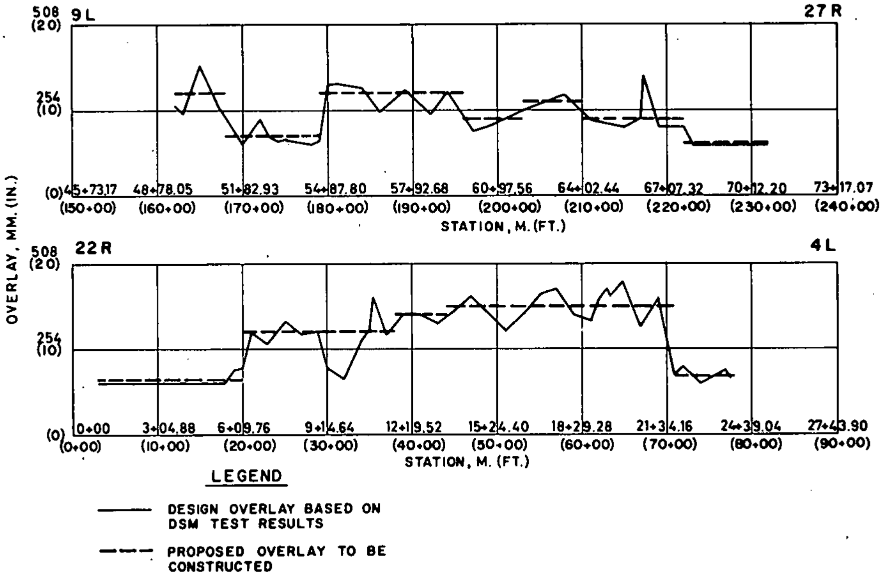

Figure 3. Overlay design for runways 9L-27R and 4L-22R.

be possible to develop a minimum strength for various types of pavements in terms of the dynamic stiffness modulus, which ranges from 1000 to 6000. However, these programs will take time, and correlation through FAA and the Corps of Engineers on pavements at other airports should be studied.

Decisions about the construction and maintenance of runways are also affected by operational and environmental considerations. Consequently, the rehabilitation of existing pavements, rather than the construction of new, may be necessary. This requires that all the available information be obtained about such factors as traffic, existing pavements, and soils. New methodologies such as nondestructive testing should be investigated to supplement present technologies, so that rational decisions supported by facts about how to most economically maintain airport pavements can be made.

REFERENCES

1. Delay Task Force Study: Chicago-O'Hare International Airport. Federal Aviation Administration, Rept. FAA AGL-76-1, Vol. 1, Executive Summary, 1976.
2. F. R. Martin and A. R. Macrae. Current British Pavement Design. Institute of Civil Engineers, Nov. 12, 1970, pp. 47-58.
3. J. W. Hall, Jr., and Robert T. Sullivan. Nondestructive Structural Evaluation: O'Hare International Airport. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, Nov. 1976.

Aircraft-Pavement Compatibility Study

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An economic analysis is summarized that was performed to relate the cost of upgrading airport pavements to the penalty cost associated with adding gears and wheels to aircraft to provide adequate flotation for present-day pavement design criteria. A basic assumption was made that the wide-body jets and a 680-Mg (1.5-million lb) aircraft (categories 1 and 2 aircraft respectively) would use the 26 projected major hub airports by 1985. Three types of gear were designed for categories 1 and 2 aircraft: (a) current, i.e., flotation that is compatible with present pavement criteria; (b) median, a compromise design that considers both present pavement criteria and the optimal gear for aircraft structure; and (c) optimal, a gear optimized for the aircraft structure with no regard for the pavement flotation requirements. Costs were based on each type of gear for both categories of aircraft. Pavement data were surveyed for all 26 projected 1985 major hub airports. Thicknesses for rigid and flexible pavements were determined for categories 1 and 2 aircraft for both new construction and for overlay of selected pavement areas where the aircraft might operate. Aircraft costs were developed as associated with carrying landing-gear masses and volumes in excess of the optimal gear. Pavement-upgrading costs were determined, and cost comparisons were made. Recommendations were presented relative to policy decisions on pavement criteria.

