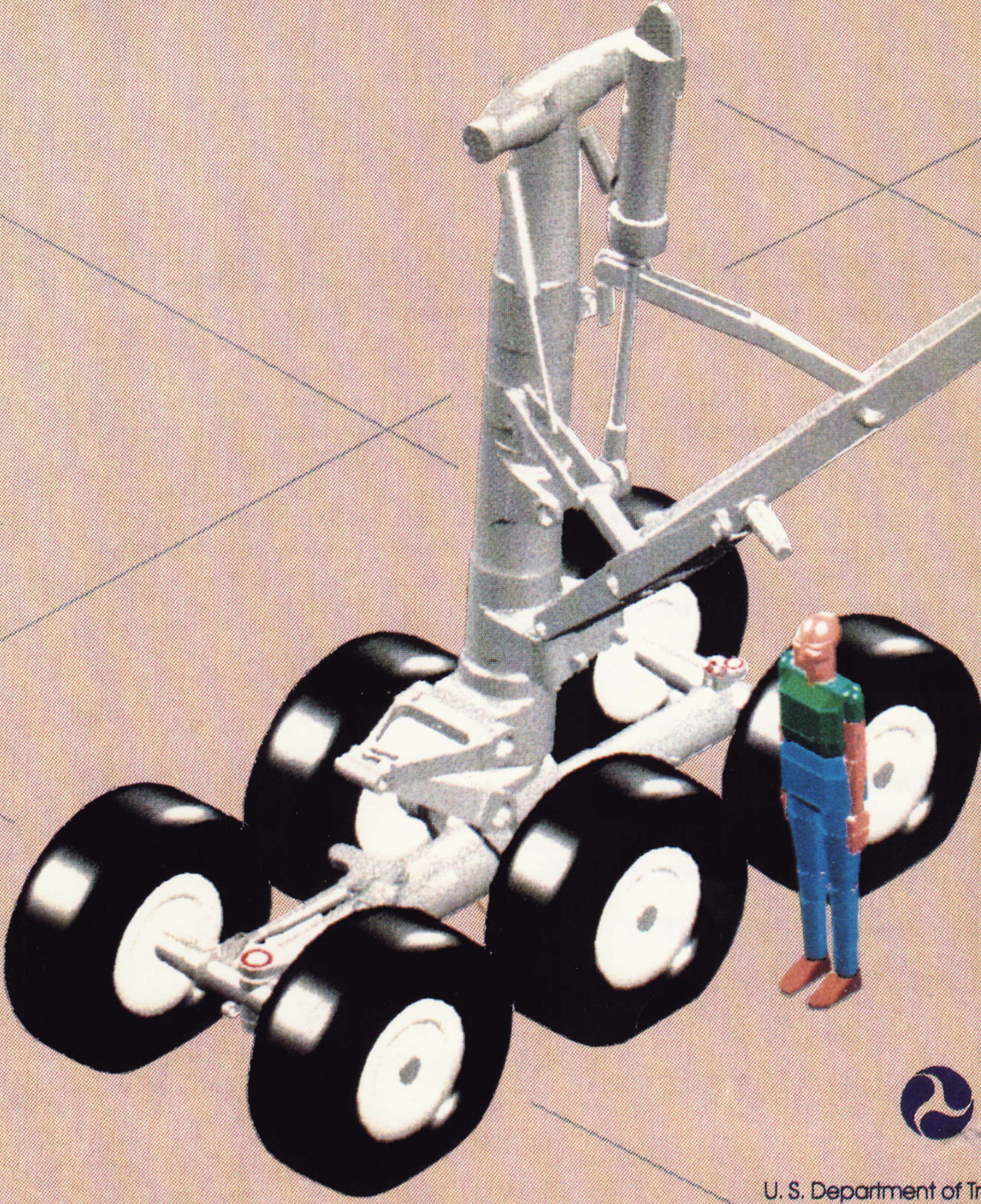
Airport Pavements

Solutions for Tomorrow's Aircraft



Boeing B-777 Landing Gear

U. S. Department of Transportation
Federal Aviation Administration

FAA Technical Center
Atlantic City International Airport,
New Jersey 08405

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Airport Pavements

Solutions for Tomorrow's Aircraft

This booklet describes the serious contemporary issues facing airport pavement design and outlines an essential Federal Aviation Administration (FAA) research and development plan to deal with these issues. The plan will introduce modern design and evaluation procedures that concentrate on long-life pavements for existing as well as new and heavier aircraft. It fulfills special national transportation needs by supporting the introduction of new aircraft, protecting the multi-billion dollar investments in U.S. airport pavements, and assuring continuing U.S. leadership in aviation technologies. The structured approach represents a return to fundamentals and will result in a common pavement design methodology based on sound theoretical principles and full-scale validation tests. It takes advantage of today's enhanced computer computational abilities and provides the flexibility to deal with new, complex landing gear configurations that were never visualized or contemplated when the current design procedures were developed. Executing the enclosed plan will reaffirm FAA's leadership responsibilities as a key player of the aerospace industry.

For more information please contact:

Research Directorate for Airport Technology
Airport Technology Branch
Federal Aviation Administration Technical Center
Atlantic City International Airport, NJ 08405

Telephone: (609) 485-5250/6686/5901

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EXECUTIVE SUMMARY

This booklet outlines the serious contemporary issues facing airport pavement design and proposes a vastly strengthened Federal Aviation Administration (FAA) Research and Development program for introducing modern design and evaluation procedures as well as related technologies of improved materials, maintenance, and management.

Durable, long-life pavements are important in controlling the costs of operating the National Aviation System. In addition to annual expenditures of approximately two billion dollars on pavements - a significant portion coming from the Aviation Trust Fund - pavement outages and downtime for maintenance and rehabilitation contribute to the costs associated with aviation system delays. It is therefore reasonable for the Government to protect its investment. An FAA program concentrating on heavy pavement loadings fulfills a special national transportation need because highway research and Department of Defense programs do not address vehicle weights comparable to those of large civil aircraft.

Airport pavement design today is very much the result of extrapolating and cobbling together empirical methods of highway engineering origins; some 50 years old. Over 20 years ago, limited full-scale tests were conducted in order to adapt these methods to accommodate heavier, more complex aircraft. These tests for "verification of extrapolations" were done for various specific loads and pavement compositions. The appropriateness of applying limited test data and design methods to aircraft of that era was questionable. These limitations precluded expanding the results to other aircraft loadings and pavement materials. The basic, underlying theoretical foundations, never very strong, offer no satisfactory way to systematically address new configurations and much higher loads. Attempts at further extrapolations yield illogical results. The time has come to return to fundamentals.

Current design methods for asphalt and concrete pavements use unrelated theories that cannot be applied when combinations of these materials are used. This is a commonly encountered problem that can only be resolved by using equivalency factors which are judgmentally chosen. Additionally, there are recognized deficiencies in the direct application of the methods when applied to conditions not originally contemplated. This approach to the design of airport pavements must be replaced with a common methodology based on sound theoretical principles and test validated models. We must take advantage of enhanced computer computational abilities that will provide the flexibility to deal with the various permutations of complex gear configurations that must be analyzed with each new proposed aircraft design.

We are now faced with the imminent introduction of a new generation of heavy civil transport aircraft. These aircraft will have landing gear layouts quite different than current aircraft; with more wheels on each landing gear strut, and the struts closely spaced around the center of the aircraft. Application of the current design procedures to these configurations will further exacerbate the deficiencies inherent in these methods.

The current FAA pavement design and evaluation methodologies are not acceptable for analyzing the pavement response and requirements of these new aircraft designs. These include the triple tandem Boeing B-777, as well as much heavier models reaching 1.3 million pounds.

As a result, the FAA is unable to deal effectively with aircraft manufacturers, the airlines, and airport owners. These key players of the aerospace industry all require an FAA/International Civil Aviation Organization (ICAO) sanctioned procedure for estimating pavement response, because it is critical in selling aircraft, in planning new airline routes and services, and in protecting the billions of dollars already invested in airport pavements. Delays in resolving these problems will jeopardize the smooth introduction of new large aircraft.

