New Designs for Commercial Aircraft Wheels and Brakes

George E. Stanton*
The Bendix Corporation, South Bend, Ind.

In high-performance aircraft stringent demands are placed on performance and reliability of all components, in particular the landing gear system. Brake systems have progressed from the organic, lined, automotive-type shoe brakes, used on DC-3 aircraft, to the high-performance, multiple-disk, ceramic-metallic brakes predominately used on present-day jet aircraft. Brake design energies have increased more than 50-fold during the past three decades. Cost of operation of the commercial aircraft wheel and brake has been and will be the dominant factor in the creation of effective designs for commercial wheel and brake equipment.

Introduction

THE aerodynamically clean jet transport of today lands at speeds of yesterday's propeller-driven transports. Landing speeds of current jet transports may be as high as 176 mph. The limited lengths of existing runways impose severe performance requirements on jet-transport brakes.

The minimum runway length for which a commercial jet is certified is based on the total distance required for acceleration to takeoff speed at maximum gross weight, followed by a maximum-effort brake stop. This stop is commonly referred to as the rejected takeoff condition (RTO) and is made without use of auxiliary braking devices such as reverse thrust or drag parachutes. The high takeoff speeds of jet aircraft, combined with restrict or short field requirements, demand that the brakes develop high torques at high energy-transfer rates, to provide the necessary deceleration.

The deceleration requirements for some jets are as high as 16 ft/sec/sec. Improved antiskid controls and improved aerodynamic design, which provide increased vertical loads on the braked wheels at high speed, are recent developments.

The maximum gross weight of jet transports has increased with introduction of new models. This, in conjunction with the necessary high deceleration rates, has resulted in vastly increased brake kinetic energy absorption requirements.

In the past ten years, as shown in Fig. 1, a 50% increase in jet brake RTO kinetic energy has resulted. The volume available to house the brake has not been increased correspondingly. In fact, because of the requirements for improved aerodynamic design, space for packaging the brakes is at a premium.

The original Douglas DC-8 brake was designed in 1957 for a 36,900,000 ft-lb RTO kinetic energy requirement. In 1967 the requirements for the 63 series Douglas DC-8 have increased to 57,000,000 ft-lb although the space in which to package the brake is essentially the same. A 44 × 16 main wheel size has been used on all models of this aircraft.

Another stringent service requirement is imposed on brakes of jets. During normal service operation, the jet aircraft brake absorbs 40 to 60% of the design normal kinetic energy. This is required in addition to the drag provided by reverse thrust devices. The piston-engine transport, with the greater deceleration provided by reverse pitch propellers, required (by comparison) that the brakes absorb only 30 to 40% of the design normal energy.

Improvements in airframes, brake antiskid controls, and the use of high-heat-treated steels (with their greater flexibility) for landing gear shock struts have made further demands on the aircraft wheel and brake industry for continued product improvements.

Commercial Wheel and Brake Design

Commercial transports are operated to earn a profit. This requires that manufacturers of equipment for these aircraft adhere to cost-conscious conservative design approaches. The objectives are simplicity, reliability, and maintainability commensurate with cost and weight.

Wheel Design

I would like to review several features of a recently developed aircraft wheel and brake which illustrate the Bendix approach to providing designs that satisfy the many requirements of the modern aircraft wheel and brake. The example I will use is the wheel and brake designed for the long-range Douglas DC-8F Jet Trader aircraft. The landing gear for this aircraft consists of two main wheel trucks, with four main wheels per truck. Each main wheel has one brake housed in an inboard wheel cavity. (The term "inboard" refers to the location of the wheel.) Each brake is attached to the truck by a brake compensating link which is required because the gear is a bogie-type truck design. The brake is supported by bronze bushings located on the main landing gear axles.

The wheel is of split-type forged aluminum alloy construction and is capable of supporting 1580 times its own weight. The entire wheel structure is supported on the axle by standard tapered roller bearings.