An economic analysis relating the cost of pavement upgrading to the penalty cost associated with adding gears and wheels to aircraft to provide adequate flotation for present-day pavement design criteria has been performed. Adequate flotation as used here implies distributing the total mass of the aircraft over a larger area to keep pavement stresses within acceptable limits. Specifically, the question to be answered was, Should the Federal Aviation Administration (FAA) policy on pavement strength—i.e., that the maximum pavement strength for which Federal-Aid Airport Program (FAAP) [which has been superseded by the Airport Development Aid Program (ADAP)] funds may be applied at any airport may not exceed that required for a 1560 kN (350 000 lbf) dual tandem gear airplane—be changed due to the advent of wide-body jets (the B-747, DC-10, and L-1011) and the possible addition of an aircraft weighing up to 680 Mg (1.5 million lb) to air carrier

Table 1. Gear designs for categories 1 and 2 aircraft.

Item	Category 1 Aircraft			Category 2 Aircraft		
	Current	Median	Optimal	Current	Median	Optimal
Gear configuration	Six-wheel bogie	Four-wheel bogie	Four-wheel bogie	Five six-wheel bogies	Four six-wheel bogies	Three six-wheel bogies
Tire vertical load, kN	172.3	285.7	258.7	211.4	264.2	352.3
Tire pressure, kPa	1380	1380	1480	1035	1380	1725
Tire diameter, cm	122	143	136	143	145	148
Bogie size, cm						
a	107	113	108	133	134	138
b	248	152	145	306	310	318
c	143	—	—	177	179	183

Note: 1 kN = 224 lbf, 1 kPa = 0.145 lbf/in², and 1 cm = 0.39 in.

Figure 1. Bogie configurations for categories 1 and 2 aircraft: (a) six wheel and (b) four wheel.

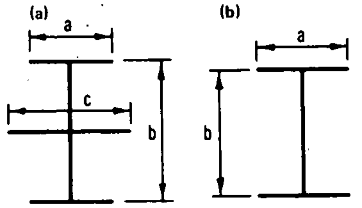
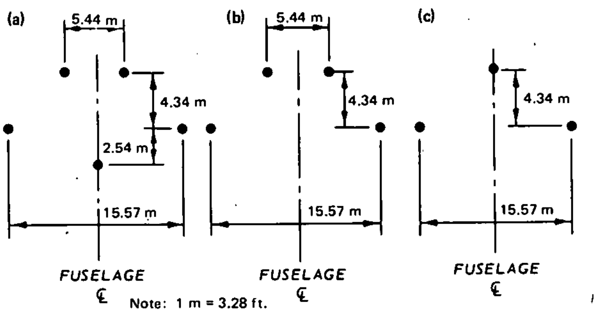


Figure 2. Gear locations for category 2 aircraft: (a) current, (b) median, and (c) optimal.



Note: 1 m = 3.28 ft.

fleets by 1985? The basis for the answer was purely economic; environmental, sociopolitical, and energy factors did not enter into the trade-off criteria. The basic assumption that wide-body jets and the 680-Mg aircraft would be using all 26 projected major hub airports in 1985 was not challenged.

AIRCRAFT COSTS

To conduct the study, a contract was let to a commercial aircraft company to develop two hypothetical aircraft types. The category 1 aircraft corresponds to the present wide-body jets, and the category 2 aircraft corresponds to the projected 680-Mg aircraft. Three types of gear were designed for both categories of aircraft. Type 1, referred to as the current gear, has a flotation compatible with the present FAAP-ADAP maximum design criteria. Type 2, referred to as the median gear, is a compromise that was designed by considering both the present FAAP-ADAP pavement criteria and the optimal gear designed with respect to the aircraft structure and, ideally, lies midway between the two with respect to flotation requirements. Type 3, referred to as the optimal gear, is optimized with respect to the aircraft structure with no regard to pavement flotation requirements.