Airport pavement R&D has been able to "lean on" the much larger field of highway research for many years, and to some extent, still does. Until recently, FAA has also profited from DOD research supporting military aircraft. At the present time, however, the largest aircraft on the boards are civil aircraft with weights exceeding military aircraft and, of course, exceeding highway vehicles by an order of magnitude. There is still ample opportunity for FAA to share and benefit from pavement R&D from these sources, but in the field of ***design and evaluation***, the FAA must take on new leadership responsibilities.

The heart of FAA's pavement R&D program for the next 5-10 years will be major efforts in developing new design methodologies, but there will be continuing needs in materials research and maintenance and management techniques as well. These are areas in which we can more easily borrow from highway research, so there is reason to believe that budget requirements will crest in the next few years and fall off after completion of major testing programs.

The first milestone will be to introduce, by December 1994, design procedures based on a "layered elastic" computer model of the pavement structure. Full-scale validation testing using the new landing gear configurations will be performed at the earliest possible date to support the introduction and further refinements of the layered elastic design procedures.

The total funding required to execute the plan... $55 Million, includes costs for the construction and operation of the necessary full-scale testing equipment.

More sophisticated design methods, based on "finite element" technology will be studied later in the program. These methods still require considerable development work, but promise an even more realistic representation of airport pavement behavior.

Essential to the full development of new standard design procedures is a comprehensive testing and validation program using full-scale pavement sections and dynamic simulated aircraft loadings. Response data for rigid pavement from current technology aircraft will be collected from an instrumented section of runway at the new Denver International Airport. Rigid and flexible performance data for existing and new gear configurations and heavier loadings will be obtained from accelerated design-life testing employing specially designed equipment that can replicate aircraft loadings and make repeated passes over test sections. These "test-to-failure " trials will be used to determine life-cycle pavement performance.

As a unifying theme throughout the proposed research and development, the FAA is committed to continue to work closely with airport operators and to enlist the help and guidance of experts from all branches of the aviation industry. In addition to FAA resources, full use will be made of existing expertise and facilities in the military, academic, and highway sectors. In this way, a consensus on the necessary pavement performance standards will more easily be achieved among all interested parties, and the standards brought to implementation as quickly as possible. Efforts are already underway to enlist the support of ICAO by asking them to establish a special study group that would facilitate ICAO's adoption of acceptable and fully sanctioned procedures that would support the introduction of new aircraft and protect airport owners from premature obsolescence of pavements.

The total funding required to execute the plan over the period 1993 to 1999 is estimated to be $55 million, including costs for the construction and operation of the necessary full-scale testing equipment. The start of the full-scale tests will coincide with the introduction of some of the early B-777s. This is less than ideal, but at the time of the introduction of the Boeing B-777, a newly introduced (though only partially validated by the Denver tests) layered elastic methodology will be available to assist in the evaluation of airport pavements that will receive early B-777 service. As the heavier stretch models of the B-777 are rolled out (about 1998), data from the full-scale test will become available for adjustments to the design methodologies should they be clearly needed. At the completion of the full-scale tests, validated design procedures will be available to meet the needs of the new generation of heavier aircraft reaching 1.3 million pounds.

INTRODUCTION

Aircraft technology has made giant strides in the past thirty years by successfully incorporating advances made in a host of other technologies such as composite materials, high temperature alloys, inertial navigation, fly-by-wire controls, and other areas where the performance and economics could be improved in even the smallest increments. In comparison, airport pavement technologies have advanced little if at all. Today, a serious gap exists between aircraft and pavement technologies, jeopardizing the efficient introduction of new and larger aircraft and placing at risk the billions of dollars invested in airport pavements. A new methodology for designing airport pavements is urgently needed.

The plan calls for FAA's largest and most significant pavement R&D effort to date.

One reason for the development of this gap is that pavement technology is frequently perceived as being mature and "low-tech," and that minimal economic gains can be realized from investing in the technology. But, in fact, this perception is false. ***Airport pavements require a high level of technology to design, build, and operate efficiently - their cost is substantial.***

Approximately $2 billion is spent annually by Federal, State, and Local governments and by airport operators, to provide operationally safe and reliable airport pavements. In comparison, only $2 to $4 million is spent on airport pavement research. By normal industrial standards this is a very low level of investment at less than one quarter of one percent of expenditures.

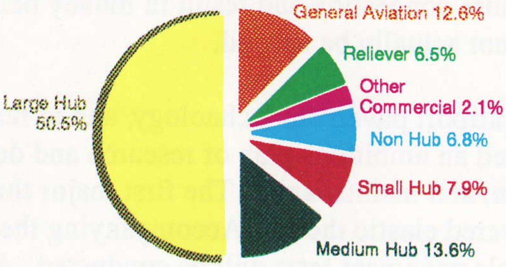
The design of future large subsonic and supersonic aircraft currently planned or envisioned will suffer from the absence of a modern, proven basic pavement design methodology. Development of this methodology requires fundamental analysis and pavement test development and execution. A validated pavement design is needed if we are to know with certainty whether existing runways or taxiways can support the kinds of loads envisioned, or whether major pavement improvements will be required. If the pavement design is performed using the existing standard design models, these aircraft will require pavement improvements (overlays), which, together with the attendant runway closures to allow for pavement strengthening, will create more congestion and result in money being spent on pavement improvements, which may not actually be needed.

To improve the level of airport pavement technology, and to realize potential economic gains, the FAA has developed an ambitious plan of research and development which covers all areas of design, construction, and maintenance. The first major thrust will be to introduce new design procedures using layered elastic theory. Accompanying the introduction of the new design procedures, large scale pavement tests will be conducted. At first, the tests will concentrate on validating the new design methodologies for application to existing aircraft; eventually the testing will address the needs of the newer and larger aircraft. To achieve these objectives, pavement research funding must be greatly increased. The plan calls for FAA's largest and most significant pavement R&D effort to date.

Figure 1. Installation of pavement instrumentation at the new Denver International Airport.

BACKGROUND

During the period 1990 to 1999, an estimated $40.5 billion in federal and local funds will be required to provide a safe, efficient, and integrated system of public-use airports under the FAA's National Plan of Integrated Airport Systems (NPIAS). Of this total, 42 percent, or $17 billion, will be spent on constructing, maintaining, and rehabilitating airport pavements. The approximately 50 airports categorized as large hubs, serving 75 percent of all passengers, will account for 53 percent of the $17 billion, and medium hubs will account for a further 20 percent. Therefore, not only will a large amount of money be expended on the nation's airport pavements, but the majority of the money will be spent at the most heavily used airports carrying the largest aircraft.



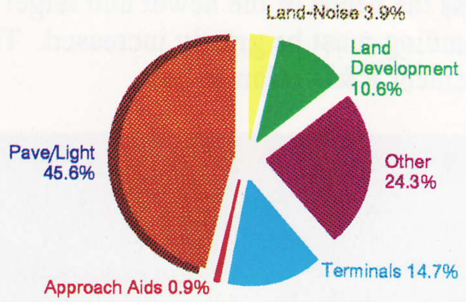


Figure 2. Distribution of NPIAS Costs by Type of Airport and Type of Development

NPIAS expenditures were estimated on the assumption that only current generation aircraft will be in operation at these airports over the next 20 to 30 years. But ***it now appears certain that the next generation of heavy transports will become operational well within the next ten years***. All of the major aircraft manufacturers have announced plans to build, either alone or as part of a consortium, two-deck transports carrying 600 or more passengers and weighing from 1 to 1.3 million pounds.

To understand the consequences of this new generation of aircraft coming into operation we must first look at the history of aircraft growth over the past half century. Each new generation has, within reasonable limits, doubled the maximum takeoff weight of the aircraft. Before 1939, the largest aircraft in regular operation weighed slightly less than 30,000 pounds.

