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AEROSPACE RECOMMENDED PRACTICE

ARP 597

Wheels and Brakes, Supplementary Criteria for Design Endurance - Civil Transport Aircraft

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Revised

1. SCOPE: To recommend supplementary design criteria to enhance the endurance, reliability, and dependability of transport aircraft wheels and brakes.

2. REFERENCE SPECIFICATIONS:

(a) SAE Spec. AS227 (TSO #C26)
(b) Civil Air Regulation Part 4b
(c) Mil Spec. MIL W 5013 (ASG)

3. DISCUSSIONS: The minimum requirements for the design of civil transport wheels and brakes are defined in reference (a) above. The performance requirements are defined in reference (b). Although not directly applicable, the design requirements and tests in reference (c) are also used, in modified form, to develop commercial assemblies.

These specifications have resulted in many successful production assemblies. However, new designs sometimes require a period of development and de-bugging during initial service. This does not mean that the brake and wheel would not satisfactorily and safely stop the aircraft. It does mean that during the first and/or second year of operation, a cooperative service development program between airline and brake and wheel manufacturer had to be undertaken to increase the endurance of some parts to a satisfactory service and economic level. Nuisance troubles such as cracked linings, oil seepage, cracked housings, warped discs, and fatigue failures of secondary parts occurred. Hence, it was apparent that existing development and qualification tests should be supplemented with additional tests which simulate service conditions.

The following pages suggest criteria for design endurance levels for wheels and brakes in various types of commercial air transport service. The types of service are designated by landing frequency because this parameter is fundamental.

The criteria recognizes that airline landings and take-offs are usually made at weights less than design weights. Also, that initial brake application speeds are approximately 80-100% stall speed, although touchdown may be as great as 120-125% stall speed. It also recognizes that some service landings and take-offs may involve abnormal energies which exceed the daily norm, but which are substantially below the level of an accelerate - stop condition.

Definitions of these service and abnormal energy conditions are given in Table III to VIII inclusive. It should be noted that the Tables include certain ground friction coefficients and braking time schedules. These have been estimated or obtained from field test and design data and can be adjusted as required to suit the airplane in question.

The suggested endurance criteria in Tables I and II are based on airline recommendations obtained in Air Transport Association surveys.

Since increased endurance is normally associated with increased weight, Figures A, B, and C are included in this report to illustrate weight trends.

4. TYPICAL WHEEL ENDURANCE REQUIREMENTS: The specifications in AS227 require a minimum roll test of 1000 miles, at maximum static load. This is a very short endurance test for aircraft which will be flown about 3000 hours per year. If the landing rate for the aircraft, for example, is two hours of flight per landing, the actual roll distance will be about (3000 ÷ 2) 3 = 4500 miles per year. Landing and take-off taxi distances each range from 1/2 to 2 miles for piston aircraft and thus average about 3 miles per flight. The taxi distances for large jet aircraft can average about 4 to 5 miles, but the landing rate is about 3 hours per landing. Thus, the actual roll distance for large jet and piston commercial transports can be about 4500 miles per year.

However, the 4500 mile figure will be reduced by the ratio of service wheels to service plus spare wheels. When spares are assumed to be about 15% of service wheels, the annual average wheel service will be 85% x 4500 = 3850 miles per year. Thus, if the wheel is expected to last five years, it could roll as much as 20,000 miles in that time. This mileage will not be at a static load equivalent to the design gross or landing weights because the operating weights during take-off and landing are generally less than the design values.

It is impractical to conduct a 20,000 miles roll test for many reasons. It, therefore, appears that good detail design, good wheel processing, plus a practical radial and canted roll test of reasonable duration at greater than maximum static load is the most rational method of developing a satisfactory wheel for commercial transports.

Suggested airline service endurance and dynamic service life roll test mileages for main and nose wheels are given in Table I for aircraft of different landing frequencies.

The effect of longer service life on wheel weight is estimated in Figures A and B.

Figure A: Variation of aircraft wheel assembly weight shows the weight of magnesium alloy (forged) wheel to be increased about 7% when the wheel roll distance is increased ten times (i.e.) 1000 to 10,000 miles.

Figure B: Wheel rating versus wheel weight shows a 3.7 lb. increase in wheel weight per 1000 lb. rating for forged magnesium wheels in the 4000-8000 mile roll test classification.

It should be noted that the increased roll life and associated increase in reliability can outweigh a potential payload penalty in terms of reduced maintenance, fewer spares, and improved passenger service due to fewer unscheduled removals of wheels and brakes.

