What Does an Aircraft Expect From the Pavement?

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It is truly an honor to be invited to be a keynote speaker for this prestigious conference. I would like to thank the organizing committee and especially Oyvind Hallquist for having the courage to invite, for the first time ever – an aircraft manufacturer to address this conference at a plenary session. No BCRA that I've ever attended, nor any Ann Arbor Conference, ever granted an airframe manufacturer the opportunity to share their views of the world of airfield pavements in a keynote speech, so I am sincerely appreciative of being granted this opportunity.

I am not going to give you a treatise today with third order differential equations or multiple matrices to invert – but I am going to ask you to listen with an open mind towards the practicalities of commercial aircraft operations worldwide as I delve into the question I was asked to answer – "What does an aircraft expect from a pavement?".

As I am sure you all know something needs to happen for airports and airlines to co-exist and to communicate their mutual needs clearly, so as to foster their common interests at commercial airports, to benefit commercial aviation and to safely serve the traveling public. Those airlines, on a daily basis continually deal with airfield pavements. When they have problems with pavement, they bring the questions to us.

So, we as a major commercial aircraft manufacturer, have airfield pavement issues delivered to our doorsteps almost daily, so that is where I will focus my comments – on airfield pavements.

PAVEMENT LOADING

Our number one issue is pavement loading. We produce aircraft that for the most part challenge airfield pavements in terms of both strength and pavement life. The gage that we use to judge our aircraft is ACN – Aircraft Classification Number (ICAO, 2004) and airports around the world, especially those who are ICAO Signatory Nations use PCN (Pavement Classification Number) to express their pavement loading capability. We strongly support and encourage this methodology, and we are heartened that a year or so ago, NATO finally acknowledged ACN/PCN and adopted the methodology for all of their airfield pavements. ACN/PCN is truly the major internationally recognized system by which airports and airlines communicate their needs and capabilities.

In 1990, when we embarked on the development of the aircraft that was to become the 777, we faced the decision of either trying to push the typical four-wheel landing gear up to wheel loads of 65,000 or even 70,000 pounds, or to develop an all-new six-wheel landing gear. We committed to the six-wheel landing gear in 1991, but our early studies indicated relatively high pavement loading numbers in the ACN system, in spite of the fact that the six-wheel gear distributed what should have been common wheel loads over an area that was more than 70 percent greater than any comparable four wheel landing gear in the commercial fleet. This caused us to revisit the derivation of the way that the CBR method (ICAO, 1983) which is at the source of ACN, dealt with multiple wheel gears.

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By now pavement engineers from around the world know that in 1995, the US Corps of Engineers, the FAA and many international bodies agreed that the CBR method did not treat the six wheel gear in a fashion that was consistent with its capability to distribute loads over a much larger area than any four-wheel gear had ever done. This was due in large part to the fact that no full scale tests to failure had been carried out with a six wheel landing gear to verify the load attributes.

The FAA National Airfield Pavement Tests (Gervais, Hayhoe and Garg, 2003) have now firmly concluded as shown in Figure 1 how six-wheel landing gears load full-scale airfield pavements both comparatively (to a standard four-wheel landing gear) and in absolute terms as well (thanks to the running of their tests through to the failure point and to coverage levels that are necessary to determine a realistic alpha factor).