The first, and most successful, of this generation was the Douglas DC-3, which supported its weight on two wheels with a tire pressure of 50 psi. The load applied by each wheel was equivalent to the load applied by ***one axle of a heavily loaded truck. Highway pavement designs could therefore be used for airport pavements.***

Further increases in aircraft size and weight occurred as shown in Figure 3, where the predicted new generation is also shown. Landing gear loads moved rapidly out of the range of typical highway practice and, in 1940, the U.S. Army Corps of Engineers started work on pavement design methods specifically intended for airport use. For both flexible (asphalt) and rigid (concrete) pavements, the Corps of Engineers adapted existing methods developed for highways. Over the ensuing years, the methods were extended to cover the increasing wheel loads and increasing number of wheels per landing gear of the larger aircraft. In 1978, the FAA adopted procedures similar to the Corps' which are now the basis of Advisory Circular AC 150/ 5320-6C, Airport Pavement Design and Evaluation. Conformance with this Advisory Circular is required for funding of U.S. airport pavement construction under the Airport Improvement Program (AIP). The methods are also used by the International Civil Aviation Organization (ICAO) as the basis of the system whereby aircraft operating weights are matched to existing airport pavement ratings, effectively regulating the maximum load factors which can be achieved by any model of aircraft when operating out of an international airport.

Each new generation of aircraft has increased its capacity by becoming longer and wider while increasing the number of landing gear to support the extra weight.

Each new generation of aircraft has increased its capacity by becoming longer and wider while increasing the number of landing gear to support the extra weight. As more and larger wheels had to be used it became more difficult to retract the landing gear into wing space without aerodynamic penalty. The landing gear are now retracted into fuselage cavities, encroaching on valuable passenger and cargo space. Nevertheless, it has been possible to increase the number of gear because fuselage width has also increased. ***But in the new aircraft, increased capacity will come from adding a full-length upper passenger deck*** with very little change in width, necessitating more wheels in the same space. Packaging the landing gear has become much more difficult and maintaining current pavement design methods and policies could result in pavement design becoming the limiting factor in aircraft design.

An indication of the possible trend in landing gear design can be seen in the Boeing 777 twin-jet due to enter commercial service in 1995. This aircraft will not be unusually heavy, weighing a maximum of 592,000 pounds, but it will have only two main landing gear, each with three dual-wheel axles close behind each other in tandem. A comparable current generation aircraft is the McDonnell Douglas DC-10-30, which has a maximum takeoff weight of 580,000 pounds carried on two dual tandem wing gear and one dual body gear (ten wheels total). Despite having two more wheels than the DC-10-30, the B-777 is predicted by the current

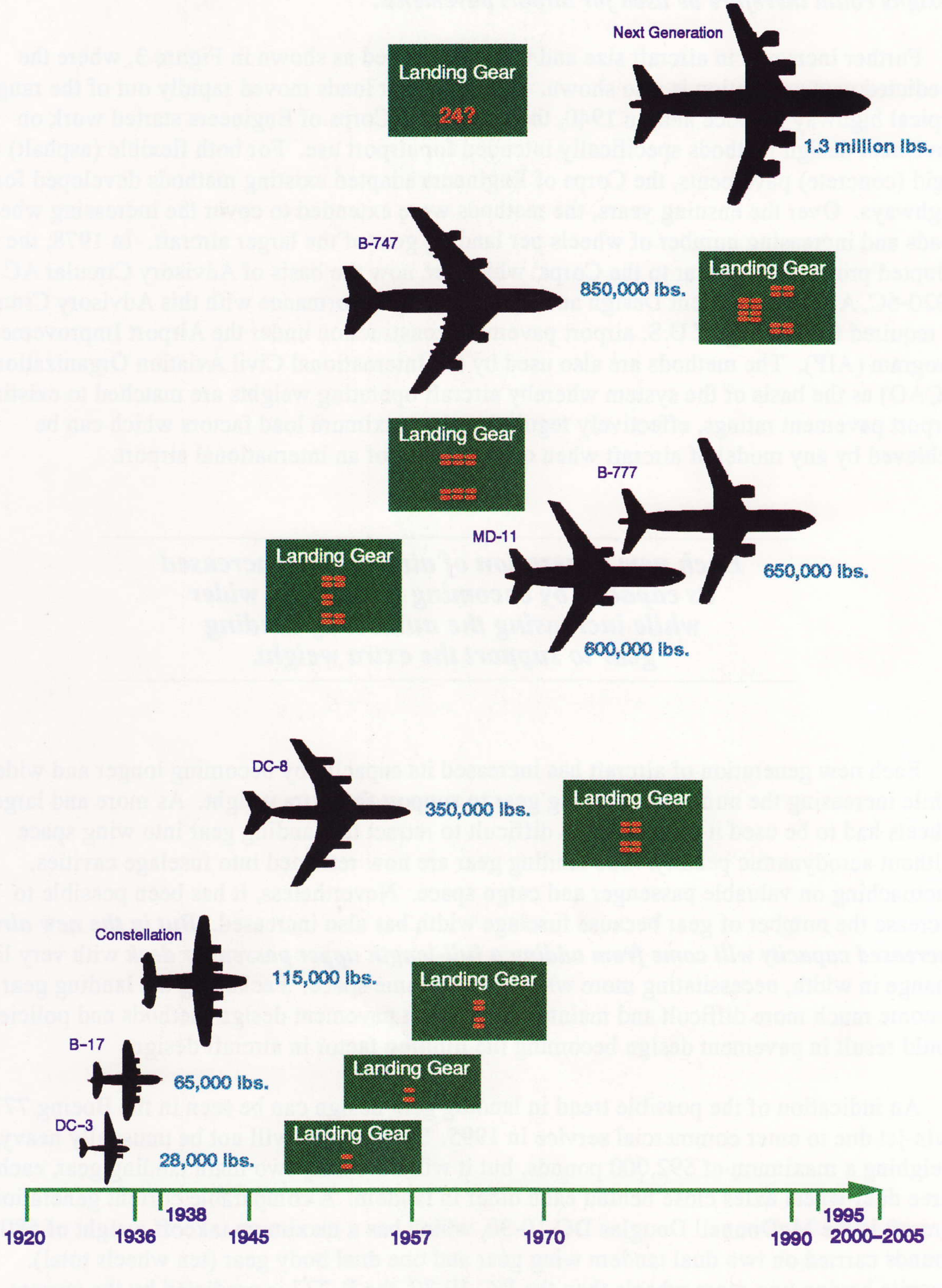


Figure 3. Evolution of Aircraft by Weight and by Number of Wheels

flexible pavement design procedure to be more damaging to flexible pavements than the DC-10-30. On the other hand, the rigid pavement design procedure predicts that it will be less damaging than the DC-10-30 on rigid pavements. This points out the need to develop a common design methodology that can be applied to both types of pavement to facilitate comparative analysis. There is some agreement among pavement engineers, but by no means a consensus, that ***the treatment of wheel load interaction effects in the flexible design procedure leads to the overprediction of damage to the pavement.*** Aircraft built to be compatible with current design criteria would result in increased operating costs.

For the same reason, there is growing concern that the current design procedure will not accurately predict the load interaction between closely spaced landing gear on the new generation aircraft. As described later, the question of whether the Boeing 777 and the new generation of aircraft will damage airport pavements more or less than predicted by the current design procedures cannot be answered using existing test data because ***triple tandem duals and very closely spaced landing gear have never been tested for their effects on pavement life.*** Damage caused to a pavement by these landing gear cannot be predicted from theoretical studies with confidence because ***test data is an integral part of the design procedures and, again, the necessary test data has not been collected.***

There is growing concern that the current design procedure will not accurately predict the load interaction between closely spaced landing gear on the new generation aircraft.

