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Landing Gear Integration in Aircraft Conceptual Design

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Abstract

Landing gear integration is one of the more fundamental aspects of aircraft design. The design and integration process encompasses numerous engineering disciplines, *e.g.*, structures, weights, runway design, and economics. Although the design process is well-documented, it appears not to have been automated for uses in multidisciplinary design optimization (MDO) procedures. The process remains a key responsibility of the configuration designer. This paper describes the development of an MDO-capable design methodology focused on providing the conceptual designer with tools to help automate the disciplinary analyses, *e.g.*, geometry, kinematics, flotation, and weight. The procedures are described and illustrated by application to a notional large subsonic transport aircraft, illustrating the methods and design issues.

Introduction

The design of the landing gear, which is considered “the essential intermediary between the aeroplane and catastrophe”,[1] is one of the more fundamental aspects of aircraft design. The design and integration process encompasses numerous engineering disciplines, *e.g.*, structures, weights, runway design, and economics, and has become extremely sophisticated in the last few decades.

The landing gear design process is well-documented by Conway[1] and more recently by Currey[2] and is experience-based and graphically-oriented in nature. As such, it is a key responsibility of the configuration designer during initial concept studies. However, as industry and government work to incorporate multidisciplinary design optimization (MDO) methods in the conceptual design phase, the need for a more systematic procedure has become apparent.

Accordingly, this paper describes a study to develop landing gear design and integration procedures for use within an MDO environment, with a special emphasis on advanced large subsonic transports. One example of an application would be incorporation into the ACSYNT program.[3] The complete details are contained in a recent MAD Center Report.[4]

Summary of issues to be considered

Several design considerations that must be addressed are briefly discussed to illustrate the complexity involved in the development of such a methodology. The list is made up of an ever-increasing, and sometimes conflicting, number of requirements, *e.g.*, component maximum strength, minimum weight, high reliability, low cost, overall aircraft integration, airfield compatibility, *etc*.

The location of the aircraft center of gravity (*cg*) is critical in the design and location of the landing gear. The nose and main assemblies must be located at a specific distance from the aircraft *cg*, in both the longitudinal and lateral directions, such that the aircraft is in no danger of tipping back or turning over on its side over the full range of *cg* locations. Another issue to be considered is the distribution of the aircraft weight, which is dependent on the distances between the aircraft *cg* and the nose gear and main gear assembly. Between 85 and 92 percent of the MTOW must be maintained on the main assemblies such that the brakes can provide sufficient energy to slow down the aircraft within a given runway length.[5]

Airfield compatibility has become one of the primary considerations in the design of landing gears for new large aircraft due to the high cost associated with infrastructure modification, *e.g.*, pavement reinforcement and runway and taxiway expansion.[6] Pavement bearing strength, which varies from one airport to another due to variations in subgrade materials, dictates the number and arrangement of tires needed to produce the required flotation characteristics, where flotation is defined

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as the capability of the runway pavement and other surfaces, *e.g.*, the taxiway and apron, to support the aircraft. In addition, the disposition of the landing gear is constrained by runway and taxiway geometry as found at the airports to be served. Since the ground track is dependent on the dimensions of the wheelbase and track, an increase in these dimensions could bring the aircraft over the edge of the pavement during certain maneuvers, *e.g.*, 180-degree turn and centerline-guidance taxiing, and cause the aircraft to bog down in soft soil.[7]

The soundness of a landing gear concept depends on the success of overall system integration. Ground clearance, particularly between the engine nacelle and the static groundline, plays a key role in determining the minimum length of the landing gear and the permissible takeoff rotation angle. Insufficient allowance can result in costly modifications, *e.g.*, lengthening of the strut or repositioning of the under-wing engines, that effectively rule out future growth options. The landing gear stowage issue must also be addressed as the number of main assembly struts increases with the increase in aircraft weight.[8] Trade-off studies concerning space availability, structural integrity, and weight penalties resulting from local structural reinforcements are needed to arrive at an optimum design.

The weight of the landing gear, which typically ranges from three to six percent of the maximum aircraft takeoff weight, is also a design consideration. With advances in flight science technologies, which result in reduced structural and mission fuel weights, the landing gear may become an increasingly large weight fraction in future large aircraft. Since the landing gear has virtually no contribution toward, and in some cases even has a degrading effect on, the profitability of the aircraft, it is not surprising that the design objective is to minimize the weight of the landing gear such that additional revenue-generating payload can be carried onboard. However, a major reduction in the landing gear weight may be hard to realize due to the fail-safe requirements associated with single load path structures.[9]

As an example of the problems facing a designer, consider the comparison of typical current landing gear weight predictions with actual data shown in Fig. 1. The figure shows trends from two methods suggesting an increase of weight fraction with increasing size (Torenbeek[5] and Douglas[10]), while one estimate (ACSYNT[3]) suggests a decreasing trend with increasing size. The ACSYNT approach reflects an increase in weight with additional struts. The existing aircraft base used to develop the methods becomes very small as the weight increases towards one million pounds and above. Note that the predictions of the methods are similar just below a TOGW of one million, but the trends are in opposite directions.

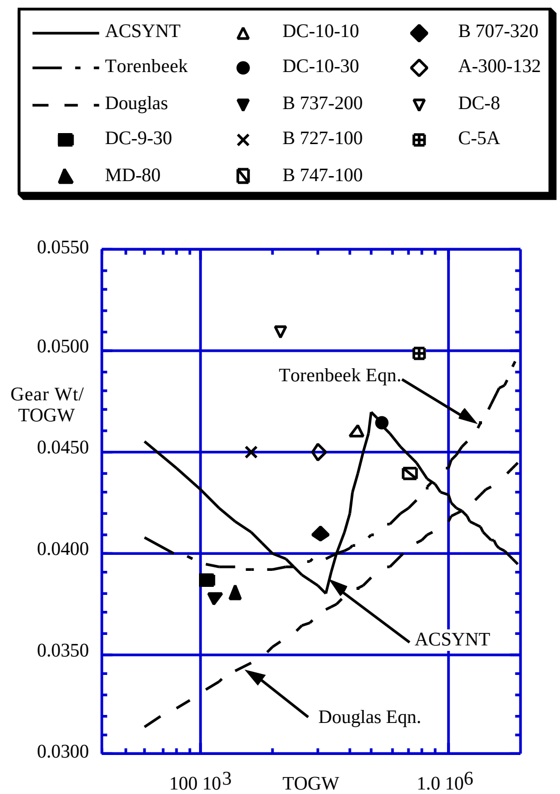


Figure 1. Comparison of classical conceptual aircraft sizing landing gear weight estimates with actual data.

With the financial challenges arising from the deregulation of the air-travel industry, the airlines have demanded that the aircraft manufacturers produce new designs with high reliability and low maintenance requirements. Recent technologies, *e.g.*, carbon-carbon heat sinks, radial tires, and high-strength steel, are being introduced. In addition, simplified design and improved manufacturing techniques, *e.g.*, die-forging and three-dimensional machining,[11] are being used to reduce the part-count associated with the landing gear system.