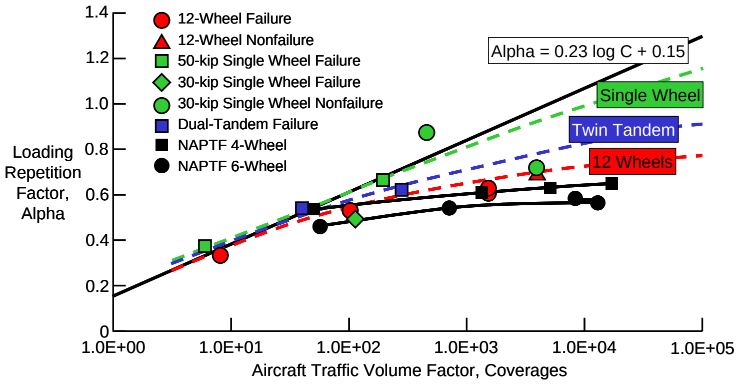
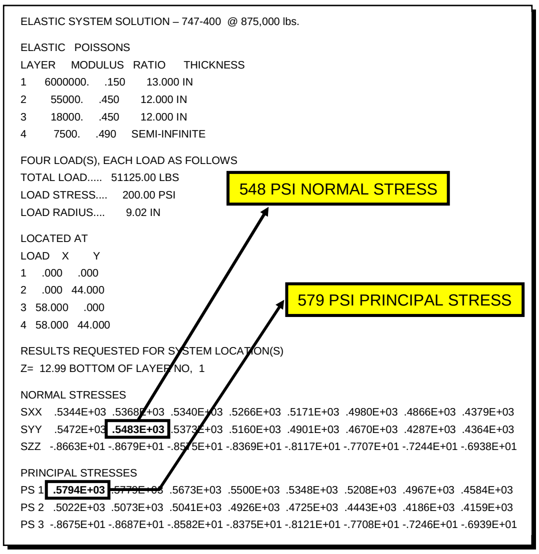


Figure 1: Revised Alpha Factor Curves From the FAA NAPTP

The results of the flexible pavement tests are by now fairly well circulated. The outcome clearly indicates that the placement of the six-wheel alpha factor curve in the original CBR Method was extremely conservative. Another observation from the FAA test results is that there is nothing wrong with the CBR Method. By now the 777 has been in commercial operation for ten years, with almost 600 aircraft in service at the present time. The airplanes are operating successfully into over 150 major airports worldwide and we know of no premature pavement failures or other pavement load related issues wherever the airplane is operated. I would proclaim this as a clear validation of the outcome of the FAA tests and of the load distribution qualities of the six-wheel landing gear. Might I suggest that even though there are cries for a widely accepted multi-layer elastic solution technique for airfield pavements, the continuation of the CBR Method does not pose a threat to early pavement failures - and to the best of my knowledge – there are no currently accepted procedures for determining PCN by way of multi-layer elastic solutions either.

Along this same subject line, how about the way that layered elastic or mechanistic – empirical methods deal with the conversion of CBR to a Young's Modulus (E-Value)? The accepted conversion is 10 times CBR equals Young's Modulus for a subgrade soil (Shook, Finn, Witczak and Monismith, 1982). Is this really an accurate reflection of the subgrade modulus (when expressed in terms of MegaPascals) in an elastic half-space? As Dr. Peter Pell ((Pell, 1977) pointed out many years ago at an Ann Arbor Conference, there are objections to this simple equivalence, but, serious pavement behavior deviations aren't generally expected unless the CBR values get extremely high (say above CBR 20) or very low (CBR's below about 3). How many runways are built on soils with these kinds of subgrade strengths? – I only know of a couple that are genuinely at the high end (there's one in the Cape Verde Islands and a few like Billund, Helsinki and Oslo) and a half a dozen or so on the low end (places like Jakarta, Manila, Bangkok, Mexico City and Rotterdam come to mind). So, even though Dr. Pell has said that the simple relationship is unsatisfactory, I wonder how much of this kind of precision we really need. I think the quote from Dr. Marshall Thompson at the Lisbon BCRA (Thompson, 2001) went something like this; "measure with a micrometer, draw with a crayon and cut with an axe", which I think is a valid way to consider the utility of the elastic systems. In our view, the CBR Method has not been compromised for any other reason than being conservative, which is not such a bad idea, when one considers airfield pavements.

On a related note, Mechanistic-Empirical solutions are becoming more and more widely used every day, but do they accurately represent the effects of aircraft loading? Figure 2 is an example of a standard multi-layer elastic program – ELSYM5. (Bisar, Julea, Alize' or APSDS would all portray similar results.)



ELASTIC SYSTEM SOLUTION – 747-400 @ 875,000 lbs.