This results in a serious dilemma for the FAA which must provide credible guidance on pavement design for the new aircraft. The FAA cannot change its design procedures without firm evidence that the new procedures will result in pavements having the desired structural capacity and useful life. ***If the current procedures overpredict the damage to pavements from existing and new aircraft, then a great deal of money will be spent unnecessarily strengthening existing pavements, or the loads carried by the aircraft will have to be restricted.*** On the other hand, underprediction of the damage will result in early and perhaps catastrophic failure of at least some existing pavements with the attendant high costs of providing emergency funding and performing rush rehabilitation projects.

RESEARCH DIRECTION

If the FAA were to continue using the current guidelines based on existing test data for pavement design it must still revise these guidelines to explicitly include, as further special cases, landing gear layouts for the new aircraft. Then, assuming that landing gear design trends continue as predicted, strengthening of pavements carrying the new aircraft will be required or restrictions will have to be imposed on aircraft takeoff weights at airports not meeting the required standards. Even then there is no guarantee that unexpected pavement failures will not occur. ***Past experience has shown that extrapolating the design procedures to cover new untested operating conditions can lead to types of failure not previously encountered.*** One example is the failure of the standard design of keyed joints in rigid pavements under wide body jet loading, as was discovered during the limited full-scale pavement tests conducted in the late 1960's and early 1970's.

A preferred alternative, and one which the FAA has chosen to pursue to the extent possible, is to develop new standard procedures capable of producing pavement thickness designs for all aircraft weights and landing gear configurations which might come into operation in the foreseeable future. The proposed plan includes short-term and long-term research so that the immediate needs arising from the introduction of new generation aircraft can be met while pursuing long-term goals for improving the efficiency of airport pavement operations. The short-term research includes the verification and proposed adoption of a design procedure based on current layered elastic analysis technology. The longer-term objective is to develop a design procedure based on new finite element technology, requiring considerable development work but promising a procedure capable of more realistically representing the most important aspects of airport pavement behavior.

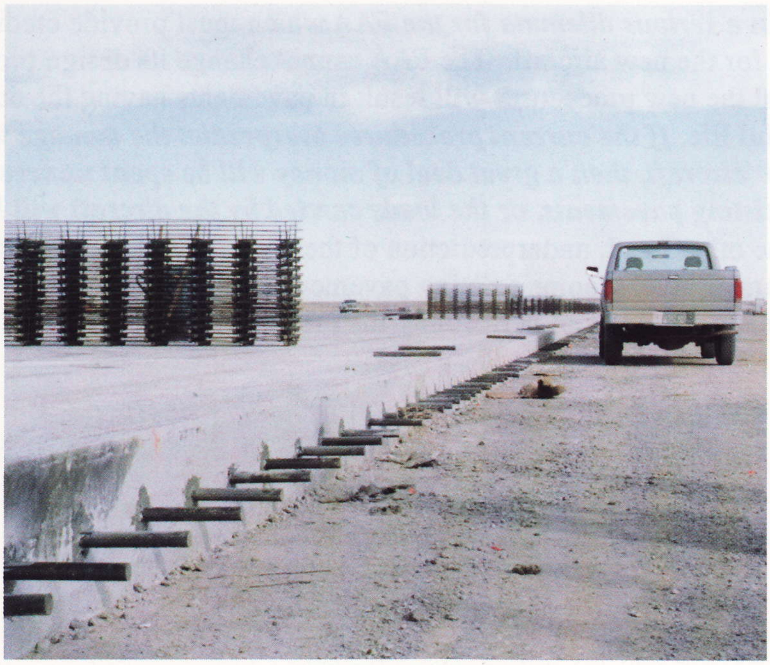


Figure 4. Joint dowels in a newly constructed runway section at Denver International Airport.

Comprehensive testing on full-scale prototype pavements will be required for development and verification of both of the new procedures. The plan is structured so that research needed to support the first goal, to develop a layered elastic design method, can also complement the longer term goal to develop a finite element design technology.

The first major milestone in this work will be to introduce a new pavement design procedure based on layered elastic theory. This methodology will be available by December 1994 and will become the new "FAA standard." It will have been initially validated by extensive comparison and sensitivity testing against the present FAA standard. While subject to the limitations of the existing design method, this procedure will be suitable for designing new pavements based on present gear configurations and weights. Follow-on steps in the validation process will involve the instrumented pavement at Denver where, starting in 1994, data will become available to compare computed strains and displacements with measured values. However, while providing useful data, these tests will address only concrete pavements, existing aircraft, and a single subgrade condition.

The main thrust of the R&D effort is to move beyond existing configurations into the realm of more complex designs, and consider various types and combinations of materials. This can only be accomplished by extensive testing using full thickness pavements, full load mock-ups of new gear configurations, and test-to-failure dynamic stress repetitions. These full-scale accelerated-life tests will be the heart of the R&D program and will provide data to modify the layered elastic procedure if required. It will also permit expanding the theory to cover new generation aircraft.

Development of new design procedures will be pursued in conjunction with other research needs, such as new materials testing, pavement evaluation, and management methodologies. Much of the development work will have parallel application in normal pavement management operations, and the full-scale testing equipment will be fully utilized with testing and demonstration of different construction methods and materials when not performing tests directly related to the development of design procedures.

Table 1. Airport Facts

Total Pavement Surface Area:	**6 Billion Square Feet**
Replacement Value:	**$100 Billion**
Annual Pavement Expenditures:	**$2 Billion**
Annual Passenger Enplanements:	**500 Million**
Airports with Paved Runways:	**7,800**
Certified Airports:	**670**
Commercial Aircraft Fleet:	**6,000**

AIRPORT PAVEMENT DESIGN METHODOLOGIES

Airport pavements are of two types, rigid and flexible. Each type currently has its own distinct design procedure. However, all structural design procedures, in whatever field of engineering, have common elements:

- Define the loading
- Define the material characteristics
- Start with a trial design
- Calculate structure response (deflection, stress, or strain) caused by the loading using a mathematical model of the structure
- Compare the structure response with criteria for material failure, i.e., is the calculated response greater or less than the predicted breaking point of the structure
- Change the design until the calculated response matches the failure criteria

A critical element in all design procedures is the selection of appropriate failure models and failure criteria. ***But behind every failure model is test data of one kind or another. Application of failure criteria outside the range of the underlying test data can result in gross inaccuracies in the prediction of pavement life.*** Caution must therefore be used when applying criteria for current pavement designs to pavement designs for the new generation aircraft.

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Like most structures subjected to repeated loading, pavements degrade incrementally with each load repetition until failure finally occurs by fatigue. A generic design methodology for airport pavement fatigue failure is shown in Figure 5. The box marked "Satisfaction of Failure Criteria" represents the fatigue failure model, where N is the number of load repetitions, or coverages, to failure for the desired pavement life. N is a complicated function of the types of aircraft and number of departures for each aircraft predicted to be operating on the pavement over its life. The final design is arrived at by adjusting the thicknesses of the various layers and by selecting materials and construction techniques to match the local soil and climatic conditions, and available materials. Therefore, even though the procedure can be mechanized as a computer program, the design engineer must still exercise considerable engineering judgement to produce a cost-effective and sound design.