In this portion of the study, the gear types were optimized with respect to cost rather than to mass.

The optimization procedures minimize acquisition, maintenance, and flight-operation costs of wheels and tires with respect to total mass, vertical load, and tire pressure; brakes with respect to total mass, rejected takeoff, landing kinetic energy, service energy, and number of brakes; bogie beam with respect to total mass, vertical load size, and labor as a function of total number of gears; gear strut, braces, and actuators with respect to total mass, takeoff gross mass, number of gears, and material as a function of gear mass; and gear-support structure with respect to total mass, takeoff gross mass, number of gears, and gear location. The gear designs for the categories 1 and 2 aircraft are given in Table 1; the bogie configurations of both are shown in Figure 1; and the gear locations of category 2 aircraft are shown in Figure 2.

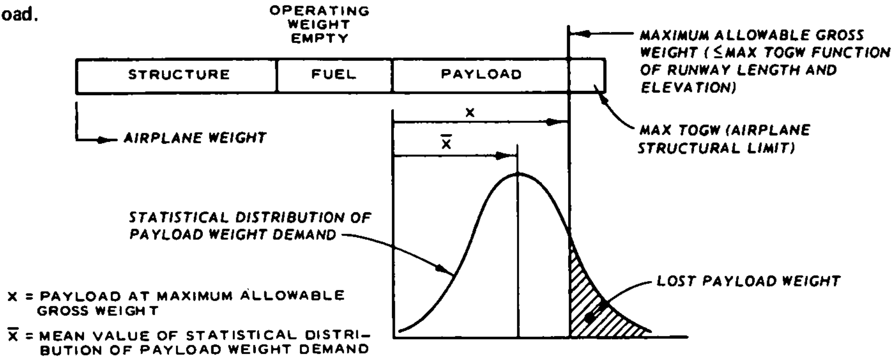
Pavement data for the 26 airports that are projected to be major hub airports in 1985—a major hub airport is defined as one that enplanes more than 1 percent of the domestic enplaned passengers—were surveyed. This survey provided a basis for designing the overlay thicknesses required for the pavement-cost section and a central source of pavement data.

Finally, the aircraft cost was developed associated with carrying landing-gear masses and volumes in excess of those optimized with respect to the aircraft structure and with no regard to the pavement strength. These costs arise from four sources—acquisition, maintenance, flight, and lost revenue.

The first three costs were included in the landing-gear design because it was based on the least cost design. The lost-revenue cost was based on the lost payload of the aircraft. Several assumptions were made to determine this payload. Figure 3 illustrates the probability assumptions, which include an average weekly payload ($\overline{X}$), a normal distribution of payload mass about $\overline{X}$, and a coefficient of variation of 60 percent. The lost revenue was calculated by the following procedure:

1. The total revenue is calculated based on the sum of the products of the number of passengers carried, the distances they traveled, and the yield per passenger per unit distance traveled and of the amounts of cargo carried, the distances they are carried, and the yield per unit amount of a cargo per unit distance carried.
2. The total mass carried is calculated based on the sum of the products of the passenger distances traveled and an average mass [91 kg (200 lb)] per passenger and of the cargo distances traveled, both divided by the flight distances.
3. The average yield is calculated by dividing the total revenue by the total mass.
4. The annual expected lost revenue by type of aircraft by distance block under various landing gear and operational empty mass assumptions is calculated by multiplying the average yield by 52 weeks/year.

Figure 3. Determination of lost payload.



5. The total annual lost revenue from operations out of the 26 airports is calculated by summing the annual expected lost revenues over all the distance blocks analyzed.

The total acquisition, operation, maintenance, and lost revenue costs in 1985 dollars for the categories 1 and 2 aircrafts relative to the optimal gear configurations are given below.