Center of Gravity and Gear Location

Perhaps the first consideration in including the landing gear is locating it appropriately. Many considerations constrain the location of the gear.

Virtually all the design constraints require the center of gravity, *cg*, range be known.

Center of Gravity Location

The location of the aircraft *cg* is essential in the positioning of the landing gear, as well as for other MDO applications, *e.g.*, flight mechanics, stability and control,[12,13] and performance. In the landing gear problem the aircraft *cg* location is needed to position the landing gear such that ground stability, maneuverability, and clearance requirements are met. An automated landing gear design procedure must address this problem. Current conceptual-level aircraft design codes do not estimate the *cg* range accurately. This job has been the domain of the configuration designer.

The connection between the landing gear and the *cg* has become even more critical with the adoption of advanced control systems. As pointed out by Holloway[14] in 1971, and illustrated here in Fig. 2, once the aft *cg* limit is no longer based on stability, the wing tends to move forward relative to the *cg* and the landing gear may “fall off” the wing. Thus, the tip-back angle may become an important consideration in determining the aft *cg* limit. Sliwa identified this issue in his aircraft design studies.[15]

The *cg* estimation problem has been discussed in an earlier paper by Chai and Mason.[16] The approach adopted there was to assign ranges for the locations of the components of the aircraft based on examination of typical locations on existing aircraft.[17-19] This produced a table of components,[4,16] which could then be used to estimate the range of *cg* locations attainable of shifting components. This range of *cg*’s can then be compared with the required *cg* range obtained from the overall system MDO analysis. If the estimate of allowable *cg* range based on shifting components includes the required *cg* range, then we can conclude that the configuration concept is viable. If the required range is outside of the allowable range, then the design concept has to be reconsidered. Figure 3 illustrates the concept by presenting the analysis for several existing aircraft. Based on the results we consider this analysis the minimum treatment that must be applied to an MDO analysis of a new concept.

In considering the issues facing designers of large aircraft, the most useful paper is the description of the B-747F loading envelope.[20] That paper describes in detail each limit that arises is the weight distribution.

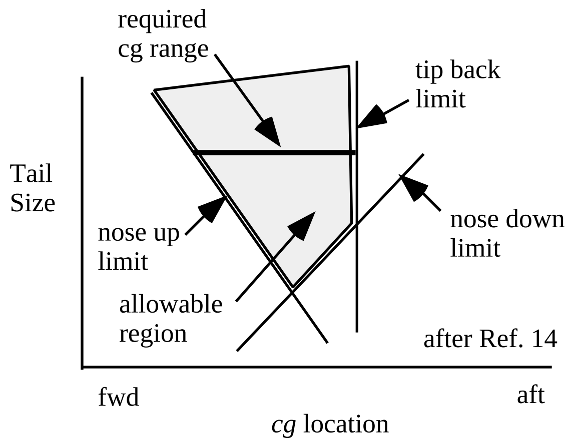


Figure 2. Typical tail sizing for modern designs with stability limit relaxed (Ref. 14)

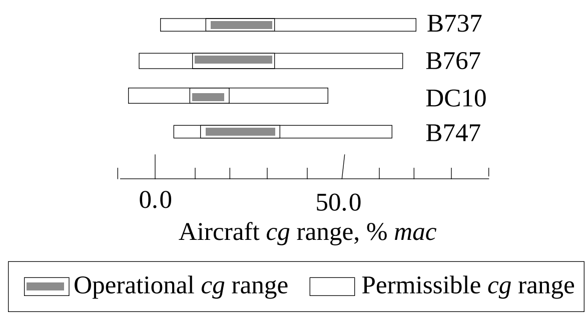


Figure 3. Actual and estimated aircraft *cg* range comparison

Finally, the precise control of the center of gravity is a difficult problem that has been studied extensively in a larger context. It apparently dates back to the 1960s, when the *loading problem* was formulated.[21] Within our context, a current example of methods to obtain a prescribed *cg* location has been given by Amiouny, *et al*.[22] A related example involving the loading of cargo on a large military transport has been discussed by Martin-Vega.[23]

Gear disposition

The design and positioning of the landing gear are determined by the unique characteristics associated with each aircraft, *i.e.*, geometry, weight, and mission requirements. Given the weight and *cg* range of the aircraft, suitable configurations are identified and reviewed to determine how well they match the airframe structure, flotation, and operational requirements. The essential features, *e.g.*, the number and size of tires and wheels, brakes, and shock absorption mechanism, must be decided before an aircraft design progresses past the concept formulation phase, after which it is often very difficult or impossible to change the design.[24] The positioning of the landing gear is based primarily on stability considerations during taxi, liftoff and touchdown, *i.e.*, the aircraft should be in no danger of turning over on its side once it is on the ground. Compliance with this requirement can be determined by examining the take-off/landing performance characteristics and the relationships between the locations of the landing gear and the aircraft *cg*. Roskam[25] has correctly noted that the landing gear location issues can determine a configuration's viability.

In our method we consider the key items required during aircraft layout. These include the angle of pitch and roll during takeoff and landing, stability at touchdown and during taxi, sideways turnover angle, braking and steering qualities, gear length, landing gear attachment, aircraft turning radius, and centerline-guidance taxiing. Taken together, these considerations can be used to locate the gear. We have checked many of our analysis by comparison with typical manufacturer's material provided to airport planners.[26] The complete document, Ref. 4, contains the details.

Besides the initial clearance considerations, allowance must also be considered for future stretching of the aircraft, which generally involves adding plugs forward and aft of the wing spars. Provided that the attitude of the aircraft will remain the same, the increase in the aft fuselage length would thus reduce the maximum permissible takeoff rotation angle, which can result in costly modifications and thus effectively rule out future growth options. Boeing abandoned further stretches of the Model 727 partially because of the difficulties encountered while attempting to maintain an adequate tail scrape angle, whereas Douglas was able to reduce the required tail scrape angle on the MD-11 by increasing the wing incidence by three degrees over that of its 22-foot shorter DC-10-30 forebear.

Tires, Wheels Brakes, and Shock Absorbers

The number of tires required for a given aircraft design gross weight is largely determined by the flotation characteristics, which will be discussed later. Assuming that the number and distribution pattern of the tires is already known, specific tires, weights and sizes of wheels, and brakes that will meet the performance requirements must be selected.

Selection algorithms were developed based on various selection criterion. Minimum size, weight, or pressure, are used to select suitable tires and wheels from manufacturer's catalogs[27] and standards[28], while a statistical database was used to size the brakes to meet the braking requirements.[2]

The basic function of the shock absorber is to absorb and dissipate the impact kinetic energy to the extent that accelerations imposed upon the airframe are reduced to a tolerable level. To accomplish the above tasks, the shock absorber must provide adequate damping to both low and high frequency excitation forces encountered during landing and taxiing, respectively. We considered oleo-pneumatic shock absorbers. The size of the shock absorbers is critical in determining the size and weight of the gear strut. The methods developed essentially automated the methodology described by Currey.[2] Here again, Ref. 4 should be consulted for complete details.