Rotor drive keys attached to the wheel engage the brake disk's rotating elements. These components are of forged steel alloy and are heat-treated to provide a hard, wear-resistant, driving surface. A continuous laminated stainless-steel heat shield, mounted between the brake and the wheel, increases tire life and protects the wheel from radiated and

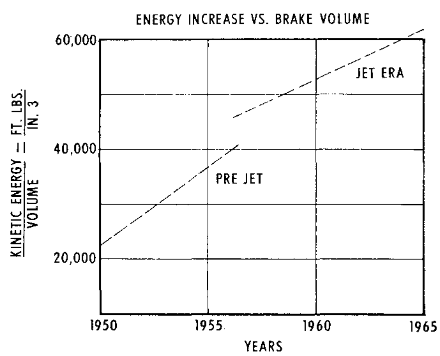

Fig. 1 Energy increase vs brake volume.

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* Chief Engineer, Aircraft Wheel and Brake Engineering, Energy Controls Division.

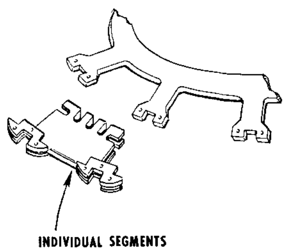


Fig. 2 Typical rotor assembly construction.

convected heat by effectively reducing the transfer of heat from the brake elements to the wheel structure.

A thermally sensitive, tire pressure-release device is provided in the pressure wall of the wheel structure. These devices, commonly called fuse plugs, are designed to completely release the contained air pressure from a tubeless tire/wheel assembly when absorbed heat reaches a predetermined level. The temperature limit is established as that which is practical and safe for the conditions under which the wheel and brake operate. The objective is to prevent tire rupture or wheel explosion which could seriously jeopardize aircraft operation or endanger personnel.

Natural convective cooling is also employed to improve the effective utilization of brake capabilities over a broad range of operating conditions by providing ventilating openings in the cone or disk sections of the main wheel. The design objective is to provide a maximum amount of open area without sacrificing structural integrity. These openings may be forged or machined open areas. It has been our experience that the most efficient opening configuration is of a noncircular shape. Photostress analyses and bonded wire strain-gage techniques are used effectively to evaluate structural alternatives during the design phase.

Brake Design

The modern aircraft brake assembly is a most interesting mechanical device. It performs the herculean task of converting aircraft kinetic energy to temporarily stored heat energy with great efficiency and reliability.

A total of 40,500 instantaneous horsepower is developed by the eight brake assemblies on the DC-8F Jet Trader during a rejected takeoff stop. The rejected takeoff demonstration requires that these brakes bring a 163-ton DC-8F, traveling at a velocity of 178 mph, to a stop in less than 30 sec from the time the brakes are applied.

The kinetic energy absorbed by the brakes totals 250 million ft-lb of energy. This is equivalent to stopping simultaneously 833 new four-door passenger cars from a velocity of 60 mph.

In order to define terms and to highlight the functions required of the brake, I'd like to discuss specific features of the aircraft disk brake used on the Jet Trader. The brake is basically a dry friction device. It consists of a multidisk arrangement of alternate static and rotating elements which are forced together by hydraulic pressure during braking.

The rotating elements (which are driven by the wheel) are referred to as rotors; the static elements (attached to the gear through the brake compensating links) as stators. In this design, the brake lining is attached to the static elements. The heat absorption capability is obtained by proper selection of material and mass distribution within the brake. The heat of the brake is the mass composed of the rotors, stators, and lining referred to as the "heat sink." Therefore, by necessity the brake design starts with these components.

Considerable development has been accomplished to obtain a heat sink that will withstand high thermal shock, have favorable strength and toughness at elevated temperatures, and provide high wear resistance over a wide temperature range. One of the best structural materials determined from this development effort is an alloy steel conforming to AMS 6302. This material, which can be heat-treated, has a maximum usable operating temperature of over 2000°F, and is widely used by brake manufacturers for both rotor and stator elements. However, the disk size and shape, when combined with the wide operating temperature range to which multirotor brakes are subjected, has been found to cause this material to distort and shrink in service. Distortion results in loss of lateral clearance between the rotating and static elements of the brake and leads to self-destructive brake drag and rapid deterioration of the braking surfaces.

Shrinkage of the elements results in difficulty in actuating the plates freely, thus producing dual problems of loss of braking capability and a requirement for early replacement of the braking components. Control of distortion and shrinkage, therefore, is a major consideration in the design of aircraft brakes.