	Cost ($)	
Aircraft	Current Gear	Median Gear
Category 1	6 673 397	1 929 880
Category 2	68 777 864	35 160 820
Total	75 451 261	37 090 700

PAVEMENT COSTS

Because of spatial and temporal variables, a statistical approach was used to develop the total pavement-upgrading costs. (The Dallas-Fort Worth Regional Airport, which has been designed for a 680-Mg aircraft, was excluded from the analysis.) It was assumed that two major runways, the associated taxiway systems, and the entire apron area at the remaining 25 airports would be overlayed with either a rigid or a flexible pavement; the type of pavement was determined from historical records. Land-acquisition costs were not included in this analysis.

The initial step in developing the unit price for each pavement-upgrading project was to determine the relation between the pavement cost and the total upgrading cost. Bid tabulations for 14 major airport paving projects published in 1971/1972 were analyzed. The upgrading costs were subdivided into seven categories, and the mean percentages of category cost to total upgrading cost and their standard deviations (σs) were computed by using small sample statistics. These values are given below.

Category	$\bar{X}$	σ
Excavation	13.10	11.08
Pavement	72.79	9.81
Subsurface structures	7.13	5.70
Wiring	1.74	2.27
Lighting	2.21	4.47
Painting	0.37	0.67
Miscellaneous	2.66	4.92

Although there are some rather large variances in the categories other than pavements, this is inconsequential. The average price of pavement as a percentage of the total contract price is 72.79 percent with a coefficient of variation of 14 percent.

An analysis of variance showed that there was no significant difference between the percentages of rigid and of flexible pavement prices to total contract price. Thus, a grouped analysis was used to determine the ratios of pavement price to total price. These parameters are given below.

Type of Pavement	$\bar{X}$	σ
Rigid	77.51	8.03
Flexible	68.06	9.60

The pavement unit prices were developed, insofar as possible, on the basis of the price per unit area per unit depth. Bid tabulations for numerous projects, which were listed on a price per unit area basis, and FAA forms 5100-1, which record the depth of each pavement layer, were collected on a regional basis. Prices were assumed to decrease hyperbolically with increased thickness within an acceptable range.

The unit prices were calculated by dividing the price per unit area by the thickness. Some national average prices for pavement products are given in Table 2.

The prices used for each of the 25 airports were derived in order of priority according to the following sources:

1. Project bid data at the particular airport if two or more tabulations were available (this requirement was for some statistical credibility),
2. Regional averaged bid data for those regions supplying adequate data, and
3. The nationwide averages given in Table 2.

The third step in developing the pavement cost was to design the pavement cross sections required for the categories 1 and 2 aircraft. FAA design criteria were used for the design at a standard 100 000 aircraft-pass level. Only those areas assumed required for operations were considered for design.

Pavement areas for costing purposes were selected subjectively. These areas were scaled from sketch drawings where possible. For those that were not scaled, suitable assumptions were made with respect to the areas involved. From a macro point of view, this was adequate.

Because the total cost varies linearly with the surface area, a sensitivity analysis with respect to area and other parameters was performed. Only two types of overlays were considered: full-depth bituminous overlays and portland cement concrete overlays. The total expected area is 25 029 452 m^2 (29 939 536 yd^2), of which 32.2 percent is runway area, 23.4 percent is taxiway area, and 44.4 percent is apron area.

A comparison between the total aircraft and the total pavement costs was made in terms of the equivalent annual costs in 1985 dollars. The total pavement-upgrading cost was developed by summing the products of the price

Table 2. Average prices for pavement products.

