Chapter 10 Parametric Studies

10.1. Introduction

The emergence of the next-generation high-capacity commercial transports [51 and 52] provides an excellent opportunity to demonstrate the capability of the landing gear analysis package as detailed in the previous chapter. Landing gear design variables were varied parametrically to show their effects on the weight, flotation, and stability characteristics. Dependencies between the variables and characteristics 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 so that the desired characteristics can be obtained.

10.2. The Ultra-High-Capacity Transports

A conceptual ultra-high-capacity transport (UHCT) was established based on a study by Arcara *et al*. [53] and industry forecasts [54, 55 and 56]. Configuration characteristics of the aircraft are presented in Table 10.1. Note that the aircraft is classified as a Design Group VI aircraft according to its wingspan, which is slightly over the specified 262-foot upper 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 wing *mac* and hence the aircraft *cg* location and the attachment position of the main assembly are slightly forward of where they would be in the actual design.

Twenty-four main assembly tires arranged in a triple-dual-tandem configuration, *i.e.*, six tires per strut, are used as an initial design. 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. For the landing gear structure, 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. Given this information, the analysis package as described in Chapter Nine is used to determine the design characteristics associated with this particular aircraft-landing gear combination. As shown in Table 10.2, all design constraints are satisfied. The landing gear weighs about 56,900 pounds and accounts for roughly 17.4 percent of the aircraft structural weight, or 4.6 percent of the MTOW.

Table 10.1 Configuration characteristics of a conceptual UHCT

	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

Table 10.2 Baseline aircraft design characteristics

	Calculated	**Constraint**
Sideways turnover angle, deg	40.7	< 63.0
Roll angle, deg	7.2	< 8.0
Available touchdown angle, deg	16.7	~ 15.0
Available 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	-
Weight fraction, %MTOW	4.63	-

The flotation characteristics are given in Table 10.3 along with actual data for the McDonnell Douglas DC10, which are highest among existing aircraft. As shown in Table 10.3, major runway reinforcements will be needed at airports with a combination of flexible pavements and a low bearing strength subgrade. Costs associated with such an upgrade could be in the $100 million range [6], an investment that might not be acceptable to airport authorities. Consequently, some major international airports with flexible pavements might not be able to handle the UHCT unless design changes are made to the aircraft. Results in Table 10.3 indicate that airports with rigid pavements are better suited in handling this class of aircraft. Note that as the subgrade strength approaches its upper limit, the required flexible and rigid pavement thickness for the new aircraft are actually lower than the ones required by the DC10. This is consistent with the trend observed in Chapter

Seven, *i.e.*, as the number of wheels per strut increases, the required pavement thickness decreases with the increase in the subgrade strength.

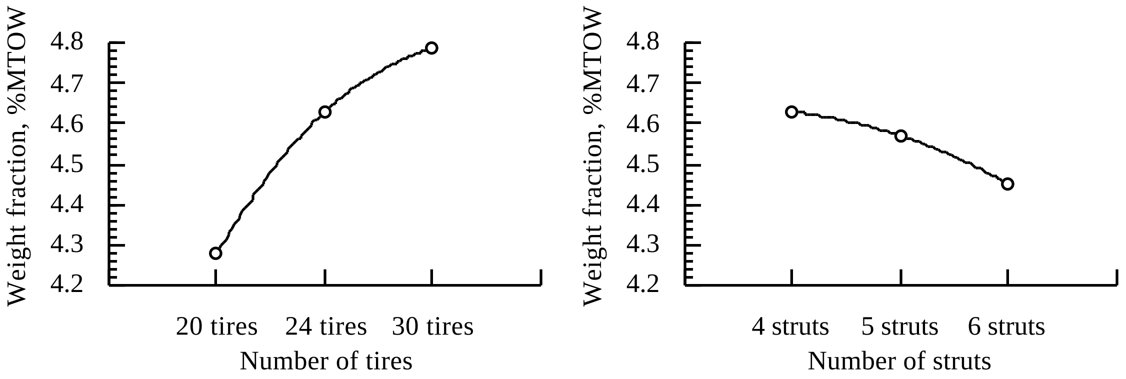
Table 10.3 Baseline aircraft flotation characteristics