The most effective solution obtained to date is to segment the wear surfaces. Most Bendix designs incorporate rotors comprised of segments which are attached to and driven by a member called a spider. (See Fig. 2.) Each segment is thus free to expand and contract independently of the supporting or driving structure. Segmentation thus permits free lateral movement of the plates and insures freedom from the undesirable distortion effects associated with thermally stressed solid disks. As demands on the brakes increase each year, dependence on design approaches that allow distortion to occur without impairment of brake performance becomes more and more of a necessity.

The brake lining is a powder metallurgy product developed specifically for aircraft brake use. Each lining compound is tested exhaustively to determine that the desired combination of torque and wear resistance has been obtained.

Jet aircraft brakes require use of ceramic-metallic lining materials to withstand the very high heat-sink loadings (KE/lb of heat sink) and extreme surface temperatures which result during braking operations. A successful segmentation approach utilized on the lined elements provides replaceable lining segmets riveted to a full-circle, heat-treated steel stator as shown in Fig. 3. This design also permits use of refractory friction materials which do not readily form metallurgical bonds with steel. The stator material can be heat-treated to provide desired structural properties.

There are two major brake components aside from the brake heat sink which deserve mention; they are the brake carrier and the integral torque tube-backing plate. The carrier houses the hydraulic actuating pistons and automatic wear adjustment return mechanisms. Structurally, the carrier is designed to resist the axial loads produced by the brake pistons during brake application.

In some designs the carrier is also a structural link that transmits brake torque to a shock strut; this is accomplished through the brake compensator links on bogie-type gears. The carrier may be cast or forged. Forged aluminum is rated very highly, as it has very good strength, fatigue properties, and corrosion resistance.

The torque tube-backing plate is a dual-purpose structure, which resists both the torque developed in the static elements

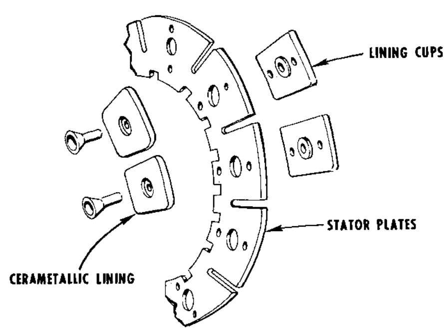


Fig. 3 Typical stator assembly construction

and the axial forces developed by the actuating pistons. It is usually made of steel (such as AMS 6202) since it must be torsionally stiff, have a minimum of axial deflection, and be strong enough to transfer the developed brake torque to the attachment points.

Cost of Operation

Published operation costs for landing gear wheels, brakes, and tires highlight the importance of these items in achieving low operating costs. Several years of jet transport operations have demonstrated adequately that cost analyses for landing gear components by number of landings are more meaningful than analyses based on the number of flying hours. These analyses have also demonstrated that tire replacements accounted for half of all landing gear maintenance costs.

The cost per landing for wheels accounted for 7.43% of landing gear maintenance costs while brakes accounted for 19.8%.[1]

Control of Cost of Operation

Each phase of the operation and maintenance of wheel and brake equipment provides an area where cost controls can be exercised. Wheel costs are primarily due to depleted fatigue life. Timely retirement of wheels by a planned progressive inspection program is recommended to obtain minimum costs. To aid in establishing the inspection program, the use of frequency techniques commonly employed to establish reliability criteria may be beneficial. Their accuracy depends, of course, on the accuracy of the raw data from which the MTBF's (mean time between failures) are established.

The data are presented as Weibull function plots (percent wheels retired on Y axis; mileage at retirement on x axis) since the predominant cause of wheel retirement was found to be fatigue damage, and the number of wheels retired, or sample size, was small compared to the size of the total population. The plot (developed by W. Weibull in 1951) is a unique means of evaluating failure data so that a mathematical equation or curve could be easily fitted to the data.

For the Weibull function to apply, the data must plot as a reasonably straight line on special graph paper for the Weibull function. If the slope (k) of the straight line is less than one, it implies the retirement rate of the population is decreasing; therefore, the retirements are in the "infant mortality" or "break-in" phase of the life cycle. A slope near unity indicates that the retirements are occurring at an increasing rate, therefore, in the area of "wear-out" on the useful life curve.

Examination of wheel retirement data helps isolate problem areas, e.g., Figs. 4 and 5. Design effort for product improvement and changes to both existing and new designs can thus be focused on the most fruitful areas. Differences between maintenance practices of operators, geographic regions, and average load conditions must be considered in interpreting the data. A typical Weibull plot for a DC-8 wheel in service with United Airlines, as shown in Fig. 6, provides an example of the technique.