Pavement Product	Cost Units	Number of Observations	Mean Price*	Standard Deviation
Portland cement concrete	$/unit area/unit depth	46	0.94	0.34
Bituminous surface course	$/unit area/unit depth	21	0.54	0.14
Crushed aggregate base	$/unit area/unit depth	8	0.19	0.03
Bituminous base	$/unit area/unit depth	13	0.59	0.22
Prime coat	$/unit area	9	0.07	0.02
Tack coat	$/unit area	23	0.03	0.02

*Prices are for unit area in square yards and unit depth in inches; SI units are not given because these prices were derived for U.S. customary units only.

per unit area per unit depth and the designed thicknesses for each pavement section of each of the 25 airports divided by the ratio of the pavement cost to the total upgrading cost. The total pavement cost in 1972 dollars was obtained by multiplying the unit price for each pavement section by the area of that section and summing over 25 airports. These prices were calculated for each category of aircraft and each type of gear relative to a zero cost for not upgrading.

The basic equation for determining the equivalent annual pavement cost in 1985 dollars can be expressed as

$$x = p \times A \times (1 + i)^n \{i(1 + i)^m/[(1 + i)^m - 1]\} \qquad (1)$$

where

x = equivalent annual cost of pavement upgrading (1985 dollars),
p = average total cost of upgrading per unit area,
A = pavement area to be upgraded,
i = interest rate,
n = number of years to construction (or bond issuance), and
m = amortization period of pavement structure.

Some basic value assumptions were necessary to make comparisons by using this five-space function. Expected values for p of $7.36, $7.77, $7.45, and $12.82 in 1972 dollars were computed for the category 1 median and optimal gears and the category 2 median and optimal gears respectively. The remaining independent variables were assumed to be i = 5 percent, n = 13 years (since construction must be concluded in 1985 for the comparison to be valid), and m = 20 years.

Because these assumptions will most certainly be challenged, a thorough sensitivity analysis was performed for each assumption and procedures were developed for recomputing x by using the challenger's own assumptions. The total costs calculated from Equation 1 by using the above assumptions are given below.

	Cost ($)	
Aircraft	Median Gear	Optimal Gear
Category 1	33 328 803	35 218 395
Category 2	33 749 362	58 097 736

Because of the difficulty of predicting future construction costs, three separate costs were developed for each type of gear. It was assumed that the probable coefficient of variation in both the unit-price and area-to-be-paved calculations was 20 percent. A lowest probable cost of pavement upgrading was computed by assuming a 20 percent low-side calculation in both p and A, and a highest probable cost was computed by assuming a 20 percent high-side calculation in both p and A. However, the original assumptions for i, n, and m were not changed.

While a variety of analyses were performed for the pavement-upgrading cost, only a single point estimate of the aircraft penalty cost has been made. This should be considered in examining conflicting alternatives.

COST COMPARISONS

This section presents the economic justifications for either modifying or not modifying the current FAA standards for pavement strength.

Category 1 Aircraft

Based on the equivalent annual cost analysis using the median probable cost for pavement upgrading, the total equivalent annual costs are

Gear	Cost ($)
Current	6 673 379
Median	35 258 683
Optimal	35 218 395

Thus, the optimal alternative is to not modify the present policy if one considers only the category 1 aircraft. The total equivalent annual costs based on the equivalent annual cost analysis using the lowest probable cost for pavement upgrading are given below and lead to the same decision.