LAYER	ELASTIC MODULUS	POISSONS RATIO	THICKNESS
1	6000000.	.150	13.000 IN
2	55000.	.450	12.000 IN
3	18000.	.450	12.000 IN
4	7500.	.490	SEMI-INFINITE

FOUR LOAD(S), EACH LOAD AS FOLLOWS

TOTAL LOAD..... 51125.00 LBS

LOAD STRESS.... 200.00 PSI

LOAD RADIUS.... 9.02 IN

LOCATED AT

LOAD	X	Y
1	.000	.000
2	.000	44.000
3	58.000	.000
4	58.000	44.000

RESULTS REQUESTED FOR SYSTEM LOCATION(S)

Z= 12.99 BOTTOM OF LAYER NO, 1

NORMAL STRESSES

SXX	.5344E+03	.5368E+03	.5340E+03	.5266E+03	.5171E+03	.4980E+03	.4866E+03	.4379E+03
SYY	.5472E+03	$\boxed{.5483E+03}$	.5373E+03	.5160E+03	.4901E+03	.4670E+03	.4287E+03	.4364E+03
SZZ	-.8663E+01	-.8679E+01	-.8575E+01	-.8369E+01	-.8117E+01	-.7707E+01	-.7244E+01	-.6938E+01

PRINCIPAL STRESSES

PS 1	$\boxed{.5794E+03}$	.5779E+03	.5673E+03	.5500E+03	.5348E+03	.5208E+03	.4967E+03	.4584E+03
PS 2	.5022E+03	.5073E+03	.5041E+03	.4926E+03	.4725E+03	.4443E+03	.4186E+03	.4159E+03
PS 3	-.8675E+01	-.8687E+01	-.8582E+01	-.8375E+01	-.8121E+01	-.7708E+01	-.7246E+01	-.6939E+01

Figure 2: Elastic System Solution 747-400

The solution shown in Figure 2 is for a typical 747-400 on a standard rigid pavement. One has to ask however, why is the stress so high? 548 psi! (I'll apologize for the English units here – this would otherwise read – 3778 kilopascals or 38.5 kg/cm2.)

Figure 3 presents the exact same load condition (k=300 pci, E=5 million, Mu = 0.15) for the standard Portland Cement Association center case. Note that a thickness of 13 inches (33 cm) is entirely suitable.