Control of corrosion and timely replacement of worn parts serve to reduce costs by extending the useful life of wheels.

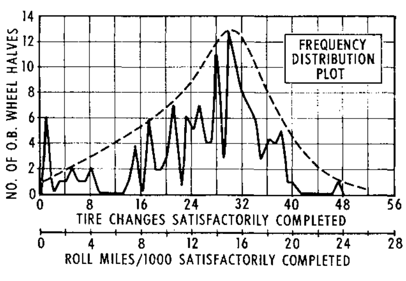


Fig. 4 Frequency distribution plot.

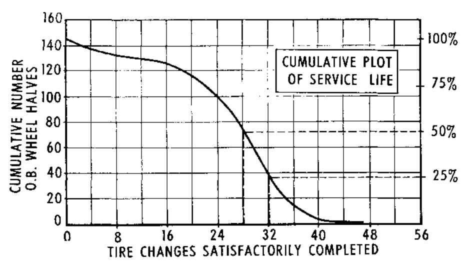


Fig. 5 Cumulative plot of service life.

Care in handling and storing the wheel assemblies during the time they are not installed on aircraft also aids in reducing costs.

We recommend that anodized aluminum alloy wheels be protected with paint. Zinc chromate and aluminum lacquer provide a finish system that has been used successfully on jet transport wheels, and which is readily removable for penetrant inspection when required.

Cooperative effort on the part of airline maintenance personnel, the brake manufacturer, and the manufacturers' service representatives has proven invaluable in insuring the attainment of maximum life and minimum costs with aircraft brakes.

Records of parts used provide identification of potential problem and cost reduction areas. We employ a cumulative technique of parts use determination for this purpose to alert us to parts use trends that are developing which require design attention.

Linings and rotors account for roughly 70% of the cost of operation of a typical aircraft brake. Well-designed rotors are retired on the basis of being at or below minimum weight required for safe operation during the next cycle of use. The lining is replaced when the thickness reaches a minimum dimension recommended by the brake manufacturer.

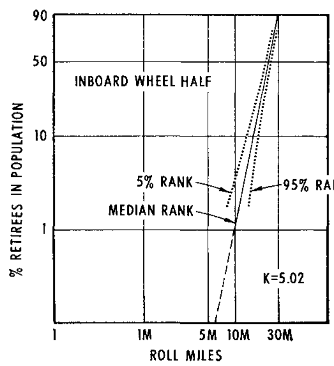
Several analysis tools are used to insure achievement of normal life for a given design. Preliminary tests are conducted in the manufacturer's laboratory to insure satisfaction of the performance requirements. Additional tests are then conducted at reduced energies under controlled conditions to establish a baseline for expected service performance.

Once the brake is in service, the number of landings between overhauls and the life of each element is studied for periods of several years (Fig. 7). One of the largest variations in brake life between overhauls noted for a given model will occur when the airplane is relatively new in a fleet.

With effective brakes, pilots become more dependent on them, and rely less on auxiliary deceleration devices such as thrust reversers. The professional pilot can contribute much to reduce costs by the judicious use of reverse thrust, and by insuring that landings are made near the end of the runway to provide maximum rolling distance before the aircraft must be stopped.

A typical curve of brake-lining wear at various percentages of normal landing kinetic energies, as shown in Fig. 8, highlights one of the means of increasing brake life between over-

Fig. 6 Weibull plot for DC-8 wheel.



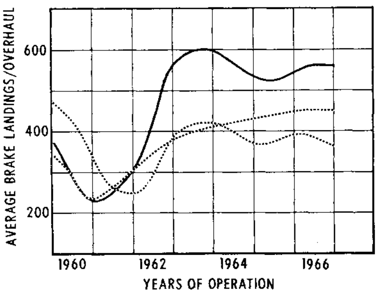


Fig. 7 Typical brake service life.

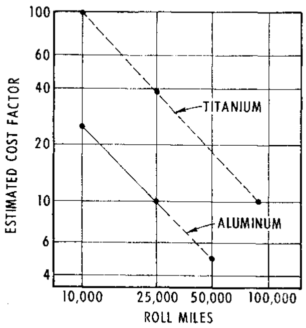


Fig. 10 Cost factor vs roll miles.

hauls. The difference between 60% and 40% normal landing energy per landing is very significant. An attendant increase in tire life will also be realized. Careful study by each operator is suggested to achieve the best economic result possible.