Gear	Cost ($)
Current	6 673 379
Median	13 943 790
Optimal	12 666 249

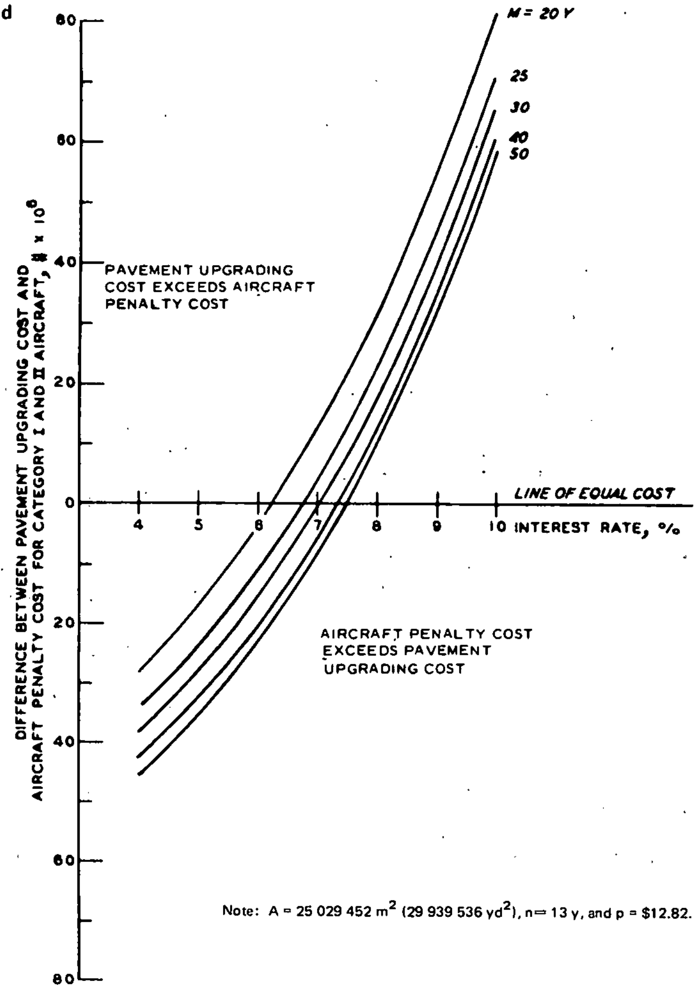
Categories 1 and 2 Aircraft

A basic assumption inherent in the following analysis is that a pavement structure upgraded for the category 2 aircraft would be adequate for the additional category 1 aircraft occurring concurrently. The state of the art in pavement analysis does not yet adequately predict the effects of mixed traffic on pavement deterioration. Based on the equivalent annual cost analysis using the median probable cost for pavement upgrading, the total equivalent annual costs are

Gear	Cost ($)
Current	75 451 243
Median	70 840 062
Optimal	58 097 736

These costs indicate that the present policy should be changed to permit the optimization of the gear to the category 2 aircraft. However, if one assumes the highest probable cost for pavement upgrading, a conflicting alternative arises as shown below.

Gear	Cost ($)
Current	75 451 261
Median	103 239 690
Optimal	113 842 221



Note: $A = 25\,029\,452\ m^2$ ($29\,939\,536\ yd^2$), $n = 13$ y, and $p = \$12.82$.

Figure 4. Effects of variations in pavement life and inflation factor.

It is reasonable to assume that the median probable cost will be exceeded in the pavement upgrading for the category 2 aircraft. In all probability, the area to be paved will exceed that computed here. The unit price differential may or may not increase. Thus, it is critical to the decision maker that a proper determination be made as to whether the category 2 aircraft will be operational in 1985, whether it will operate at all 26 projected major hub airports or perhaps at only 7 to 10 regional airports, and other operational assumptions.

Other Variable Considerations

The assumptions and parameters used in Equation 1 can be varied to permit the development of other policy derivations. Figure 4 presents a convenient method for changing the assumptions for i and m, but retaining the assumptions of median probable cost for pavement upgrading and that n = 13.

RECOMMENDATIONS

The following recommendations based on the calculations and assumptions given here resulted from this study.

1. If only the category 1 aircraft will be in operation at the 26 projected major hub airports in 1985, the current FAAP-ADAP criteria should not be changed.
2. If both the categories 1 and 2 aircraft (implied also is the category 2 aircraft alone) will be in operation at the 26 projected major hub airports in 1985, the current FAAP-ADAP criteria should be changed to permit the gear to be optimized to the aircraft. The possibility of operating the category 2 aircraft at only 7 to 10 regional airports should also be investigated.

ACKNOWLEDGMENT

This paper is a summary of a report to FAA (1).

REFERENCE

1. F. H. Griffis, Jr., and M. A. Gamon. Aircraft-Pavement Compatibility Study. Federal Aviation Administration, Rept. FAA-RD-73-206, Sept. 1974; NTIS, Springfield, VA, ADA-001-408.