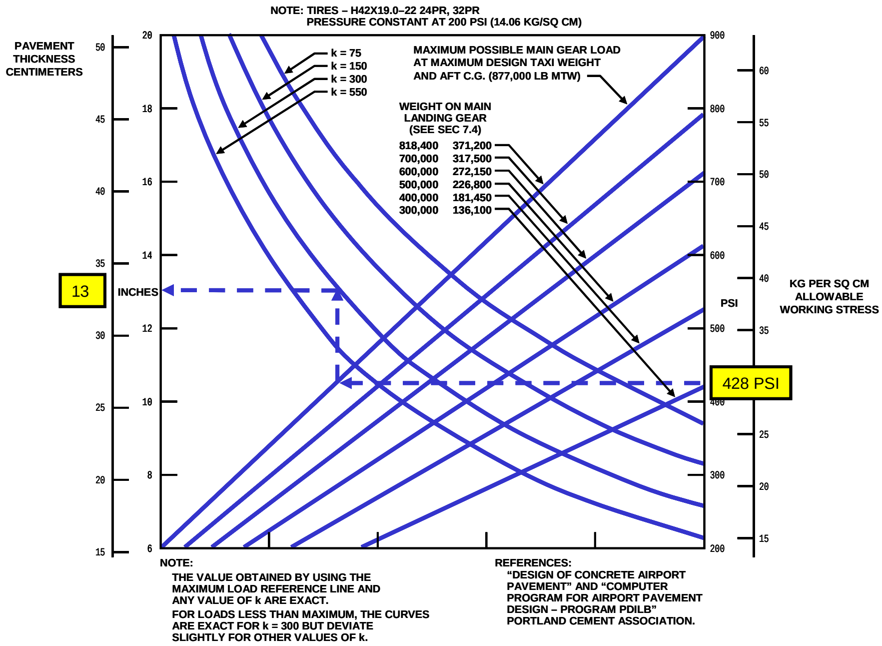


Figure 3: PCA Center Case Run for the Exact Same Conditions

This looks much more like what we are all most familiar with – 428 psi (2951 kilopascals – about 30 kg/cm2) allowed stress, for a reasonably long (say 100,000 load repetitions of pavement life) and a completely suitable 33 centimeter thickness requirement.

My point in showing you this is that we continue to find that the traditional tools render allowable stresses that are consistent with Modulus of Rupture values that are very familiar, but the results that we see when M-E tools are used are quite different, even when standard conditions apply. I fully realize that many are calling for the precision of the M-E tools, but we feel that some adjustments must still be required as there is no reason why these numbers shouldn’t be identical between the two systems, or very nearly so.

RUNWAY ROUGHNESS

How about Runway Roughness or ride quality – we have no issue with construction acceptance criteria, be it ICAO, FAA or anyone’s national specifications. But our concern is with the end-of-life decision – when is a rough runway too rough to sustain continued safe operations of commercial aircraft?

We have developed a simple criteria (Figure 4) that relates individual features along the surface of a runway (bump height and bump length), aligned with the direction of motion of an aircraft, that has suited us very well over the years.

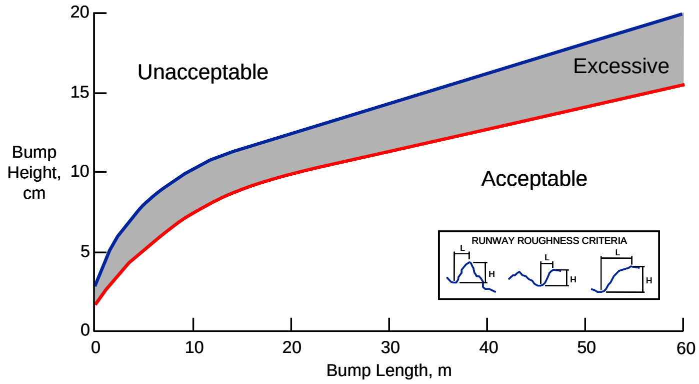


Figure 4: Boeing Runway Roughness Criteria

The basis for this criteria, is the g-loading on the main and nose gear axles during full load high speed ground rolls of a variety of dual and dual tandem (joule' and bogie) landing gear. The aircraft that created these criteria were instrumented to detect adverse stresses and were cross referenced against the longevity that we design into our commercial aircraft structures for a long suitable airframe life.

Many attempts have been made over the past ten years worldwide to ascertain a better runway roughness ride quality detection scheme, and yet here is a system that is simple to use (really nothing more than a rod and level survey along the runway centerline and the main gear wheel tracks as shown in Figure 5) and an indexing system that quickly identifies the exact locations of the most severe roughness.

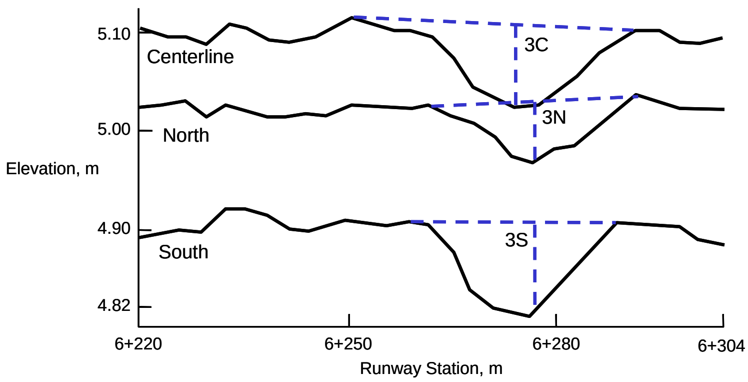


Figure 5: Sample Survey Results — Long Wave Depression

In fact the use of this system provides an immediate method to identify the simplest means of repair. I should also note that this system has been validated by almost thirty years of use. Mind you, we only get called when someone, usually the airline, thinks a runway is too rough to safely sustain commercial jet operations. Figure 6 presents an historical view of the data we have collected; I'd say the system clearly passes the test.