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

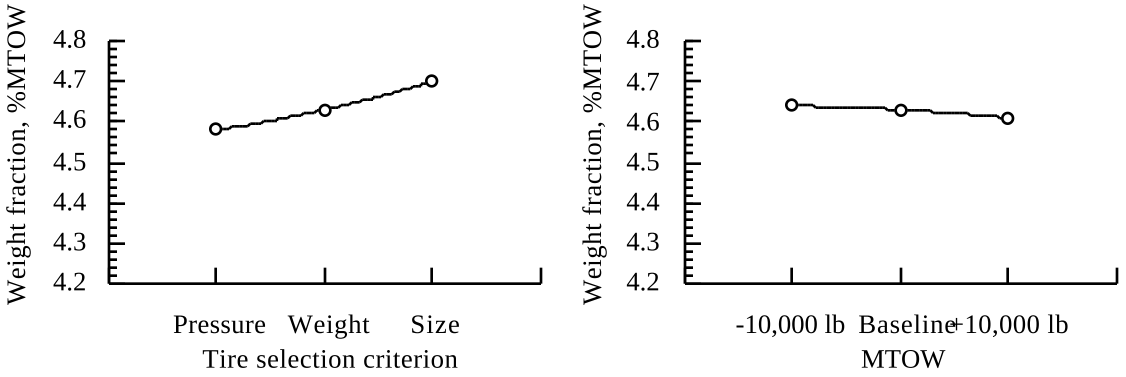
10.3. Parametric Studies

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 various control variables and resulting aircraft characteristics established from this study, as shown here in Fig. 10.1, can be used as a guideline in selecting the most effective means to alter a particular aircraft-landing gear configuration so that the desired characteristics may be obtained. Note that there are instances where flotation and stability characteristics remain unchanged despite variations in the design parameters. Thus, only the characteristics being affected will be discussed.

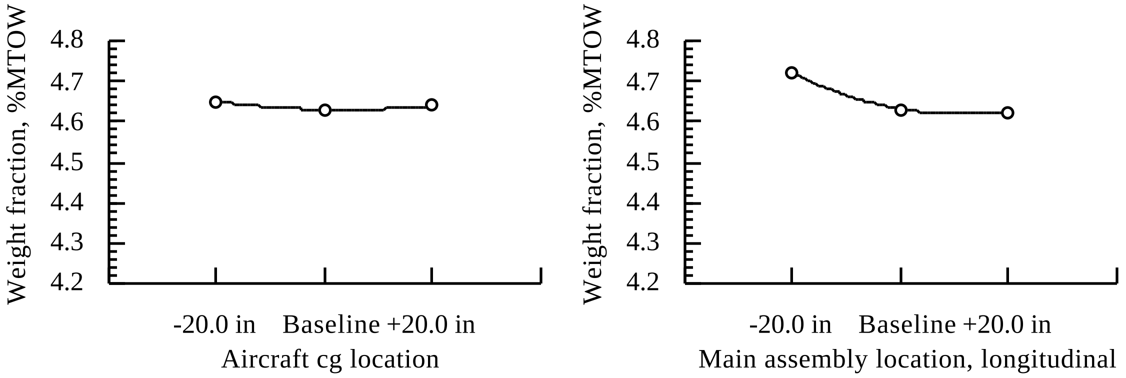
In order for the UHCT to be able to operate from current airports without extensive runway reinforcement, additional tires are required to redistribute the weight of the aircraft over a larger tire-ground contact area. Provided the number of main assembly struts remains unchanged at four, the number of tires were varied both above and below the baseline (24). As shown in Fig. 10.1a, landing gear weight fraction increases with the increase in the number of tires. Evidently, weight penalties associated with the dimension of the truck assembly as well as the increased part-count, easily outstrip weight savings obtained from lighter tire and wheel designs that come with reduced load-carrying requirements. As shown in Table 10.4, the increased tire-ground contact area leads to reductions in required pavement thickness and the corresponding ACN when compared to the baseline figures.