Kinematics

Kinematics is the term applied to the design and analysis of those parts used to retract and extend the gear. Particular attention is given to the determination of the geometry of the deployed and retracted positions of the landing gear, as well as the swept volume taken up during deployment/retraction. The objective is to develop a simple deployment/retraction scheme that takes up the least amount of stowage volume, while at the same time avoiding interference between the landing gear and surrounding structure. The simplicity requirement arises primarily from economic considerations. As shown from operational experience, complexity, in the forms of increased part-count and maintenance down-time, drives up the overall cost faster than weight. However, interference problems may lead to a more complex system to retract and store the gear within the allocated stowage volume.

The kinematic analysis developed in this study is used to establish the alignment of the pivot axis which permits the deployment/retraction of the landing gear to be accomplished in the most effective manner, and to determine the retracted position of the assemblies such that stowage boundary violations and structure interference can be identified. The stowage interference is also evaluated.

Landing Gear Weight Estimation

Statistical weight equations, although capable of producing quick and fairly accurate group weights, do not always respond to variations in landing gear design parameters. Thus, it is desirable that an analytical weight estimation method, which is more sensitive than statistical methods to variations in the design of landing gear, should be adopted. The objectives are to allow for parametric studies involving key design considerations that drive landing gear weight, and to establish crucial weight gradients to be used in the optimization process. In this work we developed an analytical weight estimation procedure to allow us to estimate landing gear weight for aircraft sizes well beyond those currently available. The method was then calibrated against existing landing gear weights.

Analytical weight estimation methods are capable of handling varying configurations and geometry, in addition to design parameters already included in the statistical methods. Using the methods of Kraus[29] and Wille,[30] the procedure consists of five basic steps: definition of gear geometry, calculation of applied loads, resolution of the loads into each structural member, sizing of required member cross-sectional area, and calculation of component and total structural weight. Although they provided an excellent guideline toward the development of an MDO-compatible analysis algorithm, detailed discussions in the area of load calculations and structure design criteria were not included.

Our generic landing gear model, consisting of axles, truck beam, piston, cylinder, drag and side struts, and trunnion, is developed based on existing transport-type landing gears. Since most, if not all, of the above items can be found in both the nose and main gear, the model can easily be modified to accommodate both types of assembly without much difficulty. Although the torsion links are presented for completeness, they are ignored in the analysis since their contributions toward the final weight estimate do not justify the amount of work involved.

For analysis validation purposes, the landing gear for the Boeing Models 707, 727, 737 and 747 were modeled and analyzed. The estimated structural weight, which includes the axle/truck, piston, cylinder, drag and side struts, and trunnion, accounts for roughly 75 percent of the total structural weight that can be represented in the model. The remaining 25 percent of the gear structural weight is made up of the torsion links, fittings, miscellaneous hardware, and the internal oleo mechanism, *e.g.*, the metering tube, seals, oil, pins, and bearings. The results are presented in Tables 1 and 2.

Table 1. Main assembly structural weight comparison

Aircraft	Estimated, lb.	Actual, lb.	Est./Act.
B737	380.8	384.0	0.99
B727	667.4	828.4	0.81
B707	1126.2	1269.0	0.89
B747	4688.5	5661.5	0.83

Table 2. Nose assembly structural weight comparison

Aircraft	Estimated, lb.	Actual, lb.	Est./Act.
B737	111.6	145.0	0.77
B727	175.0	327.3	0.53
B707	158.8	222.0	0.72
B747	937.2	1439.0	0.65

Differences between the actual and estimated structural weights in Tables 1 and 2 can be attributed to several factors. First, the models analyzed are extremely simple, *i.e.*, structural members were represented with simple geometric shapes and no considerations have been given to fillet radii, local structural reinforcement, bearing surfaces, *etc*. As for the analysis itself, simplistic equations were used to calculate the applied static and dynamic loads, and idealized structural arrangements were used to determine the member internal reactions. However, it should be noted that the results are consistent with Kraus' original analysis, where an average of 13 percent deviation was cited. Reference 4 should be consulted for more details and comparisons.

Pavement Thickness Requirements

The configuration of the landing gear has a direct impact on ground flotation requirements. Flotation is the term used to describe the capability of pavement and other surfaces to support an aircraft.[31] The number and arrangement of the wheels, along with the aircraft weight and its distribution between the nose and main assemblies, dictates the required pavement thickness for a particular aircraft. In addition, the type of the pavement found at the airports to be served by the aircraft also needs to be considered. Existing runway and apron pavements can be grouped into two categories: flexible and rigid.[7] A flexible pavement may consist of one or more layers of bituminous materials and aggregate, *i.e.*, surface, base, and subbase courses, resting on a prepared subgrade layer. People generally think of these runways as being asphalt. On the other hand, rigid pavement may consist of a slab of Portland Cement concrete placed on a layer of prepared soil. The thickness of each of the layers must be adequate to ensure that the applied loads will not damage the surface or the underlying layers.

Various flotation analyses have been developed over time in different countries and by different government agencies and organizations, and each method has a different acronym,[7] *e.g.,* the Federal Aviation Administration (FAA), the Portland Cement Association (PCA), the Waterways Experiment Station (S-77-1), and the British Air Ministry (LCN). However, the majority of these methods are based on the California Bearing Ratio (CBR) method of design[7] and Westergaard stress analysis[32]; the former is applicable for flexible pavements while the latter is for the rigid pavements.

One key concept in the establishment of the pavement thickness is the concept of the equivalent single wheel load (ESWL). In performing the standard analysis, the bogie pattern is converted to an equivalent single tire force on the surface. This concept is not necessarily precise, and in fact the FAA and Boeing are currently developing test facilities at the FAA's Atlantic City facility to establish precisely the ESWL values and verify the requirements for landing gears with the triple dual tandem configuration used in the Boeing 777.

We developed routines to compute the pavement thickness required for both flexible and rigid pavement. The routines were calibrated against published requirements, and some calibration factors were required to obtain accurate results. Reference 4 contains complete details.

The Analysis Package

Four FORTRAN programs and a spreadsheet based on the considerations outlined above were developed to provide a package for incorporation into existing MDO codes. Programs CONFIG, LIMIT, PAVE, and GEARWEI can be used together to study the global effects of variations in the landing gear design parameters on integration, airfield compatibility, weight, *etc*. In addition, the programs can be used individually to analyze a particular aspect of a given concept. In both cases, aircraft configuration characteristics have to be imported either from existing aircraft sizing codes or disciplinary analyses, while landing gear-related parameters must be specified by the user or set up as defaults. Within an optimization framework, these parameters would be treated as design variables whose optimum values would be computed by the optimizer to achieve a desired objective. However, the goal here is to demonstrate the algorithms, which can be used to automate the landing gear design process.

