EFFECTS OF AIRCRAFT TIRE PRESSURES ON FLEXIBLE PAVEMENTS

M.J. ROGINSKI
Boeing Company Seattle, WA

ABSTRACT

The ICAO ACN/PCN system for rating airport pavements has been in existence since 1981. The four tire pressure categories assigned to the PCN rating, which may have been representative of the aircraft existing at its inception, are no longer representative of the current fleet of large wide bodied aircraft operating with higher wheel loads and higher tire pressures. The four code letters Z, Y, X and W, correspond to the four tire pressure limits of 0.5 MPa, 1.0 MPa, 1.5 MPa and unlimited respectively. Due to the fact that ICAO does not make formal recommendations regarding how an airport should assign these tire pressure limits, the Boeing Company decided to perform a series of tire pressure tests at the FAA William J. Hughes Technical Center, National Airfield Pavement Test Facility in New Jersey, USA, in an attempt to arrive at tire pressure limits more consistent with today's aircraft and based on actual flexible pavement behavior under high tire pressures.

The tests consisted of three sections of varying asphalt surface thicknesses trafficked by a single wheel load device in order to contain pavement damage to tire pressure effects only. The test loading began at 18,144 kg (40,000 lb) and continued up to 24,947 kg (55,000 lb), with the tire pressure increasing 0.14 MPa (20 psi) every 500 passes. A pavement was declared failed when rutting had reached a medium severity level of 13-19 mm (0.50-0.75 inches) or severely cracked such that the PCI level was 55 or below. The conclusion was reached that high tire pressures up to 1.65 MPa (240 psi) have no adverse effects on flexible pavements with asphalt and base material quality meeting the recommended minimum standards set forth by various agencies. Our recommendation for revised ICAO tire pressure categories, to be used in the PCN rating system, are also presented.

1 INTRODUCTION

The current ACN/PCN procedure specified in the ICAO Annex 14, Aerodromes manual, has four maximum allowable tire pressure categories which are used in the reporting of pavement strength for an airport. The four categories, rated as very low, low, medium and high have previously been determined rather arbitrarily, starting at 0.50 MPa at the very low end and increasing by 0.50 MPa increments for the next two higher categories.

Boeing is of the opinion that the tire pressure categories used in an airport's PCN rating should more accurately reflect current conditions of the pavement and aircraft traffic at the airport. Airlines planning their route structure use the PCN rating to determine whether they can operate at a given airport based on their aircraft ACN and operating tire pressures, which must not exceed the airport's requirements as noted in their PCN rating. In cases where the aircraft tire pressure exceeds the published airport limit the airline has basically two options. It can choose to not pursue operations at the airport in question or try obtaining a waiver from the airport which may allow operations but on a restricted basis. Neither of these options is satisfactory to the airline which seeks to maintain positive profit margins on all of its routes. Airports are hesitant to use the unlimited tire pressure category in their PCN rating and will typically default to the next higher X category, which imposes an artificial tire pressure limit of 1.5 MPa (217 psi) which is not always indicative of the quality and load capability of the actual pavement. This is clearly made evident by the fact that for airports worldwide currently allowing operations by aircraft exceeding the 1.5MPa X category limitation, the published tire pressure limit in their PCN rating is equally split between the W and X categories.

Many airports, especially in Australia, list an exact tire pressure limit in their PCN rating in lieu of the more general X or W rating. Airports in the United States, currently rated per the FAA landing gear and allowable aircraft gross load method, will soon be upgrading to the

ICAO PCN methodology and tire pressure considerations could become more of an issue. This problem will become even more pronounced in the near future with the introduction of new generation aircraft such as the Boeing 787 and Airbus A350, both of which will most likely have tire pressures exceeding 1.52 MPa (220 psi), and will be capable of reaching a much larger number of airports which currently support aircraft with much lower tire pressures. The trend in aircraft design is to produce aircraft that are much heavier due to extended range capability, resulting in higher tire pressures and higher single wheel loads. Therefore, it is imperative that the tire pressure categories created over twenty years ago, more accurately reflect the current technology. Aircraft currently entering into service and future aircraft being planned for introduction within the next two to three years, will have tire pressures ranging from 1.52-1.65 MPa (220-240 psi).

It is for this reason that the Boeing Company recently conducted tire pressure tests at the Federal Aviation Administration National Airport Pavement Test Facility (NAPTF) in Atlantic City, New Jersey. The results of that testing and our recommendations for possible further testing leading to new tire pressure categories are described in the report.