5. TYPICAL BRAKE ENDURANCE REQUIREMENTS: Specification AS227 requires a minimum number of stops at design landing energy. In addition, one stop must be made at accelerate-stop energy. These are extreme values and represent peaks of energy applications. They are not representative of daily operational conditions. The airline brake, in daily service, must endure hundreds of stops at much lower energy. The energy level is lower due to lower operating weight, aerodynamic drag, auxiliary drag devices such as thrust reversers, prop jet propeller drag, headwinds, delayed braking, etc.

The energy can be abnormally high at times due to higher than normal touchdown speeds, hard braking, unsymmetrical braking due to flat tire or inoperative brake, or unsymmetrical braking due to lateral thrust differences when one or more engines are inoperative.

The energy can also be at a semi-emergency level less frequently due to an interrupted take-off. This is a take-off which is aborted before the V_1 speed is reached because of technical or operational problems.

The energy can also be increased by intermittent braking during taxi operations. Some piston engine aircraft must be taxied at relatively high engine RPM on one or more engines to maintain electrical power for radio communication, cabin lighting, instruments, etc. The airplane's speed would be excessive unless the acceleration is controlled by light constant or intermittent braking. Similarly, the use of two jet engines at high thrust on a 4 engine airplane, during taxiing, can require intermittent braking to avoid excessive taxi speed. The cumulative effect of the resultant energy on brakes, wheels and tires, after parking, is apparent.

Practically all airline stops are accomplished on brake assemblies that have been overhauled. These assemblies usually incorporate new or used friction parts, used housings, etc. The endurance of all parts should, therefore, be high. Moreover, the endurance of the friction parts (at the lower service energy levels) must satisfy an extended overhaul schedule in terms of flight hours, or landings. This endurance greatly exceeds that specified in AS227. This endurance must also not represent 100% lining wear to assure that the brakes are airworthy up to the time of overhaul.

The aforementioned airline service energy levels are defined in Tables III, IV, V, VI. Sample calculations for the determination of taxi energy are given in Table VIII.

It should be noted that the energy definitions suggest time intervals which can be used to establish the speed-torque schedules. A speed-torque schedule is required for each type endurance test (i.e.) normal service, abnormal, etc.

Suggested number of airline stops for design of brakes for transports of various landing frequency are shown in Table II. Also shown are the recommended dynamometer service life test stops to substantiate the design life. About 2% of these stops are higher energy stops. The endurance evaluation also includes the thermal effects of taxi braking and parking.

The 2% high energy stops are at the abnormal landing KE or interrupted take-off KE, which ever is greater.

As already mentioned, increased brake endurance is associated with increased brake weight. Figure C illustrates the variation in estimated brake weight in percent, versus normal service stops. For example, 50 normal service stops is equivalent to a 2.1% increase in brake weight.

6. TYPICAL WHEEL ENDURANCE TEST: The wheel endurance roll tests suggested in Table I should be run on a dynamometer, and should be independent of the brake development tests.

7. TYPICAL BRAKE ENDURANCE TEST:

(a) The brake and wheel shall be mounted to simulate the natural frequency and elasticity of the proposed installation.

(b) The natural frequency, damping, and amplitude of the landing gear system shall be simulated and controlled within the limits specified by the airplane manufacturer.

(c) The dynamics of the wheel brake landing gear system should be analyzed and substantiated to the satisfaction of the airplane manufacturer.

(d) In addition to other information, the following data should be recorded during each stop; or less frequently as specified by the airplane manufacturer. Brake pressure, brake displacement, brake torque, dynamometer speed, brake temperature, tire bead seat temperature, axle wall temperature, and axle flange temperature.

(e) A brake endurance test should be run on a dynamometer similar to the procedure described in Mil. Spec. 5013. The stops should conform with the speed torque program established by the airplane manufacturer. The brake friction parts shall be new when the test is started. The parts shall not be replaced during the test.

(f) If an overhauled production brake is used for these tests, its previous time and test history must be known.

(g) The brake assembly and friction parts must remain serviceable throughout the test and be capable of further endurance to the limit of its design stops, including reserve stops of 10%.

(h) The thickness of all wearing friction materials must be carefully measured and recorded prior to the test.

(i) Consistent with note (c) of Table II, some of the brake stops shall be run with actuation pressure making one complete on-off cycle per second down to 30 knots; then constant pressure to 0 knots. The pressure "on" part of the cycle shall not be less than 0.5 seconds. Brake torque during each cycle shall be diminished to a value no greater than 10% of the average torque required to develop a deceleration rate of 10 ft./sec.^{2}. No deceleration rate is specified for the cyclic pressure stops. The maximum pressure used for the cyclic pressure stops should equal the average pressure required during the last prior non-cycling pressure stop run to the same condition.

8. RECOMMENDED DESIGN FEATURES: The following features should be incorporated in airline wheels and brakes to facilitate maintenance and stores control, or extend the service life of the parts.