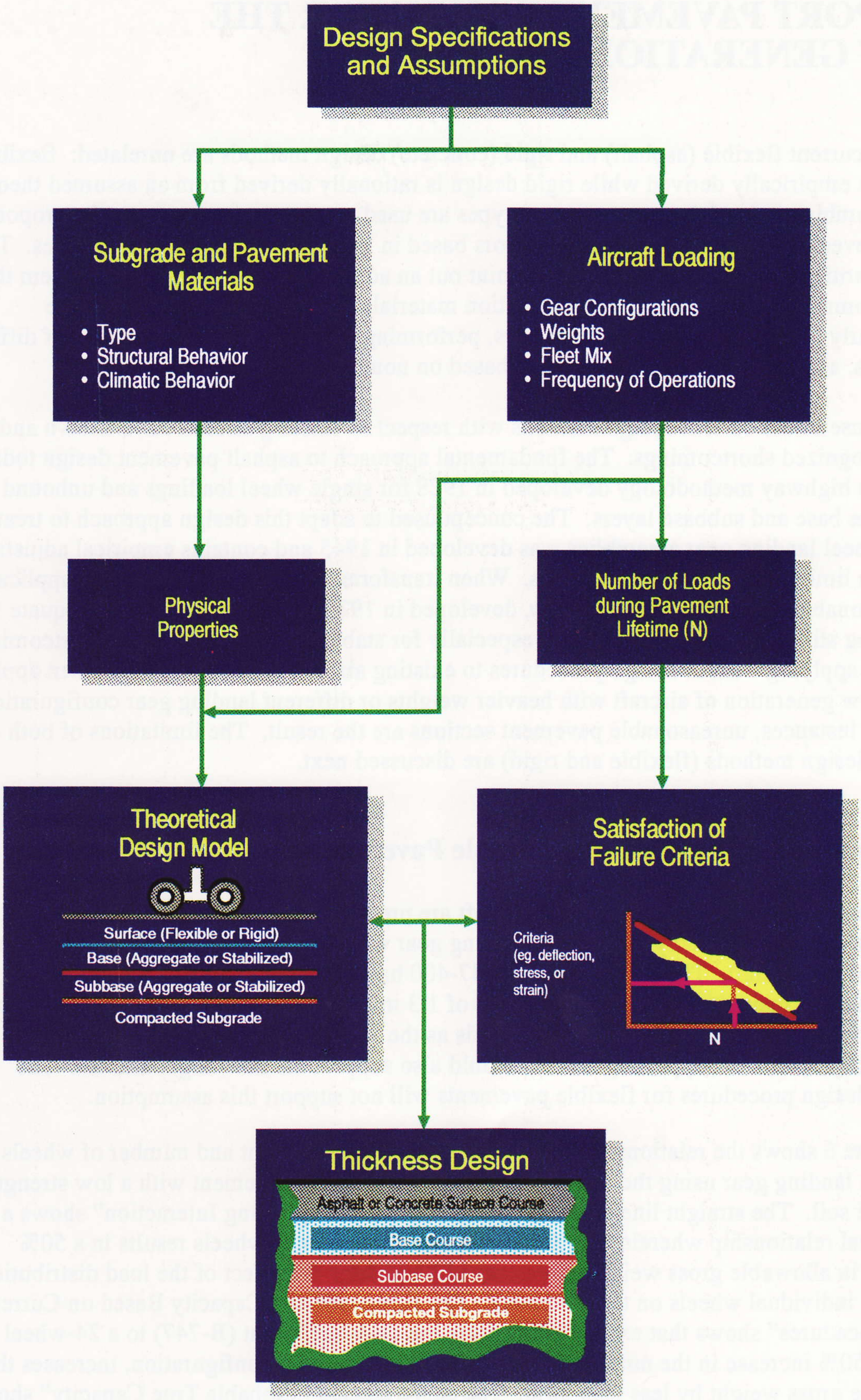

Figure 5. Generic Design Methodology

AIRPORT PAVEMENT DESIGN FOR THE NEW GENERATION AIRCRAFT

The current flexible (asphalt) and rigid (concrete) design methods are unrelated: flexible design is empirically derived while rigid design is rationally derived from an assumed theory. When combinations of the two pavement types are used, a common occurrence, the proportions are achieved by the gross equivalency factors based in large part on judgmental choices. The dissimilarities between the two methods point out an additional need for a design system that uses a common theory to treat all construction materials. A common system would be particularly useful in the design of overlays, performing studies using combinations of different materials, and analyzing loading capacity based on nondestructive testing.

The use of the current design methods with respect to existing aircraft have known and well-recognized shortcomings. The fundamental approach to asphalt pavement design today is based on highway methodology developed in 1928 for single wheel loadings and unbound aggregate base and subbase layers. The concept used to adapt this design approach to treat multi-wheel landing gear assemblies was developed in 1945 and contains empirical adjustments based on limited specific test conditions. When transferred to other conditions, the applicability is questionable. The rigid design theory, developed in 1926 for highways, is not adequate for modelling stiff supporting foundations, especially for stabilized subgrades. The shortcomings noted in applying current design procedures to existing aircraft are compounded when applied to the new generation of aircraft with heavier weights or different landing gear configurations. In many instances, unreasonable pavement sections are the result. The limitations of both of the current design methods (flexible and rigid) are discussed next.

Load Interaction Concerns on Flexible Pavements

The new generation commercial jet aircraft are predicted to weigh as much as 1.3 million pounds and to have as many as 24 main landing gear wheels closely spaced around the center section of the aircraft. The current Boeing 747-400 has a maximum takeoff weight of 870,000 pounds and 16 main gear wheels. An aircraft of 1.3 million pounds and 24 wheels would have almost exactly the same individual wheel loads as the 747-400, and it would seem that pavements capable of supporting the 747 would also support the new larger aircraft. The current design procedures for flexible pavements will not support this assumption.

Figure 6 shows the relationship between allowable gross weight and number of wheels in the main landing gear using the FAA procedures for a flexible pavement with a low strength subgrade soil. The straight line labeled "Theoretical Line Neglecting Interaction" shows a theoretical relationship wherein a 50% increase in the number of wheels results in a 50% increase in allowable gross weight. Two curved lines show the effect of the load distribution from the individual wheels on the pavement. The curve labeled "Capacity Based on Current FAA Procedures" shows that extrapolating from the 16-wheel point (B-747) to a 24-wheel point, a 50% increase in the number of wheels for a similar gear configuration, increases the allowable gross weight by less than 30%. The curve labeled "Probable True Capacity" shows a point somewhere between the theoretical line and the current FAA procedure line. This curve is based on recent investigations that indicate that the current design procedure for flexible pavements may overestimate the interaction, resulting in thicker pavements than may be necessary. The degree of overestimation, and the possible increase in available capacity for current pavements, is indicated on the figure by the line marked "Probable True Capacity." A number of options are available for modifying the FAA design guidelines for flexible pavements to increase the available capacity. But first it must be established that the current procedure does, in fact, lead to overly thick pavements, and, if it does, to verify that any changes to the guidelines do not swing too far in the other direction and produce pavements which are too thin.

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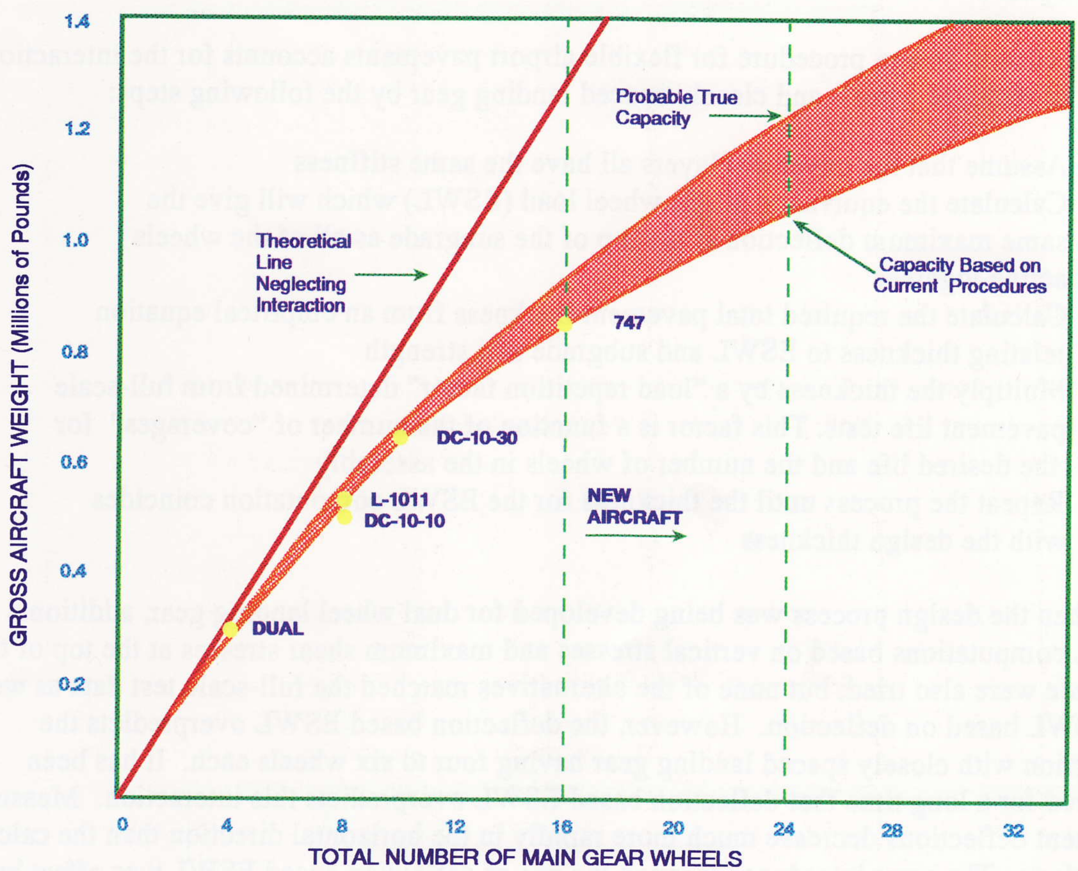