2 TEST DESCRIPTION

The tire pressure testing was performed using a single wheel module in order to prevent premature pavement deterioration and rutting not due to tire pressure effects. Typically, the effects of high tire pressures are more localized and concentrated in the upper layers of pavement. In previous testing on a similar flexible pavement cross section trafficked by multiple wheel dual tandem and tridem gear configurations, the onset of pavement rutting within the subbase and subgrade layers due to the overlapping wheel loads took place very early in the testing. In this earlier testing, over two inches of rutting had developed after only 850 passes. Therefore, in order to avoid premature structural failure due to non-tire pressure related effects, the decision was made to use the single wheel module.

2.1 Test Item Cross Sections

The test sections were constructed from a previously built, but untested low strength area of pavement at the NAPTF. The old asphalt material was removed and replaced with new asphalt using a PG 64-22 binder, starting at 15.0 cm (six inches) and transitioning to 10.0 cm (four inches) and 5.0 cm (two inches), thereby creating three test items for the tire pressure tests. The test item cross sections are shown in Table 1.

Each test item was 3.7 m (12 feet) wide by 9.1 m (30 feet) long, with a transition ramp between sections.

Table 1. Test Item Cross Sections

TP-5 cm (2 inch)	TP-10 cm (4 inch)	TP-15 cm (6 inch)
5 cm (2 inches) P-401	10 cm (4 inches) P-401	15 cm (6 inches) P-401
20 cm (8 inches) P-209	20 cm (8 inches) P-209	20 cm (8 inches) P-209
109 cm (43 inches) P-154	109 cm (43 inches) P-154	109 cm (43 inches) P-154
CBR 4 - Subgrade	CBR 4 - Subgrade	CBR 4 - Subgrade

2.1.1 Material Properties

The existing P-209 base material was of high quality and determined to have a CBR of 100 or better. The P-154 subbase material was of higher quality than required by FAA standards, which specifies a minimum CBR of 20 for subbase materials, and was tested to be between CBR 30 - 35. The critical asphalt properties were as noted in Table 2.

Table 2. Asphalt Properties

Asphalt Content %	Flow %	Air Voids %	VMA %	Stability lb
5	8-9	3 - 3.5	15 - 17	2700 – 2900

2.1.1.1 Loading

The single wheel module used for the testing consisted of a 49 x 19-20 34 bias ply tire. Three wander positions were used, center and 25.4 cm (10 inches) either side of center, which provided overlap with each successive pass of the single wheel module without having to traffic the exact same location. The initial wheel load and tire pressure was set at 18,144 kg (40,000 lb) and 0.97 MPa (140 psi), which is typical for older versions of the 737. This tire pressure was also the minimum allowed due to concerns over exceeding the rated tire deflections. Initially, loading was done in only one direction due to concerns over trafficking the transition ramps between test sections, and being able to maintain consistent wheel loading over each test section. Once this concern was alleviated, the testing was performed in both directions in order to expedite the testing. Figure 1 shows the single wheel module on the test pavement sections.

The testing schedule for wheel load and tire pressure was as follows: Prior to testing, the entire test area was proof rolled in order to get all of the initial settlement out of the test items. The testing was started with a 18,144 kg (40,000 lb) single wheel load and 0.97 MPa (140 psi) tire inflation pressure at a test speed of 4 kilometers per hour. All three test sections were trafficked for 500 passes. If failure was not reached on any of the sections then the tire pressure was increased to 1.10MPa (160 psi) for another 500 passes. The testing was continued in this manner, increasing tire pressure in increments of 0.14 MPa (20 psi) and trafficking for 500 passes until failure was reached. Once failure was determined for a section, traffic was to be discontinued on that section and continued only on the remaining unfailed sections. Once 3000 passes were reached, tire pressure at 1.65 MPa (240 psi), and the sections were still not at the failure condition, the single wheel load was increased to 22,680 kg (50,000 lb) and trafficking continued at 1.65 MPa. It was determined that this single wheel load and tire pressure were high enough limits to be representative of existing widebody aircraft. The testing was continued until 5000 passes or coverages were reached. It was felt that 5000 coverages was a good indication of total operations for a high tire pressure aircraft operating at an airport for about a ten year traffic cycle.

The actual testing had two slight deviations from the original plan. First, the initial 500 passes at 0.97 MPa (140 psi) were stopped at 250 passes due to lack of significant deterioration, and the plan was followed up to the final concluded value of 4750 passes. At this point, since none of the test sections had failed at the highest tire pressure, it was decided to continue testing at 24,947 kg (55,000 lb) and 1.65 MPa (240 psi) until the required failure criteria was reached. The entire load and tire pressure schedule is shown in Table 3.