A. Wheels

1. Incorporate permanent part and serial number on each wheel half; do not create stress raisers by stamping.

2. Install identification plate or pad to record modification or date "in service".

3. Install provisions for dynamically and statically balancing wheel and tire assembly.

4. Impregnation of cast wheels shall be resistant to paint stripping solutions and Skydrol.

5. Install standard bearings and cups.

6. Provide adequate material in hub to allow for rework to install oversize bearing cups or bushings.

7. Design tubeless wheel seal areas to protect them from handling damage.

8. Use aircraft standard (AN, NS, or NAS) hardware wherever possible.

9. Design wheels so that tubeless tire type wheels can be converted to tube wheels, contingent on airline experience with tubeless tires and wheels.

10. Forged wheels shall be adequately protected from corrosion with a finish which can be easily stripped to facilitate inspections, if necessary.

B. Brakes

1. Design for minimum disassembly to replace frictional components.

2. Provide adequate material in piston cylinders to facilitate repair using oversized or replaceable sleeves or pistons.

3. Provide automatic adjustment or simple manual adjustment which is accessible without removal of wheel.

4. Avoid high heat treat materials.

5. Avoid cad plating on parts exposed to temperature exceeding 500°F, to prevent cadmium stress alloying of parts which reduces strength.

6. Use aircraft standard (AN, MS or NAS) hardware wherever possible.

7. Provide readily visible and usable lining wear indicator.

8. Incorporate permanent serial number and part number identification; do not create stress raisers by stamping.

9. Design for minimum fluid displacement from brake "off" to "on".

10. Design to minimize deflections under maximum operating brake pressure.

11. Bleeder valve should be readily accessible and designed so that it can be turned on and off with the bleeder hose installed.

12. Bolts requiring torque specifications shall be large enough to permit a broad tolerance in torque during installation or assembly. This is especially required for bolts which must be torqued at locations where torque wrenches are not readily available.

TABLE I

WHEEL ROLL LIFE CRITERIA - DYNAMOMETER TEST

Landing Frequency Flight-Hrs/Ldg.	Nom. Airline T.O. Wt. % Design GTOW	Airplane Type & Range	Recommended Airline Miles for Design	* Recommended Dyn. Svc. Life Test for Main & Nose Wheels in Miles
0.70 to 1.4	100%	Piston Engine Short	20,000	5,000
1.4 to 2.8	85%	Piston Engine Intermediate	15,000	4,000
2.8 to 4.0	90%	Piston Engine Long-Domestic	15,000	4,000
4.0 to 5.5	100%	Piston Engine Long-Intl.	12,000	3,000
0.70 to 1.6	95%	Propjet and Jet - Short	20,000	5,000
1.6 to 2.0	87%	Propjet & Jet Intermediate	15,000	4,000
2.0 to 2.7	86%	Jet Long - Domestic	15,000	4,000
3.0 to 5.5	86%	Jet Long - Intl.	12,000	3,000

* Perform Dynamometer Service Life Roll Test to Chart Conditions Below.

Type of Roll	Load	Degrees of Cant	% of Total Mileage	
			Main Whl.	Nose Whl.
Straight	$S_L \times Y_1$	0°	90%	65%
Straight	$D_L \times Y_2$	0°	---	25%
Canted - Inboard	$S_L \times Y_3$	$X^{\circ}{}_1$	5%	5%
Canted - Outboard	$S_L \times Y_4$	$X^{\circ}{}_2$	5%	5%

(1) Overload factors Y and degrees X to be established by airframe and wheel manufacturers, based on analysis of aircraft's ground operational loads.

(2) Overload factors Y must be 1 (one) or greater.

(3) S_L - Load per wheel assigned by airframe manufacturer, based on aircraft maximum gross T.O. weight condition.

(4) D_L - Dynamic load per wheel assigned by airframe manufacturer, and should equal or exceed the maximum radial reaction to which the wheel is subjected as a result of aircraft deceleration rates.

TABLE II
BRAKE LIFE CRITERIA - DYNAMOMETER STOPS

Landing Frequency Flight-Hours/ Landing	Nom. Landing Weight: % Design	Airplane Type and Range	Minimum Number Airline Stops Required for Design (A)	Recommended Dynamometer Service Life Test (E) 1 Stops/ Table III (A)	2 Stops@ 50% KE of Table IV	3 Stops/Table V or VI (D)
0.70 to 1.4	96%	Piston Engine Short	600	264	528	6
1.4 to 2.8	94%	Piston Engine Intermediate	500	220	440	5
2.8 to 4.0	94%	Piston Engine Long-Domestic	450	176	352	4
4.0 to 5.5	94%	Piston Engine Long - Intl.	450	176	352	4
0.70 to 1.6	95%	Propjet - Short	600	264	528	6
1.6 to 4.0	94%	Propjet - Inter. & Long	500	220	440	5
0.70 to 1.6	96%	Jet Short	600	264	528	6
1.6 to 2.0	94%	Jet Intermediate	500	220	440	5
2.0 to 3.5	94%	Jet Long Dom & Intl.	450	176	352	4

NOTES:

(A) Based on reduction of dynamometer service life test data, the friction parts shall have 60% of their service life remaining after completion of the service life test. This includes the 10% reserve required of the brake design (e.g.) 264 stops equals (600 + 10% x 600) (100%-60%).