Figure 6. Gap in Predicted and Probable Pavement Capacity

To see why the current procedure for flexible pavements is thought to be overconservative, a brief look must be taken at the interaction mechanism and the design procedure itself. Pavements are designed to withstand maximum allowable vertical deflections and stresses (pressures). The subgrade type defines the maximum allowable vertical pressure. For a single wheel load, the maximum vertical pressure at any depth in the pavement occurs directly below the center of the wheel and falls off in the horizontal direction as shown in Figure 7a. As depth increases, the maximum pressure decreases roughly as the inverse square of the distance from the surface, but the shape of the pressure distribution in the horizontal direction does not change. If a second wheel is placed close to the first, as shown in Figure 7b, the vertical pressure at any depth is made up of the sum of the pressures from the two wheels. Close to the surface there is very little interaction. But as depth increases, the "cones of influence" start to overlap and the maximum pressure becomes significantly greater than for a single wheel until, eventually, the pressure distribution and the maximum pressure become indistinguishable from what would result if the dual wheels had been replaced by a single wheel carrying the same total load. For normal subgrade depths, the closer the wheels are moved together the higher the maximum pressure will be and the thicker the pavement must be made to protect against failure of the subgrade, even though the total load has not changed. The above discussion on the interaction of wheels within a landing gear is also applicable to closely spaced landing gear assemblies. That is, interaction between landing gears must be considered when they are closely spaced.

The current design procedure for flexible airport pavements accounts for the interaction effects of multiple wheels and closely spaced landing gear by the following steps:

- Assume that the pavement layers all have the same stiffness
- Calculate the equivalent single wheel load (ESWL) which will give the same maximum deflection at the top of the subgrade as all of the wheels acting together
- Calculate the required total pavement thickness from an empirical equation relating thickness to ESWL and subgrade soil strength
- Multiply the thickness by a "load repetition factor" determined from full-scale pavement life tests. This factor is a function of the number of "coverages" for the desired life and the number of wheels in the assembly
- Repeat the process until the thickness for the ESWL computation coincides with the design thickness

When the design process was being developed for dual wheel landing gear, additional ESWL computations based on vertical stresses and maximum shear stresses at the top of the subgrade were also tried, but none of the alternatives matched the full-scale test data as well as the ESWL based on deflection. However, the deflection based ESWL overpredicts the interaction with closely spaced landing gear having four to six wheels each. It has been observed for a long time that deflection based ESWL overpredicts this interaction. Measured pavement deflections decrease much more rapidly in the horizontal direction than the calculated deflections. The error introduced through the use of deflection based ESWL was offset by empirically derived load repetition correction factors obtained from full-scale testing. ***These correction factors are applicable only to the gear configurations, loads, and pavement sections tested*** and a more rational method of computing pavement response with interaction is

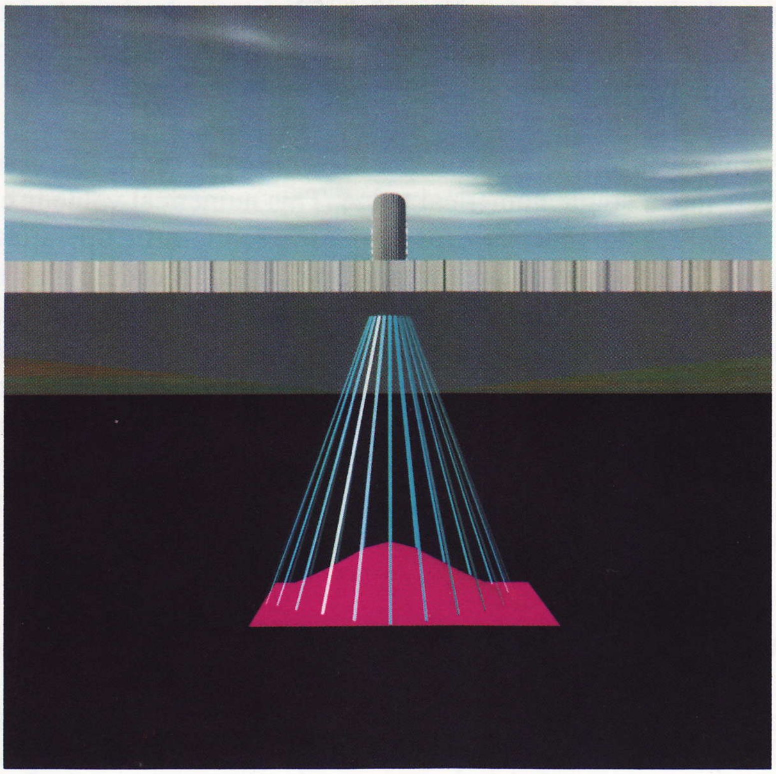


Figure 7a. Flexible Pavement with Single Wheel Load

Figure 7b. Flexible Pavement with Multiple Wheel Load Showing Interaction

required. The problem is deciding which model to use and which measures of pavement response to choose as the basis of the failure model. The predictions must also agree with full-scale measurements, or suitable factors must be derived from full-scale tests to match predictions with measurements.

The number of coverages to failure is another factor used in the design procedure which lumps multiple effects into a single numerical value. This numerical value is effectively the traffic, and failure model for the procedure, and represents all traffic operating on the pavement throughout its lifetime. This is also an area where the current procedure may be overconservative for the new aircraft, including the Boeing 777. The coverages relationship counts wheels in tandem as contributing two complete load repetition cycles for each pass of the aircraft, and the load repetition factors compensate (from test data) for inaccuracies in the assumption used to determine the number of cycles to failure (and, in fact, for any other unknown aspects of the pavement failure process). ***The test data used to develop the current procedure did not include tests run with six wheel triple tandem dual landing gear, and directly applicable load repetition factors are not available.***

Rigid Pavement Design Concerns

The behavior of rigid pavements differs from flexible pavement behavior mainly in the way in which loads are distributed through the pavement layers down to the subgrade. Since concrete is stiffer than asphalt, heavy loads are more uniformly spread over a wider area. The load distribution mechanism is similar to the way in which floating ice can sustain loads. In fact, the basis for the current rigid pavement design procedure stems from mathematical studies of the load carrying capacity of frozen bodies of water. Because of the different load distribution mechanism in rigid pavements, load interaction is much less of a problem than in flexible pavements.

. . . the single gear load of the Boeing 777 is expected to exceed the single gear load of the B-747-400 by 37 percent . . .