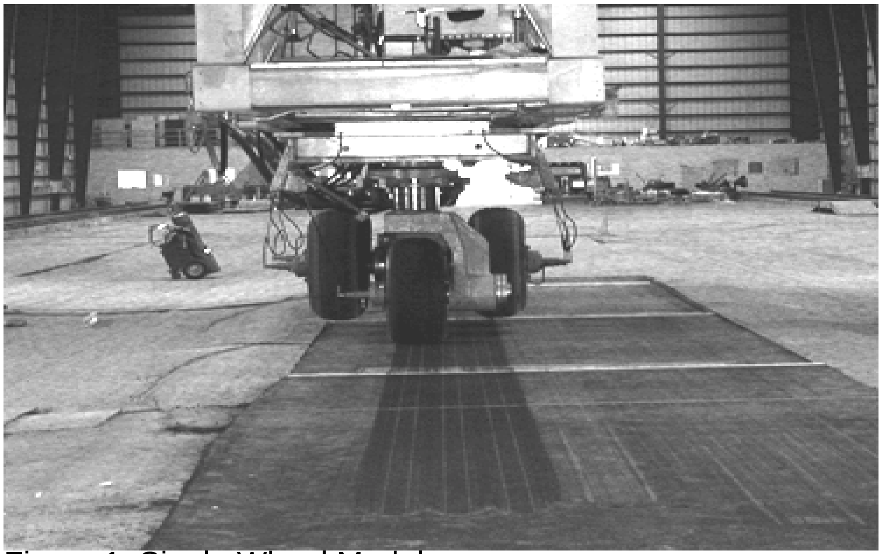
Figure 1. Single Wheel Module

Table 3. Load and Tire Pressure Schedule

Tire Pressure MPa (psi)	Wheel Load kg (lb)	Total Passes	Rut Depth cm TP-5cm	TP-10cm	TP-15cm
.97 (140)	18,144 (40,000)	0	0	0	0
.97 (140)	18,144 (40,000)	250	.16	.23	.17
1.10 (160)	18,144 (40,000)	750	.29	.39	.32
1.24 (180)	18,144 (40,000)	1250	.36	.57	.39
1.38 (200)	18,144 (40,000)	1750	.43	.64	.47
1.52 (220)	18,144 (40,000)	2250	.47	.71	.59
1.65 (240)	18,144 (40,000)	2750	.53	.75	.66
1.65 (240)	22,680 (50,000)	3250	.64	.86	.75
1.65 (240)	22,680 (50,000)	3750	.67	.87	.78
1.65 (240)	22,680 (50,000)	4750	1.10	1.18	.98
1.65 (240)	24,947 (55,000)	5000	1.28	1.27	1.22
1.65 (240)	24,947 (55,000)	6326	1.49	1.46	1.49

3 FAILURE CRITERIA

The attempt was made to isolate pavement failure due to tire pressure effects only, and not to test the pavement to complete failure. Therefore, the failure criteria chosen were to be indicative of sufficient pavement damage that would result in an airport's decision to repair the damage. The criteria chosen were to test until a Pavement Condition Index (PCI) of 55 was reached or pavement rutting had reached a medium severity level of 1.3-1.9 cm (0.50-0.75 inches). The PCI level of 55 or medium severity rutting corresponds to a pavement condition which has gone from good to fair condition, which is typically when an airport would undertake some sort of rehabilitation to restore the pavement to its original condition.

After every 500 passes the pavement was inspected for cracking and rutting in order to determine the appropriate PCI rating. After 3,000 passes it became clear that pavement rutting would most likely be the first indication of failure since not a single crack had been observed in any of the test sections. Figure 2 shows the technique used for rut depth measurement.