(B) Test Cycle
One stop per Column No. (1) and without cooling period, 1 stop per Column No. (2), Cool brake to ambient. Run 1 stop/Column No. (2) and cool brake to ambient. Re-run complete cycle. Follow each 44 cycles with 1 stop per Column No. (3).

(C) 75% of stops per Column No. (1) will be run with a brake pressure needed to meet deceleration requirements. The remaining stops will be run at cyclic pressure per paragraph 8_i.

(D) Design and test for K.E. of either Table V or Table VI, whichever is greater.

(E) Tests do not supersede those specified in AS227 which require an ultimate RTO test.

TABLE III
DEFINITION OF AIRLINE SERVICE LANDING
(For Calculation of Normal Kinetic Energy)

Listed below are factors which must be known or assumed in order to permit the calculation of brake energy (as differentiated from an estimate).

The numerical values shown below are suggested as being typical; however, they will not necessarily be rational for all aircraft types. Items 5, 6, and 7 are particularly significant. The designer should examine each assumption and decide whether a different figure would be appropriate.

1. Airport Conditions:

   A. Airport altitude 1000 ft.
   B. Air temperature: Standard (55°F) plus 20° = 75°F.
   C. Density altitude corresponding to above is 2250 ft. and density ratio is 0.935.
   D. Wind: 5 kts. headwind
   E. Runway slope: zero

2. Landing Weights as specified in Table II.

3. Wing Flaps:

   A. In normal landing position at touchdown.
   B. May be assumed to be retracted after touchdown, if this is to be standard for the airplane involved. However, speed at initiation of flap retraction shall not be greater than 0.9 of stalling speed.

4. Spoilers and/or speed brakes:

   A. In normal landing position at touchdown.
   B. After touchdown, position as per standard procedure for aircraft.

5. Touchdown air speeds: 120% of power-off stall speed with above conditions.

6. Powerplant Controls:

   A. All powerplants operating normally at touchdown.
   B. Two seconds after touchdown, powerplant controls placed in normal operating position for landing roll-out. See note below.
   C. Powerplant controls remain in above position until ground-speed reduces to 30 kts.
   D. At 30 kts., powerplant controls changed to normal taxi conditions.

7. Brake Controls:

   A. Initial brake pressure applied 3 secs. after touchdown.
   B. Initial brake pressure sufficient to produce a tire-to-ground coefficient of friction = 0.25.
   C. Brake pressure changed during roll-out as required to maintain a tire-to-ground coefficient of friction = 0.25 at all speeds.

D. However, the ground coefficient of friction at any speed need not be assumed higher than as necessary to produce a deceleration rate of $10f_{ps}^2$ including aerodynamic drag and powerplant effects.
E. All brakes operating equally.
F. Brake pressure released at 30 kts. Landing roll-out assumed concluded at this point, and taxi phase begins.

NOTE: Credit shall be taken for aerodynamic drag and negative/or reverse thrust after touchdown and before taxi. Normal reverse thrust data shall be determined by the aircraft manufacturer and clearly stated in the analysis.

TABLE IV
DEFINITION OF NORMAL AIRLINE TAXIING PRIOR TO TAKE-OFF OR AFTER LANDING
(For Calculation of Taxi Kinetic Energy)

Listed below are factors which must be known or assumed in order to permit the calculation of brake energy (as differentiated from an estimate).

The numerical values shown below are suggested as being typical; however, they will not necessarily be rational for all aircraft types. Items 2, 4, and 7 are particularly significant. The designer should examine each assumption and decide whether a different figure would be appropriate.

1. Weight: Average between max. design take-off weight and max. design landing weight, adjusted per Table I and II data.

2. Taxi Speed: Oscillates between V kts. and V-3.79 kts. (obtain V from airplane manufacturer). V represents approx. taxi speed. The 3.79 kts. speed decrement is derived from the braking assumption of Para. 5 and 6 below. See typical calculations in Table VIII.

3. Aerodynamic drag: Assume zero.

4. Powerplant thrust: Equal to aerodynamic drag plus tire rolling resistance plus excess thrust sufficient to recover in ten seconds of time, the speed lost in Para. 2. More thrust and less time shall be assumed if known to be typical.

