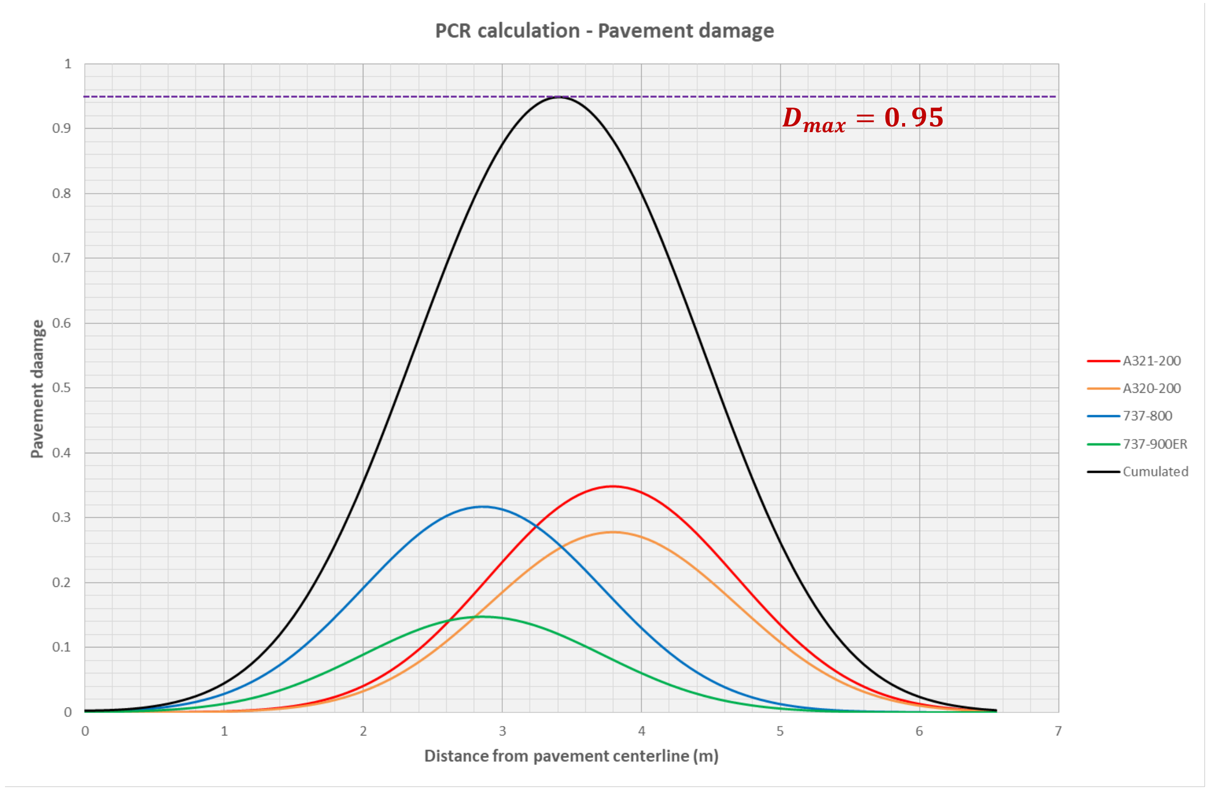
- The decision to allow overload operations falls to the airport operator, depending on the impact of such operations on pavement life and its pavement management policy
- A cost-benefit analysis (loss of pavement life vs. additional revenues) can support such decision-making

Overload operations

Example

- A flexible pavement runway has been designed (using the French rational design method) to accommodate a pure single-aisle/medium-range aircraft traffic (~ 25 daily departures over 10 years)

Aircraft	Operating weight (t)	Passes	ACR @ operating weight
A320-200	77.4	34 500	450 F/C
A321-200	93.9	17 000	550 F/C
737-800	79.2	30 000	420 F/C
737-900ER	85.4	14 500	440 F/C



- The designed pavement structure has a maximum CDF = 0.95
- The PCR is calculated and published as **PCR 560 F/C/W/T**

Overload operations

Example

- A new airline is willing to operate one daily departure to a long-haul destination with a fully loaded A321neo LR

- The ACR of the A321neo LR at Maximum Ramp Weight (97.4 t) is **580 F/C** and therefore exceeds the PCR (560 F/C)