It is suggested that analyses to establish cost factors per brake landing be based on cumulative averaging techniques. This technique minimizes seasonal variations. Figure 9 is a graph of the variance that can occur if these data are plotted monthly.

Analyses of individual elements by cumulative averaging techniques over periods of several years provide the most satisfactory results. The resulting trends are significant for design and maintenance attention.

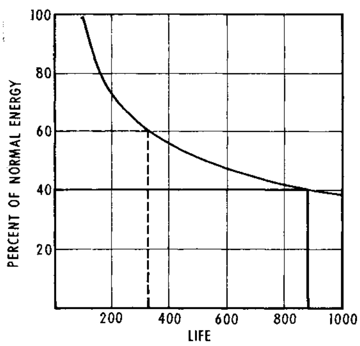


Fig. 8 Normal energy vs life.

Abnormal Service Usage

We have talked about design problems and philosophies and some of the requirements for certification of the jet aircraft wheel and brake. In service the wheel and brake assembly is subjected to a variety of operating conditions—some of them approaching the extreme of a rejected takeoff. Several conditions come to mind that can be costly to the operator and should be avoided. The first is a normal stop followed by prolonged taxi over long distances, with either intentional or unintentional use of the brakes, or with dragging of the brakes for an extended period of time.

A second condition is a series of short route segments or a pilot training schedule requiring a series of landings and full stops in rapid succession without time for energy to dissipate through cooling. Each succeeding stop has added energy to the brake until the total energy absorbed, less the relatively small amount dissipated by cooling, is equal to or greater than the rejected takeoff energy. The unusually high temperatures produced in the brake will be then transmitted to the wheel, tire, axle, and carrier. If adequate care is not exercised to limit the use of the brakes, or to provide timely in-flight cooling during such operations, reduced brake life or equipment failure will result.

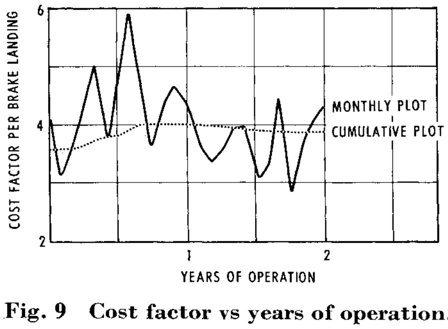


Fig. 9 Cost factor vs years of operation.

A brake energy nomograph for each aircraft brake installation may be constructed to aid the operator in determining a suitable frequency for continued use. In some aircraft, provision to monitor brake temperatures has been provided to alert crews of unusual operating temperatures.

What Is on the Horizon for Aircraft Wheels

Continued heavy dependence on forged aluminum wheels is foreseen. Steel wheels are no longer given serious consideration, and titanium wheels, while practicable, are still quite expensive. The graph of cost per roll-mile for aluminum and titanium wheels illustrates the advantage of aluminum wheels (Fig. 10). The industry can, however, furnish wheels fabricated of titanium if the operator will accept the higher initial cost. Most of the premium for titanium wheels results from the expense for the forging itself. Current quotations for titanium, closed-die forgings are 10 to 11 times those of forged aluminum material, e.g., Fig. 11.

Another problem is the present state-of-the-art of titanium forging tolerances. No one has been successful in producing a titanium aircraft wheel forging with the precision obtainable from an aluminum forging. Machining of all surfaces is thus required to control weight and obtain the desired form (Fig. 12).

The Air Force has a program, sponsored by the Materials Development Laboratory at the Aircraft System Divisions, to investigate the possibility of obtaining close tolerance titanium 6Al 6V 2Sn die forgings for a wheel similar in size and complexity to a Douglas DC-8 main wheel. The goal of the program is to match the present state-of-the-art in aluminum. Successful completion of this program should aid materially in making selected use of this material possible within the next

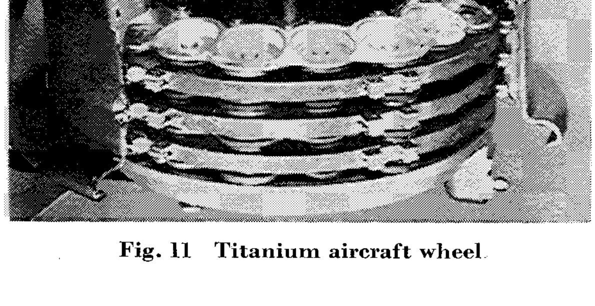


Fig. 11 Titanium aircraft wheel.