5. Brake pressure: As required to produce deceleration of $3.2f_{ps}^2$ while overcoming excess thrust in Para. 4.

6. Brake application time: 2 seconds.

7. Number of applications: 10 applications per flight consisting of five before take-off and five after landing.

8. In addition to the above application, the airplane must be stopped twice per flight from taxiing speed, per Item 8E and 8F.

   A. Assume average weight as in Para. 1.
   B. Assume powerplant thrust is zero as is aerodynamic drag.

C. Assume initial speed is V kts., resulting from the last ten seconds acceleration with excess thrust.
D. Assume brake pressure as required to stop airplane at an average rate of $5f_{ps}^2$.
E. The number of complete stops after landing shall be assumed to be one.
F. A complete stop just before take-off shall be assumed to occur.

9. Airport conditions:

A. Airport altitude 1000 ft.
B. Air Temp. - standard plus 20°F = 75°F.
C. Wind: zero.
D. Runway slope: zero.

NOTE: The above assumptions are based on the premise that the only reason for using brakes during taxiing is to prevent excessive ground speed. Excessive ground speed, in turn, is due to powerplant thrust level in excess of the sum of tire rolling resistance, wheel bearing drag and aerodynamic drag at some lower speed. This excess will cause acceleration from the lower speed to some higher speed at which equilibrium will occur.

TABLE V
DEFINITION OF ABNORMAL LANDING
(For Calculation of Abnormal Kinetic Energy)

Listed below are factors which must be known or assumed in order to permit the calculation of brake energy (as differentiated from an estimate).

The numerical values shown below are suggested as being typical; however, they will not necessarily be rational for all aircraft types. Items 5, 6, and 7 are particularly significant. The designer should examine each assumption and decide whether a different figure would be appropriate.

1. Airport conditions:

A. Airport altitude 3000 ft.
B. Air Temp. = std. plus 40° = 88°F. Dens. alt. = 5500 ft. Dens. ratio = .848
C. Winds: zero
D. Runway slope: zero.

2. Landing weight: As specified in Table II.

3. Wing Flaps:

A. In normal landing position after touchdown.
B. May be assumed to be retracted after touchdown, if this is to be standard procedure for the type. However, speed at initiation of flap retraction shall not be greater than 0.9 of stalling speed.

4. Spoilers and/or Speed Brakes:

A. In normal landing position at touchdown.
B. After touchdown, position per standard procedure for aircraft.

5. Touchdown air speed: 125% of power off stall speed with above conditions.

6. Powerplant Controls:

   A. One engine out before landing and negative drag or reverse thrust not useable from this engine; plus loss of available thrust from other symmetrical engine.
   B. OR: In the case of a propjet, one engine producing excessive forward thrust (e.g.) (flight idle prop position) with remaining engines producing negative thrust, but not reverse thrust, and the resulting yaw being counteracted by brakes and rudder.
   C. 10 secs. after touchdown powerplant controls placed in position to correct the yaw induced per (A) or (B) for landing roll-out.
   D. Powerplant controls remain in above position until ground speed reduces to 30 kts.

7. Brake Controls:

   A. Initial brake pressure applied 3 secs. after touchdown.
   B. Initial brake pressure sufficient to produce a tire-to-ground coefficient of friction = 0.30.
   C. Brake pressure changed during roll-out as required to maintain a tire-to-ground coefficient of friction = 0.30 at all speeds.
   D. However, the ground coefficient of friction at any speed need not be assumed higher than as necessary to produce a deceleration rate of $12 f_{ps}^2$, including aerodynamic drag and powerplant effect.
   E. Some tires blown out making half of the brakes on one gear ineffective, contingent on the landing assumed.
   F. Brake pressure released at 30 kts. Landing roll-out assumed concluded at this point, and taxi phase begins.

<u>NOTE</u>: Assumed situation would be propjet landing wherein one prop stayed in flight idle unexpectedly and the yaw at the touchdown was counteracted by rudder and one set of brakes which blew one tire. Pilot would "cut" all engines, use brakes to stop and possibly resort to reverse on remaining good engine-if he isolated bad one meanwhile.

TABLE VI
DEFINITION OF INTERRUPTED TAKE-OFF CONDITION
(FOR CALCULATION OF I.T.O. KINETIC ENERGY)

Listed below are factors which must be known or assumed in order to permit the calculation of brake energy (as differentiated from an estimate).

The numerical values shown below are suggested as being typical; however, they will not necessarily be rational for all aircraft types. Items 5, 6, and 7 are particularly significant. The designer should examine each assumption and decide whether a different figure would be appropriate.

1. Airport Conditions:

   A. Airport altitude 1000 ft.
   B. Air temp: std. (55°F) plus 20° = 75°F.

C. Density altitude corresponding to above is 2250 ft. and density ratio is 0.935.
D. Winds: 5 kts. headwind.
E. Runway slope: zero.