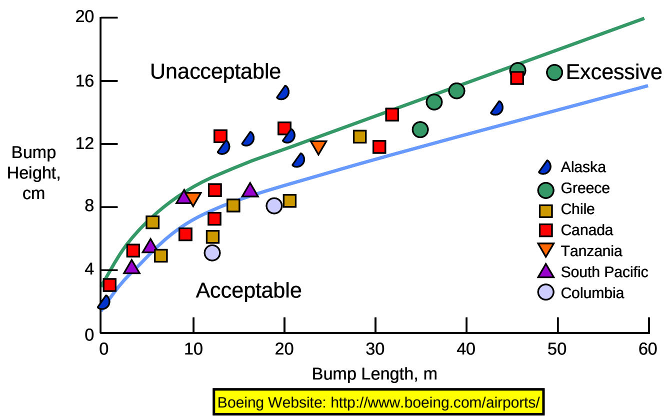


Figure 6: Example of Results From Worldwide Roughness Testing

My challenge to you in this area is simply this – in addition to looking down when you study and analyze runway roughness (I know there are many research efforts underway to develop a rapid means to measure runway ride quality) but try to look up as well, at aircraft response. Individual aircraft response is crucial to the determination of ride quality and the effects on an aircraft can run from landing gear axles, to the pivot points of the landing gear at truck beams, and even into the fuselage. The Boeing Bump is fully documented (DeBord, 1995) and is freely available from our website, and I strongly encourage you to use it.

RUNWAY FRICTION

Finally - What about friction. How is measured? And - are these measurements really meaningful to an aircraft?

Over the years, various elements of the aviation industry have been performing runway friction measurement programs. The aim of some of these programs has been to establish a relationship between aircraft stopping distances and runway surface friction characteristics during freezing or snow-covered conditions. In light of the regulatory requirements on commercial aircraft, one might ask - what do the airframe manufacturers consider an acceptable correlation between ground vehicle friction measuring devices and airplane braking? There are at least two answers to the question, depending on the context.

(1) A very high degree of correlation is required if the ground vehicle friction reading is to be used to establish limits that would define aircraft operational capability. (Boeing has been skeptical that existing ground vehicles can achieve the necessary accuracy.) Or,

(2) A lesser level of correlation would be acceptable if the purpose of the ground vehicle measurements is to provide operational guidance to the crew, when they must operate from runways with degraded traction. It is this second answer that is discussed below.

Of key criticality in this regard is the case when an aircraft accelerates to just before the decision speed (V1), and then suffers some on-board failure, such as an engine malfunction. At that point the aircraft must be able to cease its’ acceleration and come to a full stop on the runway surface. Figure 7 presents a plot of takeoff distance relative to the Federal Aviation Regulation (or “FAR”) runway length, for a dry pavement.