Description of Programs

The primary task for program CONFIG is to develop a landing gear model that can be used as the baseline configuration. Given the aircraft weight, configuration characteristics and the number of struts and tires, the program determines the loads on the tires and total braking energy to be absorbed by the brakes. Suitable tires, wheels, and brakes are either selected from manufacturers' catalogs or sized statistically. The length of the structural components, *e.g.*, axles, truck beam, piston, cylinder, and trunnion, are determined based on the attachment scheme and clearance requirements. As for the linkages, a generic attachment scheme derived from existing commercial transports is used to determine the arrangement and required length of the drag and side struts. Combining the initial input data with the intermediate results, the program establishes a mathematical model of the notional landing gear in three-dimensional space, which is used by the remaining programs for detailed analysis.

Program LIMIT is used to examine the design and kinematic characteristics of the landing gear. Given the configuration characteristics of the aircraft and the model of the notional landing gear, the turnover angle, pitch and roll angles during takeoff/landing, ground clearance, and turning radii are calculated. The calculated values are then compared with a list of specified requirements to identify possible constraint violations. From the dimension and arrangement of the landing gear and the allocated stowage space, pivot axis and retraction angle are determined using mathematical kinematic analysis. In addition, the retraction path, swept volume, and stowed position are established and compared with stowage boundaries for possible structural interference.

The flotation characteristics of the aircraft are determined by program PAVE. Flexible and rigid pavement bearing stresses associated with specified loading conditions are calculated using pavement design procedures. The required pavement thickness is converted to the standard pavement bearing strength reporting system and tabulated for comparison purposes.

The component and group weights of the landing gear are calculated by program GEARWEI. As detailed previously, the structural weight of the landing gear is determined analytically from the notional landing gear structural model, while the weight of the non-structural components is determined from a statistical database. These weights are combined to arrive at the landing gear group weight.

The programs are organized as shown in Fig. 4. Aircraft weight and configuration characteristics, as well as a limited number of landing gear-related design parameters, enter the package through program CONFIG. The former set of data is obtained either from existing aircraft sizing codes or disciplinary analyses, *e.g.*, ACSYNT[3] and FLOPS,[33], whereas the latter is user-specified or is set up as defaults. Using this information as a starting point, program CONFIG not only generates a notional landing gear model, but also data sets to be used as input to programs PAVE, LIMIT and, GEARWEI. These programs then assess flotation, operational stability, maneuverability, and stowage aspects of the aircraft/landing gear concept. If all the design constraints are satisfied, the weight can be estimated in program GEARWEI. The user then specifies modifications to the design to resolve the violations of constraints and the programs are rerun. The execution of all the programs is essentially instantaneous.

The current state of the analysis package is a compilation of a number of separate analyses. The package does not have the capability to generate the required landing gear-related parameters, *e.g.*, the number of tires and struts, attachment location, and stowage space, based on imported aircraft configuration characteristics. However, these are easily changed by the user. The proper use of the package is to make parametric studies to select the best combination of the total system and landing gear layout.

Data required by the analysis package are listed in Table 3**.** The majority of this information consists of geometric and weight characteristics associated with the aircraft: wing area and span, quarter chord sweep, fuselage length and width, maximum takeoff/landing weight, aircraft *cg* location, *etc*. These design parameters are readily available from existing aircraft sizing codes and can easily be rearranged into the card-style inputs used by the analyses. The remaining information consists of landing-gear related parameters, and as mentioned in the previous section, must be provided by the user or selected from defaults.

A description of the results generated by individual analysis are listed in Table 4. It should be pointed out that these data only represent part of the information that is produced by the analyses. Intermediate results, *e.g.*, constraint boundaries, landing gear loads and induced stresses, that might be of interest or importance to a particular discipline are currently internal to the analyses.

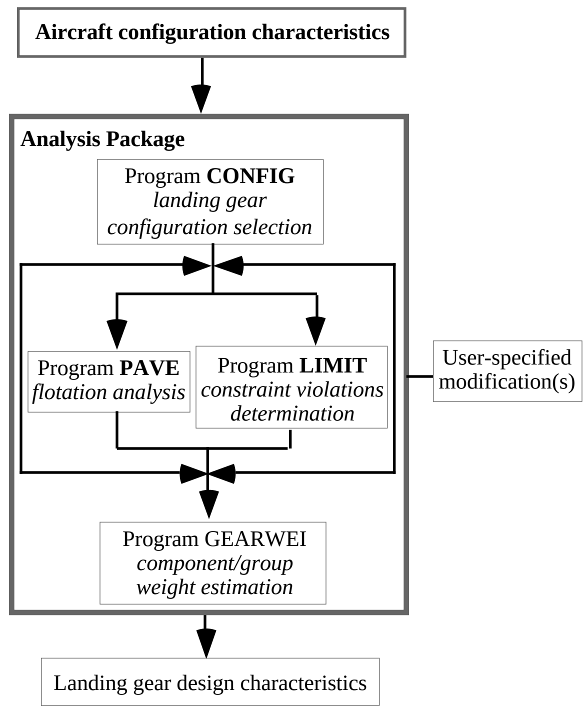


Figure 4. Information flow in analysis package

Table 3. Required input data

Parameter	Type	Description
Wing	Imported	Geometric characteristics; location
Fuselage	Imported	Geometric characteristics
Engine/ Nacelle	Imported	Geometric characteristics; location
Weight	Imported	Takeoff/landing weights; weight distribution; aircraft *cg* location
Landing gear	User-specified or default	Design/selection criteria; number of tires/struts; location; clearance; stowage space

Table 4 Analysis-generated output data

Program	Description
CONFIG	Selected tires/wheels; strokes; load-stroke curve; mathematical landing gear model
LIMIT	Trunnion alignment; retracted landing gear position; stability/operational characteristics; constraint violations
PAVE	*ESWL*s; concrete bearing stresses; pavement thickness; ACNs
GEARWEI	Structural member dimensions; landing gear component/group weight

Design Studies

The emergence of the next-generation high-capacity commercial transports[34,35] provides an excellent opportunity to demonstrate the capability of the landing gear analysis package. Thus, we study a large aircraft. Landing gear design variables were varied parametrically to show their effects on the weight, flotation, and stability characteristics. Dependencies between the variables and characteristics, as well as the magnitude of the effect, established from the parametric analysis can be used as a guideline in selecting the most effective means to alter a particular aircraft-landing gear configuration such that the desired characteristics can be obtained.

The Ultra-High-Capacity Transports

A conceptual ultra-high-capacity transport (UHCT) is conceived based on a study by Arcara *et al*.[36] and industry forecasts.[37-39] Configuration characteristics of the aircraft are presented Table 5. Note that the aircraft is classified as a Design Group VI aircraft due to its wingspan, which is slightly over the 262-foot limit.[7] To match the geometric model of the aircraft as found in ACSYNT, the wing is modeled as a simple trapezoid without an inboard trailing-edge extension, *i.e.*, the Yehudi. As a result, the location of the mean aerodynamic chord and hence the aircraft *cg* location and the attachment position of the main assembly are slightly forward than they would be in the actual design.