- The ACR exceeds the PCR by less than 10 %

And

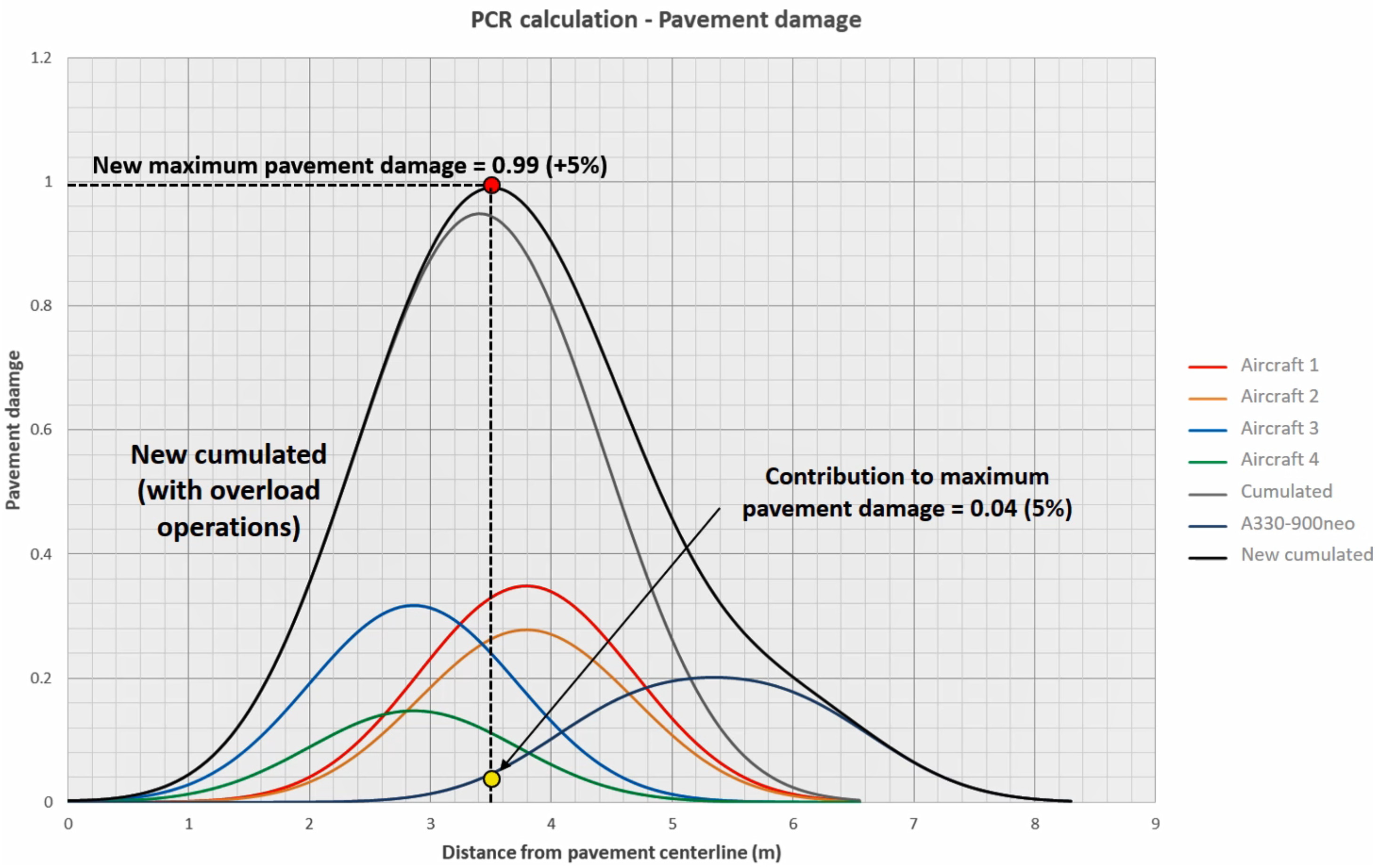
- The number of overload movements (1/day) would not exceed 5 % of the total movements (25/day)

⇨ Overload operations can be granted as per the “ICAO allowance”

Overload operations

Example

- The airline now contemplates the introduction of one daily departure of A330-900neo



- The ACR of the A330-900neo at Maximum Ramp Weight (251.9 t) is **710 F/C** and therefore exceeds the PCR (560 F/C) by more than 25 %

- The technical analysis shows that the actual impact is limited to an increase of pavement damage by 5 %

⇨ **Based on its cost-benefit analysis, the airport may allow these overload operations**

- If overload operations are allowed, the pavement condition should be regularly be inspected

PCR update

- The validity of the PCR depends on the validity of the input data (traffic, pavement life). Because input data will change over time, a PCR should never be determined once and for all, **any significant change in the input data should trigger a PCR update**

- The PCR **should be re-evaluated if the traffic changes significantly**. Significant changes in traffic may result from:
  - Introduction (or removal) of a new aircraft type
  - Increase (or decrease) in traffic levels not accounted for in the original PCR analysis

- The PCR **should be re-evaluated** if the expected design (or remaining) life changes (e.g. if the airport operator is inclined to rehabilitate the pavement earlier than initially planed in order to develop its traffic)

- Failing to update the PCR may result in an inadequate use of the ACR/PCR method, and ultimately in an non-optimal use of the pavement infrastructure

DEMO

QUESTIONS ?