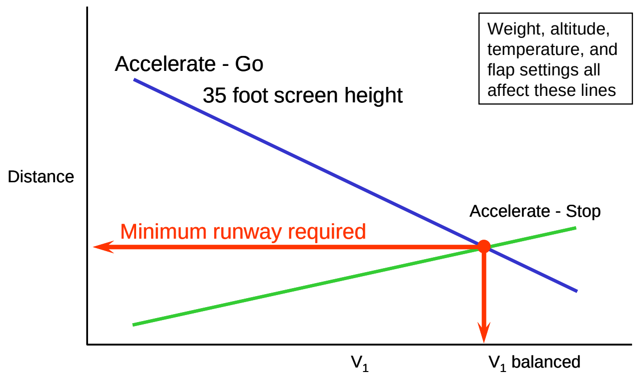


Figure 7: Dry Runway—Typical Twin Engine Airplane

This chart depicts the takeoff roll of an aircraft on a dry runway. The lower horizontal line (green) is a plot of the increase in velocity as the aircraft rolls along the runway towards the decision speed. The upper horizontal line (blue) can be thought of a distance remaining line. As the distance remaining decreases and aircraft approaches the decision speed, the aircraft must be able to come to full stop on then runway if any anomaly occurs before the airplane reaches the decision speed (V1). The point at which these two (accelerate – stop, and accelerate – go) lines intercept is what is called the balanced field length. In the 'go' case the aircraft can continue the takeoff to the desired height at the far end of the runway even if an anomaly has occurred after the V1 speed was reached. This is the manner by which all commercial operations are calculated and decided. The minimum F.A.R. required takeoff field length for a dry runway is determined by the condition where the distance required to continue the takeoff after an engine failure at V1, and to reach a height of 35 feet, is equal to the accelerate-stop distance (on a dry runway) from the same V1 speed. [Note that in the world of commercial aviation the pilot is required to have a takeoff analysis which indicates shows that he or she is in complete compliance with all of the appropriate regulations, and he or she cannot violate any of the takeoff performance limits of the aircraft.]

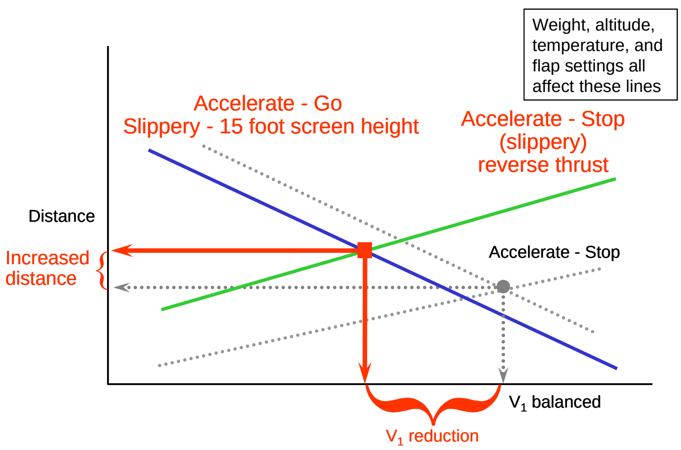
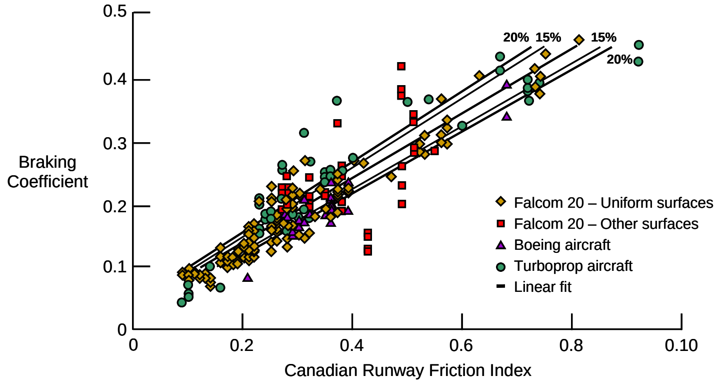


Figure 8: Contaminated Runway

Figure 8 adds information for the situation of degraded braking. You can see that a number of conditions begin to exhibit themselves in ways that drastically change the decision speed and the takeoff distance available. You can see for instance that the stopping distance increases. You can also see that the accelerate-go takeoff distance decreases. However, on a real runway, the available distance is fixed. One cannot increase the runway length, so to accommodate the distance required, the weight of the airplane may have to be reduced. The airline cannot reduce fuel, and they cannot reduce the airplane weight, so in field length limited cases, the only thing to reduce is the payload (which in commercial aviation is the only reason to fly). The economic consequences of restricting takeoff weights and payloads due to ground vehicle readings which might be 15 to 20 % too low, are unacceptable in our view.