A triple-dual-tandem, *i.e.*, six tires per strut, configuration consisting of 24 main assembly tires is provided as a starting "guesstimate". Tire selection is based on the minimum weight criterion. Forged aluminum and carbon are selected as the construction materials for the wheels and brakes, respectively. As for the landing gear structures, 300M high-strength steel is used. The attachment scheme calls for two main gear units mounted on the wing and two units on the fuselage. The wing-mounted units retract inboard, while the fuselage-mounted units retract forward into the fuselage. The ensuing wheelbase and track dimensions are approximately 102 and 39 feet, respectively. As illustrated in Table 6, all design constraints are satisfied by this particular aircraft-landing gear combination. The landing gear weights about 56,900 pounds and accounts for roughly 4.6 percent of the MTOW.

Table 5 Configuration characteristics of a conceptual ultra-high-capacity transport

	Baseline
Passenger capacity	800
Range, nmi	7,500
Fuselage length, ft	250.0
Fuselage width, ft	24.0
Wingspan, ft	264.0
Wing area, ft^2	8,324
Aspect ratio	8.4
MTOW, lb	1,230,000
Fuel, lb	550,000

Flotation characteristics are listed in Table 7 along with actual data for McDonnell Douglas DC-10,[40] which are the highest among existing aircraft. The ACN, or aircraft classification number, is one of the standard measures of runway requirements.[2] As indicated by the data, major runway reinforcements will be needed at airports with flexible pavement and a low subgrade bearing strength to support the new aircraft. However, costs associated with such an upgrade could be in the $100 million range,[41] an investment that airport authorities are not happy about. Some major international airports with flexible pavements have a problem. However, data presented here indicate that airports with rigid pavements may not have a serious problem.

Parametric Studies

Given the baseline aircraft-landing gear combination as characterized in the previous section, landing gear design variables were varied parametrically to show their effects on the weight, flotation, and stability characteristics. Dependencies between the variables and performance, established from the parametric analysis as well as the magnitude of the effect, can be used as a guideline in selecting the most effective means to alter a particular aircraft-landing gear configuration such that the desired characteristics can be obtained.

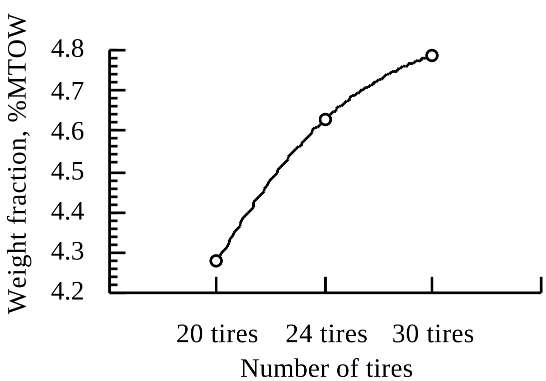
Note that there are instances where flotation and stability characteristics remain unchanged despite variations in the design parameters. Thus, only the ones that are being affected will be mentioned in the discussion.

Table 6 Baseline aircraft design characteristics

	Calculated	Constraint
Sideways turnover angle, deg	40.7	< 63.0
Roll angle, deg	7.2	< 8.0
Touchdown angle, deg	16.7	~ 15.0
Takeoff rotation angle, deg	15.4	~ 15.0
Nacelle-to-ground clearance, in	10.0	> 7.0
Castor angle, deg	37.0	< 60.0
Turning radius, ft	78.4	< 100.0
Gear weight, lb	56,885	N/A
Weight fraction, %MTOW	4.63	N/A

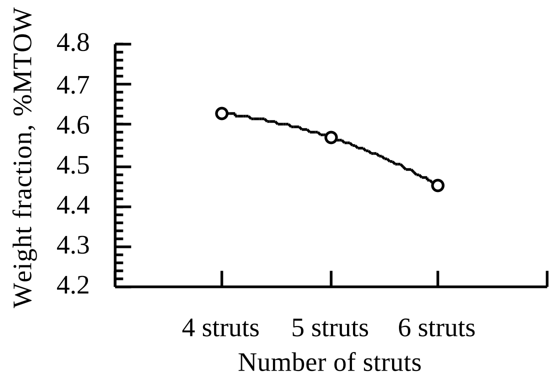
Table 7 Baseline aircraft flotation characteristics

Subgrade strength	Thickness, in (UHCT/DC10)	ACN (UHCT/DC10)
Flexible		
Ultra-low	73.5/63.9	134/97
Low	39.1/37.8	80/70
Medium	25.5/26.9	60/59
High	16.0/20.2	47/53
Rigid		
Ultra-low	18.6/17.0	96/75
Low	16.4/15.2	79/64
Medium	13.3/13.0	62/53
High	11.5/11.8	50/44

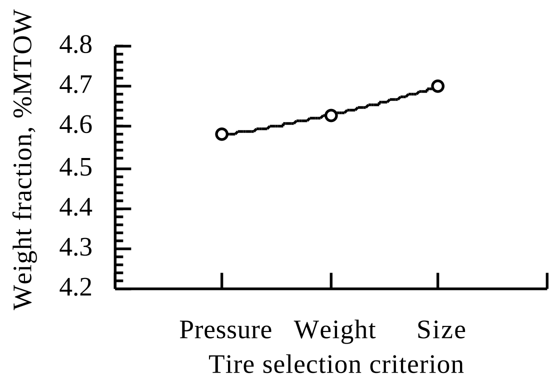


a) Number of tires, four-strut configuration

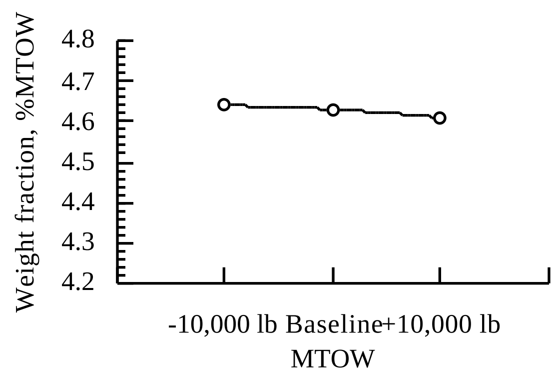
Figure 5. Changes in landing gear weight fraction due to design parameter variations