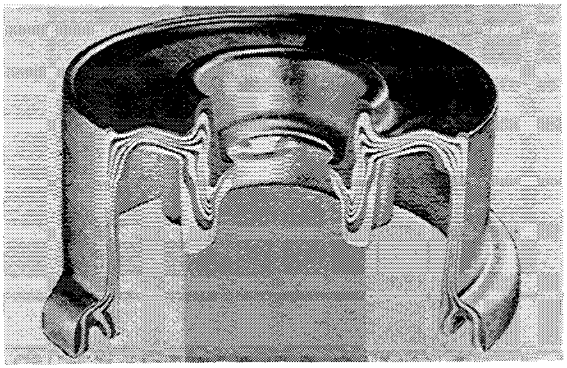


Fig. 12 Aluminum forging for aircraft wheel.

few years. Other aluminum alloys such as 2618 offer serious competition to titanium for elevated temperature use.

Recent design trends to obtain longer-life wheels have been noted. Several new aircraft operating over short route segments, with resultant higher frequency of landings, require wheels with extra margins of durability and reliability. These requirements have been successfully satisfied with wheels of forged aluminum. To obtain the desired fatigue life, a combination of the proper heat treatment for relief of quenching strains and selective cold work during fabrication is necessary.

Potential for Beryllium in Aircraft Brakes

Commercial jet aircraft brakes utilizing beryllium, as shown in Fig. 13, are not expected to be forthcoming in the near future due to the high cost of this material. The industry has the ability to produce brakes containing beryllium, but the question still remains as to whether such brakes would result in lower operating costs for the airlines. The major incentive for use of this material is the attractive possibility of reducing brake heat-sink weight. The use of beryllium in high-performance aircraft brakes of the future will depend on the design, manufacturing, and related economic problems. Several designs show promise for the future.

Potential for Titanium in Brake Construction

Some interesting developments in the powder metallurgy, casting, and forging of titanium are taking place. These developments could mean that certain structural components of future high-performance brakes would be fabricated of titanium alloys. However, the premium cost of this material would have to be offset by added passenger or payload capability.

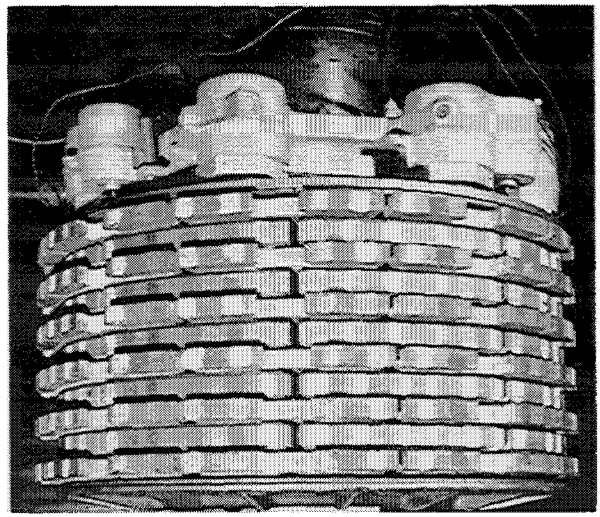


Fig. 13 $17\frac{1}{8} \times 11\frac{3}{8}$, 6-rotor brake assembly with beryllium heat sink.

Tomorrow's Commercial Jet Aircraft Brake

My view is that the commercial jet airline brake of the future will probably be a fundamentally sound basic design proven by airline use, modified to satisfy increased performance requirements, and offered at a competitive price. The use of exotic materials or other systems for heat dissipation in the near term commercial aircraft brake will be highly selective.

The industry is designing, evaluating, and preparing for the special requirements of the future. Low costs per landing, combined with safety and reliability, are the prime requirements. Satisfaction of these needs will require concentration on the best way to accomplish the braking function, at the lowest cost, without compromising performance, reliability, or safety.

Reference

[1] Davis, J. E. and Curry, R. C., "The cost of landing an airplane," Soc. Automotive Engrs. J. **71,** 47 (December 1963).