With rigid pavements, the emphasis shifts from the subgrade to the performance of the concrete slab under heavy loads. The concrete slab is designed to allow for an acceptable amount of bending without cracking. Repeated bending under the imposed aircraft loading results in fatigue cracking and ultimate failure of the concrete surface. Since the bending stresses in the slab are highest when the loads are applied close to the joints, this loading condition is considered to be the critical design case in the current procedure.

Limited full-scale airport pavement tests conducted in the late 1960's and early 1970's, revealed that heavy loads were causing premature failures in the concrete joints. ***Since the single gear load of the Boeing 777 is expected to exceed the single gear load of the B-747-400 by 37 percent, there is renewed concern over the performance of rigid pavements under these***

heavier loads. The full-scale tests on which the current design procedure is based were conducted with rigid pavements constructed on grade. The FAA found from experience that the performance of rigid pavements for loads over 100,000 pounds could be improved with the use of a stabilized subbase (i.e. aggregate materials bound with cement, asphalt, or other stabilizing and strengthening agents). ***While it is known that a stabilized subbase decreases the stress levels in the concrete slab and provides support at the joints, these materials cannot be treated properly in the current design procedure because the response model used in the procedure is based on a single layer support system.***

PAVEMENT RESEARCH PLAN

Clearly, as landing gear designs become more complex, an alternative to the equivalent single-wheel load concept is required for flexible pavement design, and reevaluation of joint and support models is required for rigid pavement design. In addressing this issue, the first priority will be to introduce, by December 1994, design procedures based on a layered elastic model. The more sophisticated design methods, based on finite element technology requiring considerable development work but promising an even more realistic representation of airport pavement behavior, will be studied later in the program.

An essential element in the development and implementation of new design procedures is a comprehensive test and verification program performed on real pavements subjected to full-scale loading.

An essential element in the development and implementation of new design procedures is a comprehensive test and verification program performed on real pavements subjected to full-scale loading. To meet this need, response data for rigid pavement from current technology aircraft will be collected from an instrumented section of runway at the new Denver International Airport. Rigid and flexible performance data for existing and new gear configurations and heavier loadings will be obtained from accelerated design-life testing employing specially designed equipment that can replicate aircraft loadings and make repeated passes over full depth pavement test sections. These test-to-failure trials will be used to determine life-cycle pavement performance.

While the new design procedures are being developed and verified, other airport pavement research needs will be met by parallel projects in the areas of Materials and Construction, and Pavement Management.

Layered Elastic Based Procedure

The layered elastic model represents the pavement as a layered system with each of the layers extending continuously in the horizontal plane and allowed only elastic deformation. This assumption necessitates an analytically derived adjustment to the stresses calculated at joints in rigid pavements. Within the constraints of these basic assumptions, the model is capable of predicting theoretical load interactions for any landing gear configuration and wheel loading. Traffic loading and pavement failure models are also included in the procedure. But the performance of the procedure has not been verified against full-scale test data to the same extent as the current procedures. The procedure is not suitable for hand calculation and requires significant computer power to implement efficiently. Development started in 1970 using main frame computers and it is only recently, with the advent of powerful personal computers, that it has been possible to consider the procedure for use as a general purpose and widely disseminated design office tool.

Under a current FAA project, the layered elastic based procedure is being tested for compatibility with the current rigid and flexible design procedures. In addition, pavement response data from the Denver airport sensor system will be compared with theoretical predictions from the model. If design compatibility and response predictions are sufficiently well demonstrated, it would be possible to introduce, in 1994, a standard based on layered elastic design for use with existing aircraft and for first generation B-777 aircraft. Additional steps will be required to enhance the application of layered elastic design procedures to existing aircraft and to extend the procedures to more complex and heavier aircraft. These steps include the development of full specifications for measuring and quantifying input parameters related to material properties, and full scale tests to verify the procedure's ability to predict pavement life. It will also be necessary to integrate the complete procedure into periodically released software packages suitable for use by consultants in everyday design work.

. . . integrate the complete [design] procedure into periodically released software packages suitable for use by consultants in everyday design work.

Finite Element Based Procedure

It is prudent to look beyond the era of layered-elastic-design-based methodologies into sophisticated approaches that can handle more detailed and complex characterizations of construction materials. At the present time the most promising of these is the finite element modelling approach, which when supported by more powerful computers, can possibly further advance the state-of-the-art.

In finite element modelling the structure is divided into a large number of small elements. Each of the elements can, within certain constraints, be given properties different from its neighbors or be dependent on the behavior of its neighbors. Each of the layers in a pavement can therefore be modelled according to its inherent material properties, with the connected mesh of all of the elements providing a comprehensive representation of the complete structure. Visco-elastic and plastic deformation can be included in the models and "joint elements" can be added to rigid pavements.

Despite, or perhaps because of, the great generality of finite element models and their ability to represent any structure, adoption of a finite element based procedure as a design standard presents numerous difficulties. To be a true standard, the model should have specified element formulations, material properties, and element sizes for each of the layers, since each of these factors can affect the predicted response and the design engineer will expect consistent behavior from his design tool. A consensus has not yet been reached on the best mechanization of a finite element model for the very difficult problem of modelling pavements and much work remains to be done before this can be achieved.

A long term plan [for developing finite element models] is being formulated which will enlist the cooperation of industry experts and build on the experience gained with the introduction of layered elastic design procedures.

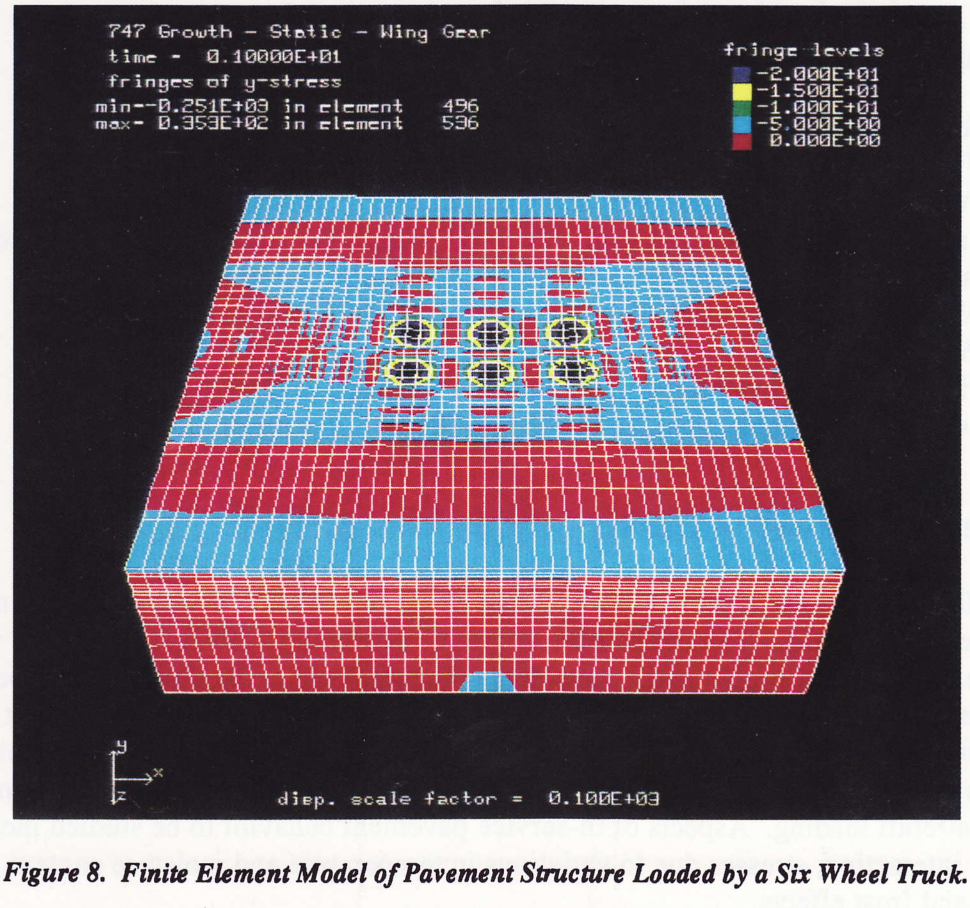


Figure 8. Finite Element Model of Pavement Structure Loaded by a Six Wheel Truck.