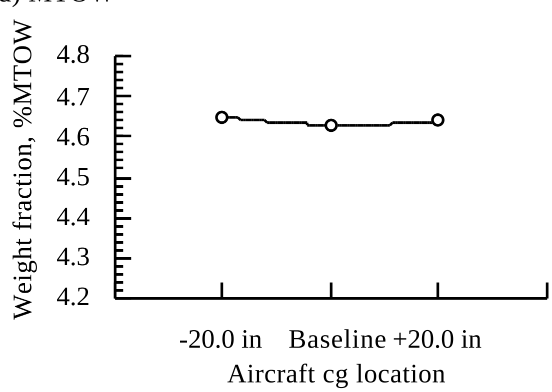
b) Number of struts, 24-tire configuration



c) Tire selection criterion

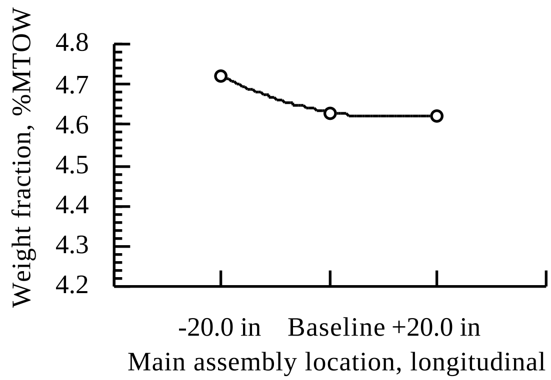


d) MTOW

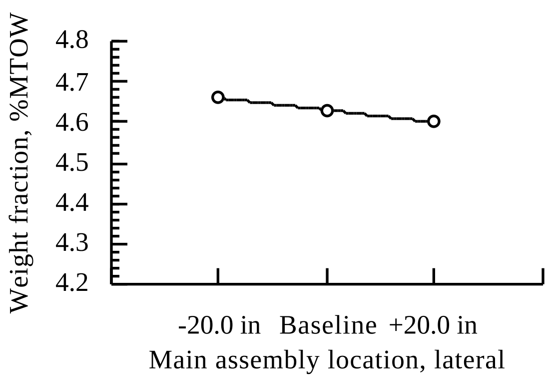


e) Aircraft *cg* location

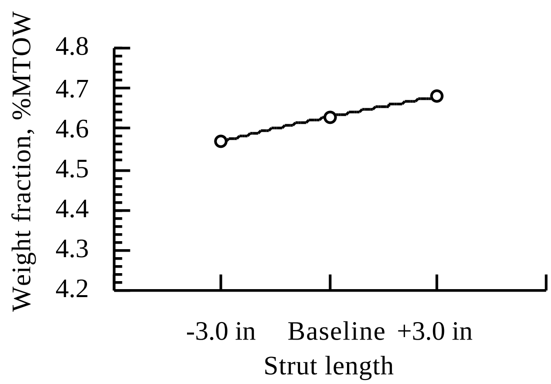
Figure 5. continued



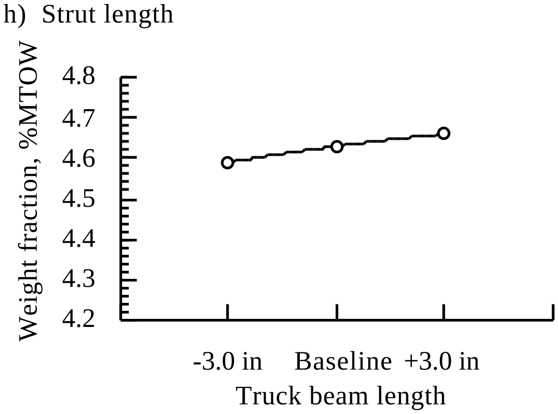
f) Main assembly location, longitudinal



g) Main assembly location, lateral

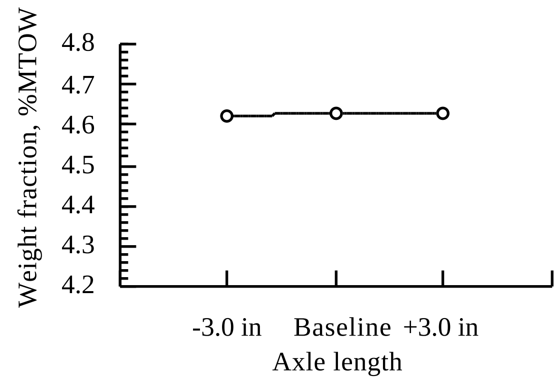


h) Strut length



i) Truck beam length

Figure 5. continued.



j) Axle length

Figure 5. Concluded

For the next-generation high-capacity transports to operate from current airports without extensive runway reinforcement, additional tires are required to redistribute the weight of aircraft over a larger area. Provided that the number of main assembly struts remains unchanged at four, the number of tires were varied both below and above the baseline figure of 24. As shown in Fig. 5a, landing gear weight fraction increases with the increase in the number of the tires. Evidently, weight penalties associated with increased part-count, as well as the dimension of the truck assembly, easily outweigh weight savings obtained from lighter tire and wheel designs that come with reduced load-carrying requirements. On the other hand, an increase in the number of tires, and hence greater tire contact area to distribute the weight of the aircraft, leads to a reduction in the required pavement thickness and the corresponding ACN. However, as shown in Table 8, the required pavement thickness is still above the DC-10 values, which implies that additional work must be done to satisfy the pavement requirements.

Table 8 Number of main assembly tires, four-strut configuration

Subgrade strength	Thickness, in		ACN	
	20 tires	30 tires	20 tires	30 tires
Flexible				
Ultra-low	71.1	68.5	127	118
Low	39.0	35.7	80	68
Medium	24.6	22.6	56	48
High	15.6	13.6	45	37
Rigid				
Ultra-low	19.6	17.6	106	86
Low	17.3	15.5	88	70
Medium	14.1	12.6	69	55
High	12.2	10.9	56	45

Varying the number of main assembly struts is another option to be considered in producing the desired flotation characteristics. As shown in Fig. 5b, provided that the number of tires remains unchanged at 24, a reduction in the landing gear weight fraction is realized with an increase in the number of main assembly struts. The reduction can be attributed to the decrease in the number of tires found on each strut, which effectively lowered the combined load on the structural members and resulted in a lighter structure. As shown in Table 9, a similar effect is evident for flotation consideration. Recall that in multiple-wheel assemblies, the flexible pavement bearing stresses are directly proportional to the number of tires involved. As a result, the required pavement thickness varies inversely with the number of struts found in a given configuration.

Table 9 Tire selection criteria, 24-tire configuration

Subgrade strength	Thickness, in		ACN	
	five struts	six struts	five struts	six struts
Flexible				
Ultra-low	73.5	67.4	135	115
Low	39.1	36.1	80	69
Medium	25.5	22.2	60	46
High	16.0	13.6	47	37
Rigid				
Ultra-low	18.6	18.6	96	96
Low	16.4	16.4	78	78
Medium	13.3	13.3	62	62
High	11.5	11.5	50	50

Besides increasing the number of main assembly tires and struts to bring about the desired reduction in the required pavement thickness, the most natural choice is to select a tire with lower inflation pressure. As shown in Figure 5c, the minimum inflation pressure candidate offers the lowest landing gear weight fraction of the three selection criteria. A reduced inflation pressure also means an increased tire-ground contact area, hence reduced pavement loads and less demanding pavement thickness requirements as shown in Table 8. It should be noted that all but a handful of tires are capable of meeting the unique requirements imposed on this class of aircraft, *i.e.*, the inflation pressure, size and weight of the above candidates are nearly identical. As a result, the effects due to such variations might not be as apparent as they would be for the other types of aircraft.