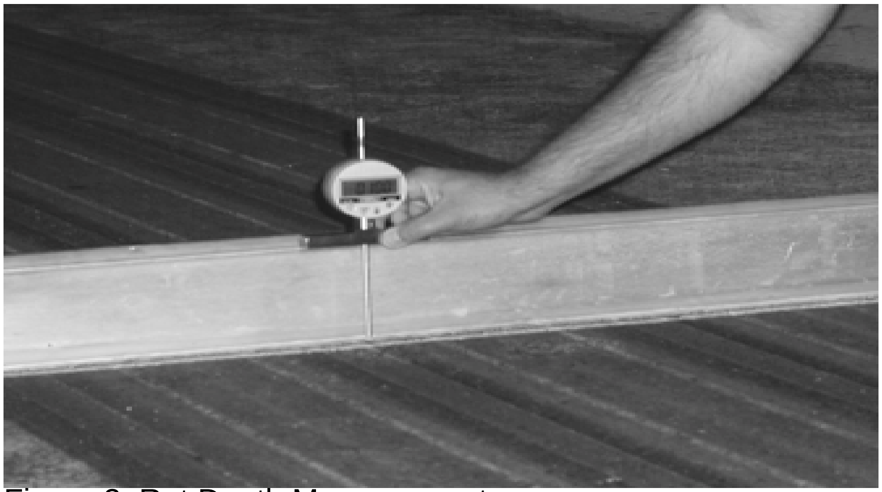

Figure 2. Rut Depth Measurement

4 ANALYSIS OF TEST RESULTS

The test results are graphically displayed in Figure 3 for each of the three test sections. The testing was concluded when all test sections had exceeded the failure criteria of 1.3 cm (0.50 inch) rut depths.

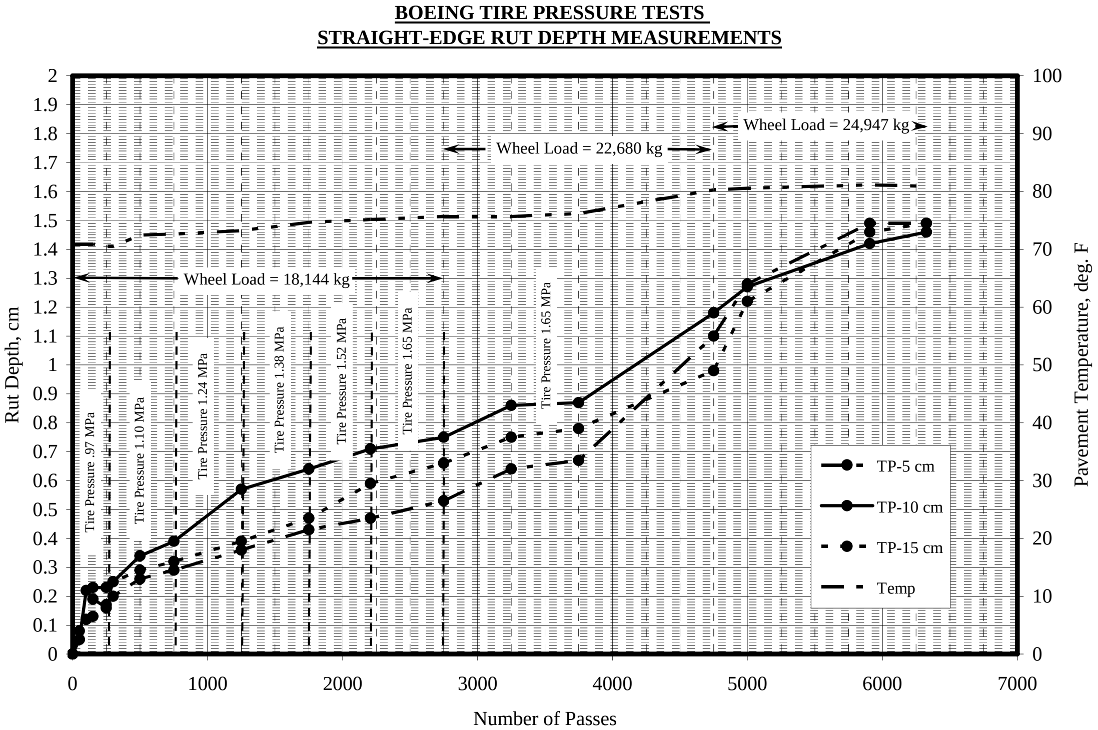

Figure 3. Rut Depth and Temperature vs. Number of Passes

The initial rutting in the 10 cm (4 inch) and 15 cm (6 inch) test items exceeded the 5 cm (2 inch) test item primarily due to the densification under traffic of the thicker asphalt surface course. The air void content of the asphalt mixture was between 3-4 % at the start of testing and most likely was reduced as the trafficking progressed and the asphalt became more compacted. From previous studies done on asphalt mixtures (Ford 1988) the relationship between void content and rutting is significant. As the air voids approach 3% or less, the increase in rutting is much greater. This may be part of the reason for the sudden increase in rutting for all test items around 4,000 passes when the asphalt was fairly well compacted. Another reason for the increase in rutting at this point was that the initial testing was stopped after 3,750 passes and was put on hold for one month. During this time the asphalt surface temperatures had increased by an average of ten degrees Fahrenheit resulting in a less stiff asphalt surface course possibly more susceptible to rutting.