Hopefully these slides exhibit for you just how crucial runway friction is to successful commercial operations. Our problem however has been that almost every study of this phenomenon that we have seen, indicates that there is a wide scatter in measured data such that correlations of runway surface friction and aircraft braking characteristics simply do not agree very well. The logical question is "Do ground measurement vehicles exhibit correlations that fall within an acceptable range of agreement with aircraft braking action?"



Braking coefficients for all aircraft for all aircraft versus Canadian Runway Friction Index

Figure 9: Correlation of Aircraft Braking With Runway Friction Measurement

The Transportation Development Center of Transport Canada carried out a series of studies using at least three different types of friction measuring devices and evaluated six different aircraft types (Croll, Bastain, Martin & Carson, 2002) as shown in Figure 9. A number of conferences have been held, and the results of these studies have been presented. The major sponsors of this program claim that a consistent friction reading can now be provided through the use of the Canadian Runway Friction Index (CRFI) and that a good correlation between airplane braking and friction index has been demonstrated. Our position has been that a satisfactory correlation between friction measurement and airplane braking has not yet been demonstrated. I've superimposed 15 and 20 % variation lines on this data and you can see how many data points fall outside of the boundaries. There is simply too much variation in the friction readings on runways with ice and compacted snow conditions, and the readings are un-reliable in our opinion on runways with slush and standing water. Therefore, these friction measurements should only be considered as one piece of information the flight crew should use when operating on contaminated runways.

Interestingly, I also found some data from a Swedish Research Institute study (Fristed and Norrborn, 1980) that was performed in the early 1980's which reporting virtually identical results - and data scatter, as seen in Figure 10.

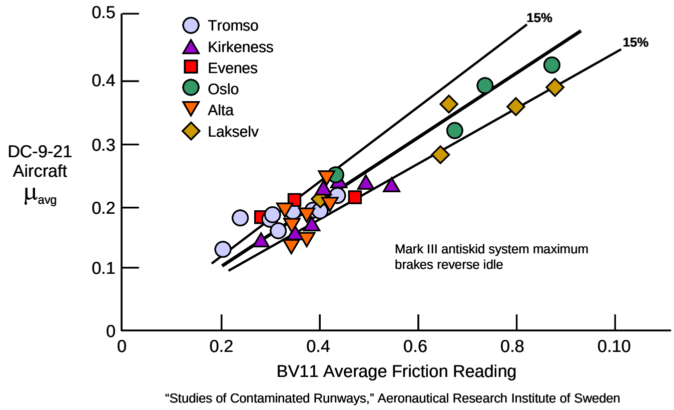


Figure 10: Comparison of DC-9 Average Friction Coefficient and BV: 11 Friction Readings

This study compared friction measurements from one airplane model and a different friction measuring device than was used in the Canadian study, but similar results were found. The measurements in this case were made on six different airports and included numerous "poor" braking conditions. The data shows that that even for this ideal situation a 15 % tolerance is optimistic.

I should also mention to you that we are aware of an in-service event wherein a friction vehicle indicated a mu-value of 0.40 and the aircraft braking coefficient on the runway during a landing was slightly less than 0.10! It should be very clear from this, that as long as correlation tolerances remain as large as they presently are, ground vehicle readings should be used only for advisory purposes and not to rigorously limit the allowable operating weight of the airplane.

I'll conclude this portion of my remarks with the conclusion that the correlation between aircraft braking capabilities and those predicted by ground vehicles still needs to improve by one or two orders of magnitude before such devices should be relied upon to be used to specifically define airworthiness limitations. We believe that unless ground vehicles and airplanes can be shown to correlate more precisely than 15 or 20 %, our preference is that such information remain as advisory, in order to be meaningful to pilots.