2. Take-off weight as specified in Table I.

3. Wing Flaps:

   A. In take-off position.

4. Spoilers and/or Speed Brakes:

   A. Use per standard procedure (probably actuated 2 secs. after max. ground speed reached).

5. Ground Speed: 85 kts. or 75% V_1 whichever is greater.

6. Power Plant Controls:

   A. All in idle position.
   B. Controls remain in idle position until speed is reduced to 30 kts.

7. Brake Controls:

   A. Initial brake pressure applied when max. ground speed attained.
   B. Initial brake pressure sufficient to produce tire-to-ground coefficient of friction = 0.30.
   C. Brake pressure changed as required during roll-out to maintain a tire-to-ground coefficient of friction of 0.30 at all speeds. Assume continuous braking, unless the airplane is equipped with an automatic skid control system in which case, the max. coefficient achievable and intermittent characteristics of the braking system should be accounted for.
   D. The ground coefficient at any speed need not be assumed higher than necessary to produce a peak deceleration of 12 ft./sec./sec., including aerodynamics drag and powerplant effects.
   E. All brakes operating equally.
   F. Brake pressure released at 10 kts. and begin taxi phase.

<u>NOTE</u>: Interrupted take-offs occur due to (1) fire alarm system malfunction during the high power regime, (2) heat effect on the fire alarm system due to leaking jet bleed air duct, (3) poor take-off acceleration, (4) traffic problem, (5) other operational or maintenance effects. Such instances might occur for 1-2% of all flights.

TABLE VII-1 SHEET (a)
EXAMPLE - AIRLINE SERVICE LANDING BRAKE ENERGY CALCULATIONS
(Refer TABLES VII-2, 3, 4)

1	2	3	4	5	6	7	8	9
V_A	V_G	V_G	L	W-L	F_B	F_D	$F_{P.P.}$	F_T
Air Speed	Ground Speed	Ground Speed	Wing Lift = $3.67V_A^2$	95000 lbs. - Wing Lift	Braking Force (See Table VII -2)	Airframe Drag = $.551\ V_A^2$	Power Plant Drag	Total Decelerating Force
KTS	KTS	FPS	LBS	LBS	LBS	LBS	LBS	LBS
113.7	108.7	183.6	47,400	47,600	0	7,100	6,000 Fwd	1,100
113.2	108.2	182.8	47,000	48,000	0	7,050	6,000 Fwd	1,050
108.0	103.0	174.0	42,800	52,200	9,080	6,420	14,000	29,500
102.0	97.0	164.0	38,200	56,800	9,780	5,720	14,000	29,500 lbs. Total Decel. force required to attain 10 fps^2.
97.0	92.0	155.5	34,500	60,500	10,320	5,180	14,000	
90.0	85.0	143.7	33,400	61,600	11,440	4,460	13,600	
80.0	75.0	126.8	23,500	71,500	12,780	3,520	13,200	
70.0	65.0	109.9	18,000	77,000	14,000	2,700	12,800	
60.0	55.0	93.0	13,200	81,800	15,120	1,980	12,400	
50.0	45.0	76.1	9,150	85,850	16,120	1,380	12,000	
40.0	35.0	59.2	5,860	89,140	17,020	880	11,600	
35.0	30.0	50.7	4,500	90,500	17,425	675	11,400	29,500

Start Taxi Phase Table IV

TABLE VII-1 - SHEET (b)
EXAMPLE - AIRLINE SERVICE LANDING BRAKE ENERGY CALCULATIONS
(Refer TABLES VII-2, 3, 4)