Other concerns which must be addressed before adoption of a finite element based design procedure include: identification of suitable failure criteria, development of a traffic model, and testing for numerical stability and accuracy over the full range of inputs. Current models also require far more computer power than layered elastic models and either more efficient models must be formulated or adoption must wait until the performance of desk-top computers has increased to the required level.

The FAA has initiated development of a finite element based design procedure for airport pavements, with the expectation that a fully validated and operational procedure will not be available in time to design pavements for the new generation of aircraft. A long-term plan is being formulated which will enlist the cooperation of industry experts and build on the experience gained with the introduction of layered elastic design procedures.

Full-Scale Field Verification Tests

Under the guidance of a working group comprised of representatives from the FAA, FHWA, U.S. Army, U.S. Air Force, Boeing Aircraft Company, and McDonnell Douglas Aircraft Company, design specifications have been developed for a full-scale test track and associated loading equipment. Estimation of the cost of constructing and operating such a track is also underway and a preliminary test plan has been produced.

The major specifications for the test track are as follows:

- Test track 900 feet long by 60 feet wide
- Up to twelve independent test pavements along the length of the track
- Twelve test wheels capable of being configured to represent two complete landing gear trucks having from one to six wheels per truck and adjustable to vary the distance between the trucks up to 20 feet forwards and sideways
- Wheel loads to be independently adjustable up to a maximum of 75,000 pounds per wheel
- Simulate aircraft weighing up 1.3 million pounds
- Failure of full-depth pavement

Instrumented Runway at Denver International Airport

Over 300 sensors were installed in a 140 foot by 75 foot section of runway at the new Denver International Airport when the runway was constructed in 1992. The sensors will measure deflections and strains in the pavement structure, joint deflections, and temperature and moisture content of the different layers. The lateral position and speed of aircraft passing over the pavement will also be measured. Data will be collected at the site for at least six years, and will be used to study the in-service behavior of the pavement as well as its' response to individual aircraft loading. Aspects of in-service pavement behavior to be studied include: wheel load interaction, stresses due to variations in temperature and moisture content, joint efficiency, and frost effects.

Materials and Construction

A very wide variety of construction techniques are used for pavement construction. Research and development needs in this area include standardizing material composition and characteristics, developing quality assurance procedures, and laboratory and field tests of new materials and construction methods. Current projects funded by the FAA include development of improved laboratory testing procedures for new asphalt mixes, a study of the in-service performance of a prestressed fibrous concrete pavement installed at Rockford Airport in Illinois, and a study of pavement material properties under conditions of extreme cold (in partnership with the Minnesota Department of Transportation).

Future work will utilize, to the maximum extent possible, the results of the Strategic Highway Research Program. However, the results must first be evaluated for their suitability to heavy load airport pavement requirements and to make the necessary changes in standards and guidelines before implementation. In addition, research will be fully coordinated with the Department of Defense to maximize the application of results within the government.

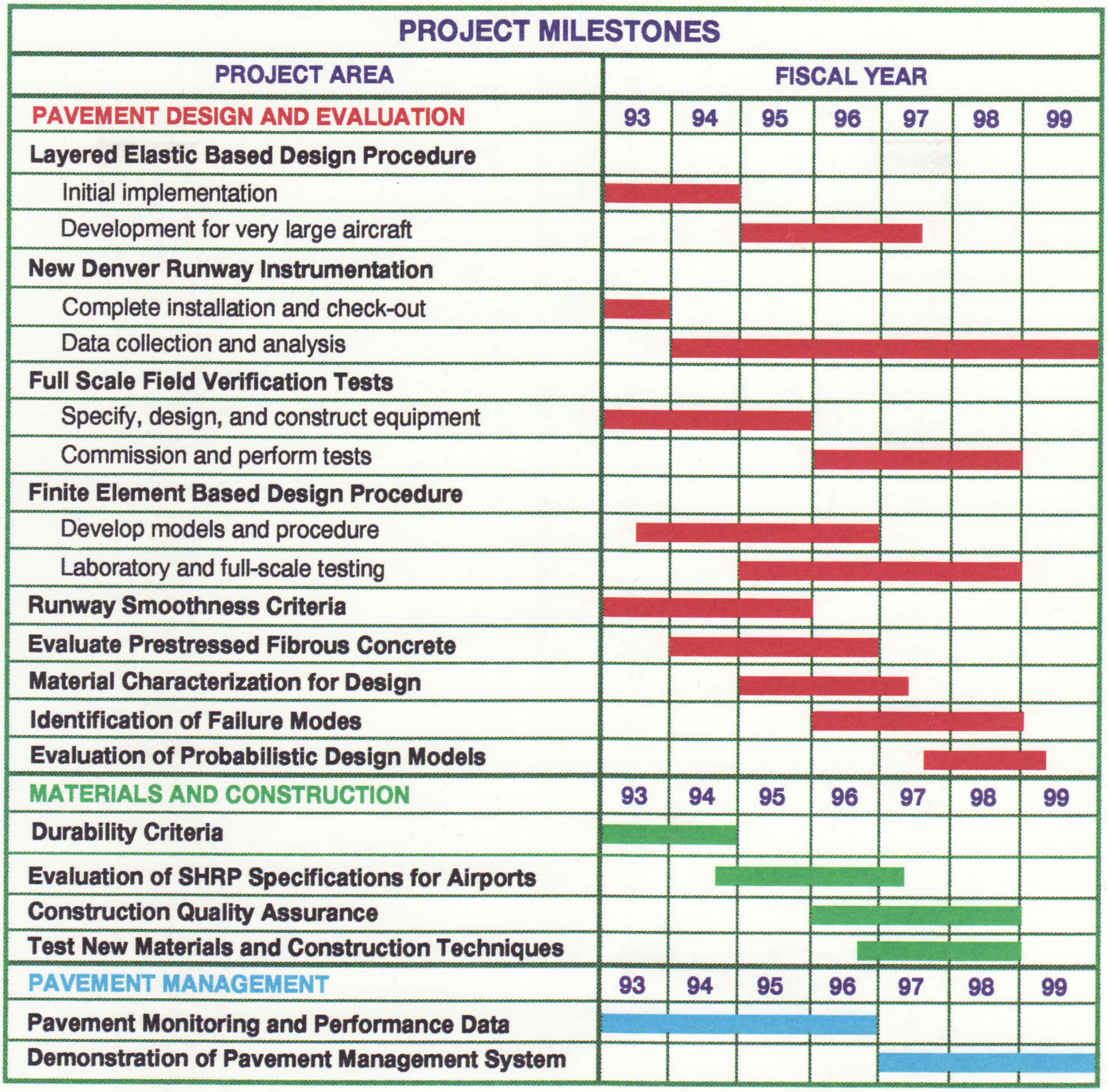
Data will be collected at the Denver International Airport site for at least six years, and will be used to study the in-service behavior of the pavement as well as its response to individual aircraft loading.

Pavement Management

A major five year study is now underway to upgrade and enhance the Pavement Performance and Monitoring System (PPMS). PPMS is a computer program for analyzing airport pavement performance from pavement condition data collected at periodic intervals. Development of the computer program will be based on data collected at a minimum of 15 airports over a period of four years. Project results will be used to develop improved pavement management procedures and will provide a substantial repository of information which can be used to study the patterns of distress and failure of airport pavements.

Notes

Table 2. Summary of Major Pavement Projects through the end of 1999



McDonnell Douglas MD-12 Envisioned Growth Model - 600 passengers, 1.2 million pounds