The 5 cm (2 inch) asphalt pavement section performed better than expected most likely due to the very high quality of the P-209 base material. It has previously been shown (Roberts 1985) that as an asphalt surface becomes thinner then the effect of a strong base becomes more significant and helps to reduce the tensile strain in the asphalt layer. For thicker asphalt surfaces, the effect of a strong base in reducing tensile strains in the asphalt is not as significant. In this case, the surface modulus is most important in keeping the strain levels low enough to prevent fatigue cracking.

A recent analytical study done at the University of Texas-Austin (Machemehl 2005) concluded that the elongated contact area of a tire causes differences in tensile strains in both the longitudinal and transverse directions at the bottom of the asphalt layer. This may lead to more longitudinal cracks at high tire loads and low inflation pressures, especially for thin pavements and more transverse cracks for increased tire pressures. Additionally, the effects of tire pressure on fatigue cracking that starts from the bottom of an asphalt layer and rutting due to the subgrade are generally less significant than the effects of tire load, especially for thicker pavements. Recent analytical models addressing non-uniform tire pavement contact stresses (Luo 2007), which are able to estimate the critical surface strains leading to top down cracking in the asphalt, could further serve as a tool in determining the critical combination of asphalt thickness, wheel load and tire pressure. The results of the testing at the NAPTF however, showed no indication of surface cracking due to higher tire pressures, even in the two inch pavement. The cores taken after testing was concluded, Figure 4, verified that no cracking had initiated anywhere through the asphalt thickness. The rutting also appeared to be caused mainly by tire loading as previous studies also confirm, with a slight increase resulting when the wheel load was increased from 22,680 to 24,947kg (50,000 to 55,000 lbs).

Figure 4. Core samples from failed test sections

In the 1950's the Corps of Engineers, Waterways Experiment Station (WES) performed a series of full scale tests which involved trafficking with 13,608 kg (30,000 lb) wheel loads and 1.38 MPa (200 psi) tire pressures. At the time, WES felt that their low pressure asphalt mix design would not be adequate for the heavier aircraft with high tire pressures being introduced. The results of that testing (White 1985) led to a new high tire pressure mix design criteria for asphalt pavements. A summary of the critical asphalt properties from the WES high tire pressure criteria are: Stability- 1800 min, Flow- 16 max, and Voids- 4-6 %. All of these requirements were met in the NAPTF testing, although the total air voids was slightly below the recommended WES value.

The U.S. Navy reported on the variations in aircraft loads and tire pressures during normal operations based on actual visual surveys and tracking of military airfield pavement performance (Brown 1967) typically utilized by aircraft with single wheel loads as high as 16,329 kg (36,000 lb) and tire pressures of 2.76 MPa (400 psi). Recognizing the fact that tire pressure increases with temperature which may result in increased distress on landing, albeit at lower wheel loads than takeoff conditions, evidence of occasional surface raveling was observed. However, part of this condition was due to the ageing of the asphalt surface itself. The final conclusion of the U.S. Navy's experience with high pressure tires was that if asphalt pavement's are designed to meet the minimum asphalt properties set forth by WES, are of sufficient thickness based on aircraft loads, and have a base course of CBR 80 or higher, then high tire pressures will not lead to additional distresses and reduced pavement performance. Tire pressure limitations should only be considered for low quality asphalt mixes or severely aged asphalt surfaces.

Concerns have been raised over the effect of high temperatures on asphalt pavements subjected to high tire pressures. Due to testing indoors, this issue could not be considered in the testing performed at the NAPTF. Recent research has also addressed the concern of top down cracking in asphalt pavements (Molenaar 2007) which is difficult to predict using current fatigue models which only address the conventional fatigue failures associated with bottom up cracking. Since field data verifies that many longitudinal and transverse cracks in the wheel path of an aircraft are discrete top down cracks, this issue will be further addressed in future testing at higher traffic levels. Additionally, comparison testing of both a low quality asphalt mix and high quality polymer modified asphalt will be included in future tire pressure testing.