In preparing this speech I was reminded of friction testing that I witnessed some years ago in a Country where severe winter conditions prevail for at least a portion of the year. In this locale airport ground vehicles were outfitted with James Brake Index decelerometers. The gages were certified twice annually, and the test was run such that the vehicle would accelerate to 100 kmph (that's 62 mph) and then the brakes would be applied immediately. The gage reading would indicate the measured deceleration in terms of JBI, and three of these tests would be used to determine an average JBI for the runway. This number was them reported to the tower and the tower would convert this into a "good" – "fair" – or "poor" rating for transmittal to air crews. Sounds pretty good eh? Well no two trucks would measure identical JBI's, and no two drivers would achieve identical numbers either, so the drivers would all refer to this as the lunch box test. The lunch box being the key to "good", "fair" or "poor" results. Are you with me on this? Okay – every airside worker brings their lunch to work each day, and the lunch box goes on the seat of the truck. Got it yet? Well, when they run the test, if the lunch box stays on the seat the braking is poor, if it slides forward a bit on the seat, braking action is fair, and if it flies onto the floor of the truck, the braking action is good. Many times airfield operations drivers would report JBI's based more on their lunch box, then on the gage readings. Admittedly, this is not done this way any longer, but it does serve to illustrate where we started on this.

I've now shared with you a series of airfield pavement topics in which aircraft manufacturer's have a direct interest. It is not my intent to claim that anyone's research or serious efforts to resolve these deficiencies have been at fault – but I do hope that my remarks have challenged you. Airlines, Airports and Aircraft all come to together in a variety of ways that demand practical solutions, clear expressions of compatibility and well designed methodologies to facilitate an ease of use across cultures, languages and differing levels of sophistication. l sincerely hope that my comments will not fall on deaf ears, but will stir each of you to a better understanding of the total environment in which these forces work, and to prompt you to find solutions that meet the needs of all the users of whatever you do.

Over design and over-protection of the pavement resource, clearly has its place in the priorities of nations, but to quote Dr. Fred Finn (Finn, 1987) "we can make a valuable contribution to the economy of nations" by prudently considering the practical outcomes and realties of what we do in the area of airfield pavement engineering".

I'd like to thank you again for inviting me to make this presentation. I sincerely appreciate being given the opportunity to share these comments with you.

REFERENCES

Croll, J.B, Bastain, M, Martin, J.C.T., and Carson, P, *Evaluation of Aircraft Braking Performance on Winter Contaminated Runways and Prediction of Aircraft Landing Distance Using the Canadian Runway Friction Index*, Canadian National Research Council Report LTR-FR-183 - Transport Canada TP 13943E, June 2002

DeBord, Kenneth J., *Runway Roughness Measurement, Qualification and Quantification: the Boeing Method*, www.boeing.com/airports, Original Release, June 1995

Finn, F.M., Keynote address on pavement design, Sixth International Conference on the Structural Design of Asphalt Pavements, Ann Arbor, Michigan, July 1987

Fristed, K. and Norrborn, B, *Studies of Contaminated Runways*, Aeronautical Research Institute of Sweden, Stockholm, 1980

Gervais, E.L., Hayhoe, G. F., Garg, N, *Towards a Permanent ACN Solution for 6-Wheel Landing Gear Aircraft*, ASCE 2003 Airfield Pavement Specialty Conference, Las Vegas, Nevada, USA, September 2003

ICAO (International Civil Aviation Organization), *Annex 14 - International Standards and Recommended Practices – Aerodromes, Volume I, Aerodrome Design and Operations*, 4th Edition, July 2004

ICAO (International Civil Aviation Organization), Aerodrome Design Manual - Part 3 *Pavements*, 2nd Edition, 1983

Pell, P.S., Moderators remarks, Session IV, 4th International Conference on the Structural Design of Asphalt Pavements, Ann Arbor, Michigan, August 1977

Shook, J.F., Finn, F.M., Witczak, M.W. and Monismith, C.L., *Thickness Design of Asphalt Pavements – The Asphalt Institute Method*, Fifth International Conference on the Structural Design of Asphalt Pavements, Ann Arbor, Michigan, 1982

Thompson, Marshall M, Keynote address on pavement systems, Eighth International Conference of the Bearing Capacity of Roads and Airfields, Lisbon, Portugal, June 2001