10	11	12	13	14	15	16	17	18	
∂	Δt	t	ΔS	S	KE_B	KE_D	$KE_{P.P.}$	μ	μ'
Rate of Deceleration $= .000339F_T$	Time Increment $= \frac{\Delta V_G}{\partial_{AVG}}$	Elapsed Time $= \Sigma(\Delta t)$	Distance Increment $= \Delta t \times V_{G_{AVG}}$	Accumulated Distance $= \Sigma(\Delta S)$	Brake Energy Increment $= \Delta S \times F_{BAVG}$	Drag Energy Increment $= \Delta S \times F_{DAVG}$	Power Plant Energy Increment $= \Delta S \times F_{P.P.AVG}$	Braking Coefficient	
FPS^2	SEC	SEC	FT	FT	FT.LBS.	FT.LBS.	FT.LBS.	Table VII-3	
0.37	-	0.00	-	0	-	-	-	0	0
	2.16	-	396	-	0	2,800,000	2,370,000	-	-
0.37	-	2.16	-	396	-	-	-	0	0
	1.70	-	303	-	1,375,000	2,040,000	1,212,000	-	-
10.00	-	3.86	-	699	-	-	-	.204	.174
	1.00	-	169	-	1,595,000	1,028,000	2,365,000	-	-
	-	4.86	-	818	-	-	-	.202	.172
	.85	-	136	-	1,367,000	741,000	1,903,000	-	-
$10fps^2$ assumed as constant rate of deceleration	-	5.71	-	1,004	-	-	-	.201	.171
	1.18	-	176	-	1,915,000	849,000	2,430,000	-	-
	-	6.89	-	1,180	-	-	-	.219	.186
	1.69	-	228	-	2,760,000	916,000	3,055,000	-	-
	-	8.58	-	1,408	-	-	-	.210	.179
	1.69	-	200	-	2,680,000	622,000	2,600,000	-	-
	-	10.27	-	1,608	-	-	-	.214	.182
	1.69	-	172	-	2,500,000	402,000	2,167,000	-	-
	-	11.96	-	1,780	-	-	-	.218	.185
	1.69	-	143	-	2,235,000	240,000	1,745,000	-	-
	-	13.65	-	1,923	-	-	-	.221	.188
	1.69	-	114	-	1,890,000	129,000	1,346,000	-	-
	-	15.34	-	2,037	-	-	-	.226	.191
	.85	-	47	-	810,000	37,000	540,000	-	-
10.00	-	16.19	-	2,084	-	-	-	.228	.193
								-	-
TOTALS (From touchdown to 30 kts.) →		16.19 Sec.		2,084 Ft.	19,127,000 Ft. Lbs.	9,798,000 Ft. Lbs.	16,993,000 Ft. Lbs.		

↑ TOTAL BRAKE K.E.

TABLE VII - 2
SAMPLE CALCULATIONS FOR AIRLINE SERVICE LANDING ENERGY
(per Table III Definition)

Refer to Table VII-1 Data Sheets -a and b

Weight: 95% of max. design landing weight
= 0.95 x 100,000 = 95,000 lbs.

Airport altitude: 1000 ft.

Ambient air temperature: 75°F.

Density ratio: 0.935

Wind: 5 kts. headwind

Flaps: Landing position

Power Plants: All operating normally and controls operated in normal manner for the type.

Wing-Area: 1450 sq. ft.

$CL_{max.} = 2.30$

$V_{stall} = \sqrt{\frac{295 \times 95000}{1450 \times 2.30 \times .935}} = 94.7$ kts. airspeed

$V_{touchdown} = 1.20 \times 94.7 = 113.7$ kts. airspeed = 108.7 kts. groundspeed

$CL_{run} = 0.80$

Wing lift = $0.80 \times 0.935 \times 1450 \times V_A^2/295 = 3.67\ V_A^2$.

$CD_{run} = 0.12$

Airframe drag = $0.12 \times 0.935 \times 1450 = V_A^2/295 = 0.551 V_A^2$.

TABLE VII - 3

Powerplant thrust is assumed to vary as follows: (Values are totals for all engines)

(a) 6000 lbs. forward thrust at touchdown and for about 2 seconds thereafter.

(b) Linear transition from (a) to (c).

(c) 14,000 lbs. max. reverse thrust attained about 4 secs. after touchdown.

(d) Linear decay towards 10,000 lbs. at zero speed.

Brake application is assumed as follows:

(a) Brakes start on sometime after about 2 secs.

(b) Brakes are well on at 3.86 secs.

(c) A braking coefficient of 0.25, in combination with drag and reverse thrust, would produce much more than the arbitrary maximum deceleration of 10fps^2. Therefore, braking force at any speed is assumed to be just enough to yield exactly 10fps^2 deceleration due to all forces. This requires gradually increasing brake pressure during the stop, but the coefficient never exceeds 0.2.

(d) The resulting braking coefficients are listed in the last column, and are calculated as $\mu' = F_B/(W-L)$.

(e) The actual tire coefficients of friction are listed in the next-to-last column, identified as μ . This is calculated separately, using the listed values of μ' , the formula of sheet 4, and an assumed wheel-base geometry for the hypothetical airplane.

SUMMARY OF RESULTS, down to 30.0 kts.

Brake energy	=	19,127,000 ft. lbs.
Drag energy	=	9,798,000 ft. lbs.
Powerplant energy	=	16,993,000 ft. lbs.
Total energy	=	45,918,000 ft. lbs.
Airplane energy	=	45,900,000 ft. lbs.
Ground roll	=	2084 ft.
Time	=	16.19 sec.

TABLE VII - 4

BRAKING COEFFICIENTS

Coefficient μ is true tire-to-ground friction coefficient, defined as:

$$\mu = \frac{\text{Braking force}}{\text{wt. - lift - nose wheel load}}$$

for aircraft not equipped with nose-wheel brakes.