5 COMPARISON OF EXISTING DESIGN METHODS

It is useful to compare the minimum asphalt pavement thickness requirements for design and the relationship to allowable tire pressures set forth by various agencies. Table 4 lists the criteria set forth by the Federal Aviation Administration (FAA), Canada, US Navy and US Army.

Table 4. Pavement design criteria for various agencies

Agency	Aircraft Weight	Tire Pressure MPa	Minimum Thickness AC Surface cm (in)	Base cm (in)
Canada	Not Applicable	.40 < tp < .70	6.4 (2.5)	23 (9.0)
	Not Applicable	.70 < tp< 1.0	9.0 (3.5)	23 (9.0)
	Not Applicable	1.0 < tp	10 (4.0)	30 (12.0)
FAA	Dual or Dual Tandem	*	10 (4.0)	15-20 (6.0-8.0)
	Tridem	*	12.7 (5.0)	13 (5.0) stab
US Navy	> 13,608 kg (30,000 lb)		All	10 (4.0) 13 (8.0)
US Army	**	Not Applicable	10 (4.0)	15 (6.0***)
	**	Not Applicable	12.7 (5.0)	15 (6.0****)

*Per (FAA 1995) section 303, part c, it is noted that tire pressure exerts less influence on pavement stresses as gross weight increases, and that the maximum of 1.38 MPa (200 psi) may be safely exceeded if other parameters are not exceeded and a high stability surface course is used.

**Requirement based on primary loading area which is the first 305 m (1000 feet) at each end of the runway and a runway length greater than 2743 m (9000 feet).

***100 CBR base

****80 CBR base

The Canadian criteria (ICAO 1983) are based solely on tire pressure considerations and a 10 cm (four inch) asphalt surface is considered adequate for all tire pressures over 1.0 MPa (145 psi). The US Navy criteria (UFC 2001) have a similar recommendation of 10 cm (four inches) of asphalt for all tire pressures. It should be noted that there are US military aircraft with wheel loads around 13,608 kg (30,000 pounds) operating on these runways at tire pressures between 1.65-2.41 MPa (240-350 psi).

The FAA criteria recommends that as long as the pavement meets the minimum thicknesses based on aircraft loading requirements, higher tire pressures will not be a problem if the asphalt design mix meets the stability requirements.

An alternative method for rating airport pavements has recently been proposed (Loizos 1999) which also indicates that the current thresholds for tire pressure in the ACN/PCN system are no longer valid. In general the effect of tire pressure on the upper layers of pavement is directly related to the material properties and overall pavement structure. In this study as well, the asphalt surface thicknesses and total pavement thickness requirements recommended for large aircraft comply with the requirements of the pavement design criteria aforementioned.

6 CONCLUSIONS

The minimum pavement requirements set forth by various agencies all require asphalt surface course thicknesses in the range of four to six inches. The tire pressure tests done at the FAA National Airport Pavement Test Facility have confirmed the fact that high tire pressures have no adverse effect on flexible pavements that meet these requirements.

The importance of both asphalt and base material quality in providing resistance to premature pavement damage due to high tire pressures has been confirmed by this testing and by field studies and tests performed in the past.

The tire pressure categories currently in use by the ICAO PCN rating system should be modified to be more compatible with the current aircraft operating at airports worldwide. This would also allow airlines to plan their routing structure more efficiently and ensure that their aircraft tire pressures do not exceed the limits imposed by the airport PCN rating. Rather than using somewhat arbitrary tire pressure categories, we believe that the four categories should be more consistent with current aircraft. We propose the following tire pressure limits:

Table 5. Proposed ICAO Tire Pressure Categories

Tire Pressure Category	Current ICAO Limits MPa (psi)	Proposed ICAO Limits psi (MPa)
W	Unlimited	Unlimited
X	1.50 (217)	1.65 (240)
Y	1.00 (1.45)	1.25 (181)
Z	.50 (72)	.50 (72)

The X category would now be set high enough to cover all of the wide body aircraft currently in use and any new aircraft currently being planned over the next ten years. The Y category would now be set high enough to be more compatible with older dual wheel aircraft operating at airports that do not have widebody traffic. The Z category would remain unchanged since it deals primarily with airports having seal coat type surfaces.

The airport is still the authority for determining its own allowable tire pressure to be used in its PCN rating. Most new construction utilizes asphalt and base material of a high enough quality that should not be a problem for higher tire pressures when the minimum thickness guidelines for a given agency are followed, and should be assigned either a W or X tire pressure category. Older pavements may need additional testing to verify that the asphalt properties are sufficient before assigning a tire pressure category.

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