Table 10 Tire selection criteria, 24-tire configuration

Subgrade strength	Thickness, in		ACN	
	Min. press	Min. size	Min. press	Min. size
Flexible				
Ultra-low	73.1	73.5	133	135
Low	39.4	39.1	81	80
Medium	24.3	25.5	55	60
High	15.3	16.0	44	47
Rigid				
Ultra-low	18.3	18.6	92	96
Low	16.1	16.4	75	78
Medium	12.9	13.3	58	62
High	10.9	11.5	45	50

Variations in MTOW have an obvious impact on the configuration of the landing gear. As a minimum, the structural dimensions of the landing gear, hence the structural weight, would vary as the design weight of the aircraft fluctuates between different configurations. As shown in Figure 5d, the landing gear weight fraction decreases even though the actual weight of the landing gear increases with the increase in MTOW. This can be attributed to the fact that the increase in the landing gear weight lags behind the increase in the MTOW and hence a decreasing weight fraction is observed. Similarly, the decrease in the landing gear weight is slower than the decrease in the MTOW and hence a higher weight fraction is encountered. The trend shown here is reinforced by survey results obtained from industry, which indicated that a 40-pound increase in the landing gear weight can be expected for every 1,000 pounds increase in the MTOW. As expected Table 11, shows that an increase in the MTOW would require a thicker pavement to support the aircraft, and vise versa.

Table 11 MTOW variations

Subgrade strength	Thickness, in		ACN	
	-10,000 lb	+ 10,000 lb	-10,000 lb	+ 10,000 lb
Flexible				
Ultra-low	73.2	73.8	134	136
Low	39.0	39.3	80	81
Medium	25.4	25.6	59	60
High	16.0	16.0	47	47
Rigid				
Ultra-low	18.5	18.7	95	96
Low	16.3	16.5	78	79
Medium	13.3	13.3	61	62
High	11.5	11.5	50	50

Although the location of the aircraft *cg* has always played an decisive role in the positioning of the landing gear, there could be instances where other design considerations become conclusive in deciding the mounting location, *i.e.*, the landing gear has to be located at a specific location such that desired stability and maneuverability characteristics can be obtained. In such cases, the location of the aircraft *cg* must be maintained at a particular position during takeoff/landing conditions through controlled loading scheme. Once airborne, the constraints can be lifted by redistributing the fuel among various fuel tanks. As shown in Fig. 5e, provided that the location of the main assembly group is fixed, an optimum aircraft *cg* location exists at a short distance aft of current position where the weight fraction of the landing gear is at its minimum.

As shown in Figure 5f, the repositioning of the main assembly group in the aft direction results in a landing gear weight fraction that is lower than the one corresponding to a shift in the forward direction. The trend can be attributed to the reduced load that follows directly from an increased offset between the main assembly group and the location of the aircraft *cg*, *i.e.*, a longer moment arm to counteract the applied ground loads. Note that when a highly-swept, high-aspect ratio wing is considered, a rearward movement of the main assembly group might not be feasible due the wing planform constraints; the size of the inboard trailing-edge extension, *i.e.*, the Yehudi, required to provide suitable attachment location, as well as sufficient space to house the trailing-edge control surfaces and the associated actuation systems, could incur drag and weight penalties that outweigh the weight savings brought on by such movement.

The repositioning of the wing-mounted assemblies in the lateral direction primarily affects the stability and maneuverability characteristics of the aircraft. As shown in Table 12, an outboard movement of the wing-mounted assemblies produces a desired reduction in the sideways turnover angle; however, such movement shifts the minimum 180-degree turn radius closer to the 100-foot upper limit imposed by the FAA. As shown in Fig. 5g, the increasing landing gear weight fraction associated with the outboard movement of the assemblies can be attributed to the increase in the length of the side strut, as well as the increase in the drag and shock struts due to wing dihedral, and hence the structural weight of the landing gear. Conversely, an inboard movement of the assemblies exhibits a higher sideways turnover angle, a smaller turning radius, and a decreasing landing gear weight fraction.

Table 12 Wing-mounted assemblies location variations, lateral

Design characteristics	20.0 in outboard	20.0 in inboard
Sideways turnover angle, deg	38.4	43.2
Touchdown angle, deg	16.9	16.5
Takeoff rotation angle, deg	15.3	15.5
Turning radius, ft	80.1	76.7

Changes in the stability characteristics due to variations in landing gear strut length are of primary interest when a growth version of the aircraft is considered. Features typically associated with the growth options are a stretched fuselage obtained from the addition of plugs forward and aft of the wing, and upgraded power plants that come with a larger fan diameter. As shown in Table 13, provided that the length of the strut remains unchanged, the growth-related modifications can result in an increased sideways turnover angle and a reduced permissible pitch angle during takeoff/landing operations and a reduced nacelle-to-ground clearance. The lagging effect similar to the one encountered in MTOW variations is again evident as shown in Fig. 5h. The trend shown here is reinforced by survey results obtained from industry, which indicated that a per-strut, 60-pound increase in weight can be expected for every inch increase in strut length.

Table 13 Strut length variations

Design characteristics	-3.0 in	+3.0 in
Sideways turnover angle, deg	40.2	41.1
Touchdown angle, deg	16.9	16.5
Takeoff rotation angle, deg	15.3	15.5

Fluctuations in the size of the tires, wheels, and brakes due to varying design parameters, *e.g.*, loading conditions and braking energy requirements can alter the dimensions of the truck beam and axles. As can expected and reaffirmed in Figure 5i and 5j, an increase in the component length leads to a higher landing gear weight fraction, and vise versa. Data presented in Tables 14 and 15 show that an increase in either truck beam or axle length will result in a more demanding pavement thickness requirement, which is similar to the observation made earlier when the number of the tires per strut was increased. Evidently, effects on the flotation characteristics due to variations in the number of tires per strut and the length of truck beam and axles cannot be separated in a clean manner.