a) Number of tires, four-strut configuration b) Number of struts, 24-tire configuration

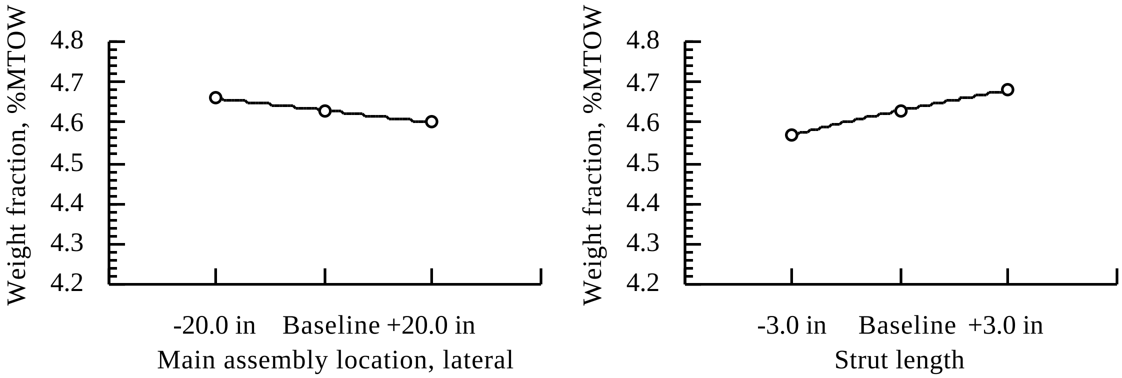


c) Tire selection criterion d) MTOW



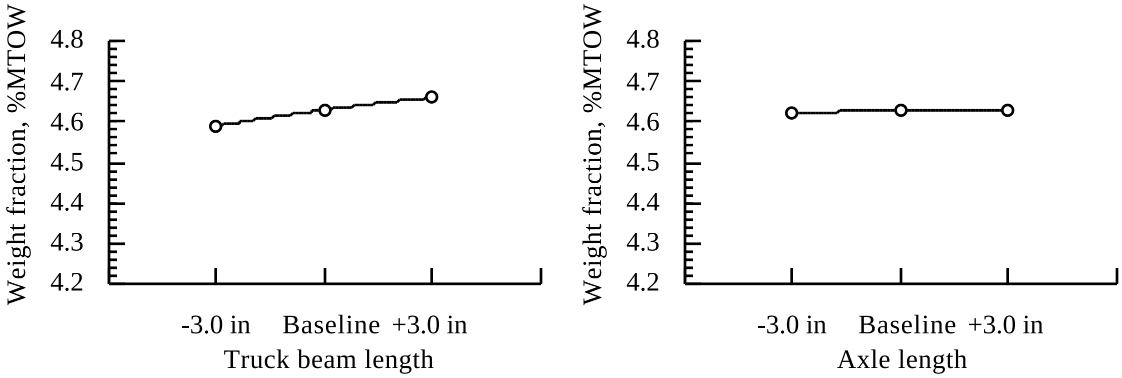
e) Aircraft *cg* location f) Main assembly location, longitudinal

Figure 10.1 Changes in landing gear weight fraction due to design parameter variations



g) Main assembly location, lateral

h) Strut length



i) Truck beam length

j) Axle length

Figure 10.1 Changes in landing gear weight fraction due to design parameter variations (concluded)

Varying the number of main assembly struts is another option to be considered in producing the desired flotation characteristics. As shown in Fig. 10.1b, provided 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 lowers the combined load on the structural members and therefore leads to a lighter structure. As shown in Table 10.5, a reduction in the required flexible pavement thickness is evident as the number of the struts increases. Recall that in multiple-wheel assemblies, the flexible pavement bearing stresses are directly proportional to the number of tires per strut involved in the calculation and hence the required pavement thickness. The rigid pavement thickness requirements remain unchanged since the stresses obtained from Westergaard's analysis are independent of the number of main assembly struts.