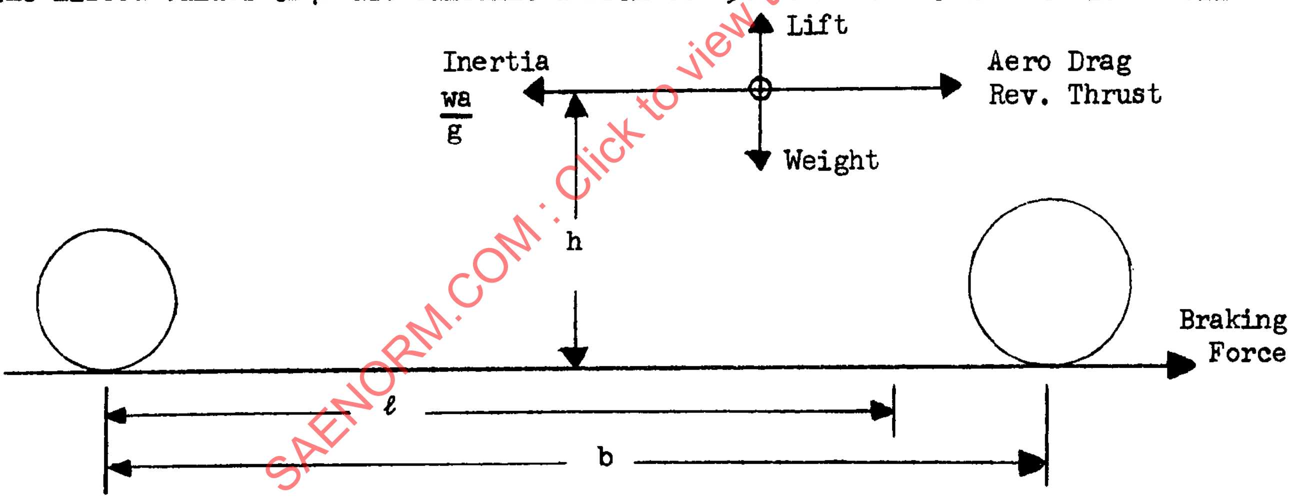
Coefficient μ' is apparent braking coefficient, defined as:

$$\mu' = \frac{\text{braking force}}{\text{wt. - lift}}$$

For airplanes not equipped with nose-wheel brakes, the two coefficients are related as follows:

$$\mu' = \frac{\mu \ell}{\mu h + b} \qquad \mu = \frac{\mu' b}{\ell - \mu' h}$$

For the hypothetical aircraft design represented by Table VII, which does not have nose-wheel brakes, the geometry results in the listed differences between μ and μ'. The listed values of μ' are calculated from the 5th and 6th columns of Table VII-1.



For aircraft equipped with nose-wheel brakes,

$$\mu = \mu' = \frac{\text{total braking force}}{\text{wt. - lift}}$$

TABLE VIII
ANALYSIS OF TAXI CONDITIONS
FOR HYPOTHETICAL AIRPLANE

Let W = airplane weight, lbs.
B = braking force, lbs., including rolling resistance.
P = excess powerplant thrust, lbs., over and above aerodynamic drag and rolling resistance.
a = rate of acceleration or deceleration, fps^2.
g = 32.2 fps^2.
t = time, sec.
S = distance, ft.
V_B = speed before decelerating, fps (To be established rationally by aircraft manufacturer).
V_A = speed after decelerating, fps (Arbitrarily defined as 3.79 kts. less than V_B.)

Deceleration Period

By arbitrary definition, $a = -3.2\ fps^2 = -0.10g$.
Hence $B = 0.10W + P$ (P as determined below)
$= 0.12W$ (acting backward) (including rolling resistance)
$t = 2$ sec. by arbitrary definition
$V_A = V_B - at = V_B - (3.2x2) = V_B - 6.4$ fps
$= V_B - 3.79$ kts.

Acceleration Period

$$a = (V_B - V_A)/10 = \left[V_B - (V_B - 6.4)\right]/10 = 0.64\ fps^2$$

$P = Wa/g = 0.64W/32.2 = 0.02W$ (excess) $= 0.04W$ (total required to balance rolling resistance and accelerate airplane).
B = rolling resistance only, assumed equal to 0.02W.
(numerically same as excess thrust, by coincidence only)
t = 10 sec.
$V_B = V_A + at = (V_B - 6.4) + (0.64 \times 10) = V_B$.

Typical Taxi Calculations

$W = (115000 + 85000)/2 = 100{,}000$ lbs. average weight
No. of wheels = 4 (2 per gear)
V_B = 39.0 mph = 57.1 fps = 33.79 kts. (assumed to be typical but may vary).