Table 14. Truck beam length variations

Subgrade strength	Thickness, in		ACN	
	-3.0 in	+3.0 in	-3.0 in	+3.0 in
Flexible				
Ultra-low	73.1	73.7	133	135
Low	39.1	39.2	80	80
Medium	25.5	25.5	60	60
High	16.0	16.0	47	47
Rigid				
Ultra-low	18.6	18.6	96	96
Low	16.4	16.4	78	78
Medium	13.3	13.3	62	62
High	11.5	11.5	50	50

Table 15. Axle length variations

Subgrade strength	Thickness, in		ACN	
	-3.0 in	+3.0 in	-3.0 in	+3.0 in
Flexible				
Ultra-low	73.4	73.6	134	135
Low	38.7	39.5	79	82
Medium	25.1	25.8	58	61
High	15.7	16.3	46	48
Rigid				
Ultra-low	18.6	18.6	96	96
Low	16.4	16.4	78	78
Medium	13.3	13.3	62	62
High	11.5	11.5	50	50

Derivatives

In today's highly competitive environment, flexibility in terms of being able to meet the vastly different requirements from various airline customers, *e.g.*, a longer range and an extended payload capacity, has become one of the primary consideration in the design and marketing of a new aircraft. To ensure that a customer will have a list of options to select from when it comes to time to place an order, derivatives are considered early on in the conceptual design phase, and more than likely, being pursued in a parallel track with the baseline aircraft.

Two derivatives were envisioned for the baseline aircraft: advanced wing and extended range. Corresponding configuration characteristics are shown in Table 16. Although the wing planform of the advanced wing derivative is slightly different from the baseline and the extended range version, it is assumed that the configuration of the landing gear on all three aircraft are identical, *i.e.*, 24 main assembly tires on four struts. Note that this assumption does not imply that the weights of all three landing gear are identical.

Table 16. Derivative configuration characteristics

	Extended range	Advanced wing
Passenger capacity	800	800
Range, nmi	8,000	7,500
Fuselage length, ft	250.0	250.0
Fuselage width, ft	24.0	24.0
Wing span, ft	264.0	261.0
Wing area, ft^2	8,324	7,423
Aspect ratio	8.4	9.2
MTOW, lb	1,350,000	1,140,000
Fuel, lb	640,000	460,000

As shown in Fig. 6, the advanced wing derivative has the highest landing gear weight fraction out of the three configurations, whereas the extended range derivative has the lowest of the three. For identical mission requirements, *i.e.*, between the baseline and the advanced wing derivative, the baseline aircraft will come out on top if the deciding factor is based on landing gear weight fraction, which implies that a greater fraction of the total aircraft weight is made up of revenue-generating payloads. As for the extended range derivative, although the landing gear weight fraction is lower than the other two aircraft, the required pavement thickness as shown in Table 17 can result in a prohibitive runway upgrade cost. However, the desired flotation characteristics can be obtained by replacing the conventional wing design with the one found on the advanced wing derivative, the reduction in mission fuel weight associated with higher performance due to the advanced wing design would then lower the MTOW of the extended range derivative and hence the required pavement thickness.

The baseline aircraft along with its derivatives are used to provide some analytically-based landing gear weight estimates that can be used to help calibrating existing statistical weight equations. Although statistical weight equations are capable of producing quick and fairly accurate group weights within the range where significant previous experience is available, their reliability is questionable at best for aircraft with takeoff weights beyond one million pounds, *i.e.*, they are constrained by what has been designed in the past. This uncertainty is made evident by the two possible weight trends available: a decreasing trend as predicted by ACSYNT and an increasing trend as predicted by Douglas and Torenbeek. As shown in Fig. 7, landing gear weight fractions corresponding to the baseline aircraft and its derivatives indicated that the weight equation used by ACSYNT is better suited than the ones used by Douglas and Torenbeek.

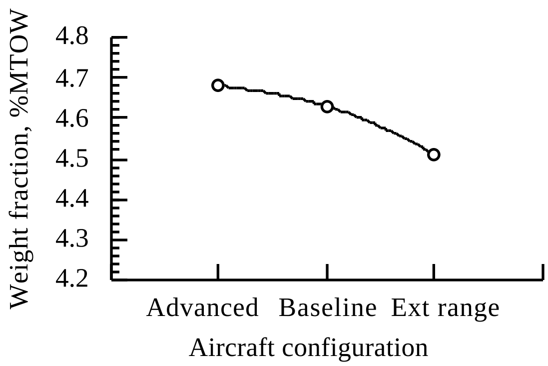


Figure 6. Changes in landing gear weight fraction due to aircraft configuration variations

Table 17. Aircraft configuration variations

Subgrade strength	Thickness, in		ACN	
	Ext. range	Adv. wing	Ext. range	Adv. wing
Flexible				
Ultra-low	77.1	70.0	148	90
Low	40.8	37.9	88	75
Medium	25.5	24.6	61	60
High	15.6	15.6	48	50
Rigid				
Ultra-low	19.3	18.2	104	122
Low	16.9	16.1	84	75
Medium	13.6	13.2	65	55
High	11.6	11.6	52	43

Conclusions

The design of the landing gear is one of the more fundamental aspects of aircraft design. The design and integration process encompasses numerous engineering disciplines, *e.g.*, structures, weights, runway design, and economics. We have incorporated most of the considerations required for the integration of the landing gear in an MDO procedure for use in the conceptual design of large transport aircraft. Accomplishments include:

- Aircraft *cg* estimation methods were studied and a new approach to *cg* estimation in conceptual design was demonstrated
- An automated landing gear model concept for large transport aircraft configurations was developed, and conformance with typical FAR requirements was assessed automatically.

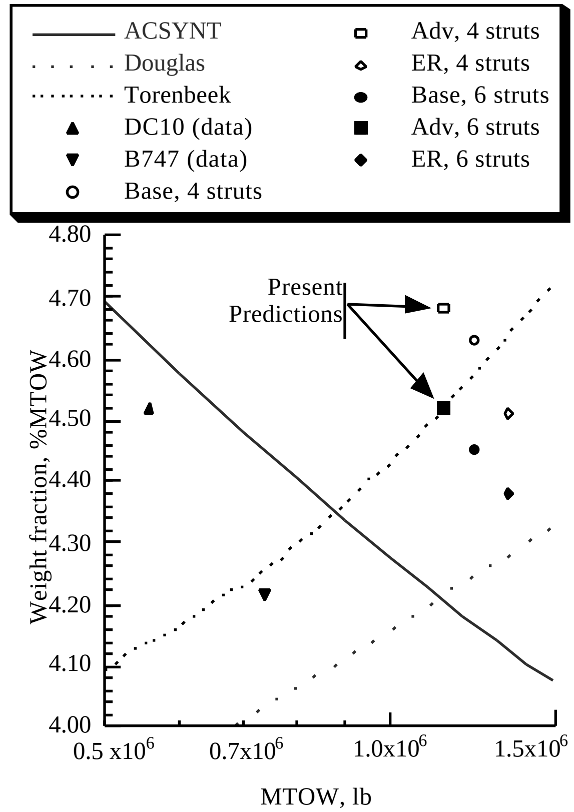


Figure 7. Landing gear weight fraction beyond one million pounds MTOW

- Airfield compatibility issues associated with pavement thickness and runway and taxiway dimensions were automated.
- An analytical structural weight estimation procedure was developed to compliment existing experience-based statistical landing gear weight estimation methods.
- Results obtained from the procedures were presented, illustrating the trade studies and parametric results available for incorporation into a complete MDO design procedure.

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