Table 10.4 Number of main assembly tires, four-strut configuration

Subgrade strength	**Thickness, in**		**ACN**	
	20 tires (Des./Base)	**30 tires (Des./Base)**	**20 tires (Des./Base)**	**30 tires (Des./Base)**
Flexible				
Ultra-low	71.1/73.5	68.5/73.5	127/134	118/134
Low	39.0/29.1	35.7/29.1	80/80	68/80
Medium	24.6/25.5	22.6/25.5	56/60	48/60
High	15.6/16.0	13.6/16.0	45/47	37/47
Rigid				
Ultra-low	19.6/18.6	17.6/18.6	106/96	86/96
Low	17.3/16.4	15.5/16.4	88/76	70/76
Medium	14.1/13.3	12.6/13.3	69/62	55/62
High	12.2/11.5	10.9/11.5	56/50	45/50

Table 10.5 Number of main struts, 24-tire configuration

Subgrade strength	**Thickness, in**		**ACN**	
	five struts (Des./Base)	**six struts (Des./Base)**	**five struts (Des./Base)**	**six struts (Des./Base)**
Flexible				
Ultra-low	73.5/73.5	67.4/73.5	135/134	115/134
Low	39.1/39.1	36.1/39.1	80/80	69/80
Medium	25.5/25.5	22.2/25.5	60/60	46/60
High	16.0/16.0	13.6/16.0	47/47	37/47
Rigid				
Ultra-low	18.6/18.6	18.6/18.6	96/96	96/96
Low	16.4/16.4	16.4/16.4	78/79	78/79
Medium	13.3/13.3	13.3/13.3	62/62	62/62
High	11.5/11.5	11.5/11.5	50/50	50/50

Besides increasing the number of main assembly tires and struts to bring about the desired reduction in the required pavement thickness, another option is to select a tire with a lower inflation pressure. As shown in Fig. 10.1c, 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 pavement thickness requirements as shown in Table 10.6. It should be noted that all but a select few of large tires available are capable of meeting the performance requirements imposed by the UHCT. That is, the inflation pressure, size, and weight of the candidate tires are nearly identical. As a result, the effects due to such variations might not be as apparent as they would be for other types of aircraft, where the selection is based on a larger pool of candidate tires.

Variations in MTOW have an obvious impact on the configuration of the landing gear and the pavement thickness. As a minimum, the structural dimensions of the landing gear and hence the structural weight would vary as the design weight of the aircraft changes between different configurations. As shown in Fig 10.1d, the landing gear weight fraction decreases even though the actual landing gear weight increases with the MTOW. This can be attributed to the fact that the landing gear weight does not increase with the MTOW in a pound-for-pound manner, and therefore a decreasing weight fraction is observed. Similarly, the landing gear weight decreases at a slower rate than the MTOW, yielding a higher weight fraction. The magnitude of the landing gear weight variation is similar to that provided by industry, where a 40-pound increase in the landing gear weight per 1,000 pounds increase in the MTOW is anticipated [App. A]. As reaffirmed in Table 10.7, an increase in the MTOW would require a thicker pavement to support the aircraft, and vice versa.

Table 10.6 Tire selection criteria, 24-tire configuration

Subgrade strength	**Thickness, in**		**ACN**	
	Min. press (Des./Base)	**Min. size (Des./Base)**	**Min. press (Des./Base)**	**Min. size (Des./Base)**
Flexible				
Ultra-low	73.1/73.5	73.5/73.5	133/134	135/134
Low	39.4/39.1	39.1/39.1	81/80	80/80
Medium	24.3/25.5	25.5/25.5	55/60	60/60
High	15.3/16.0	16.0/16.0	44/47	47/47
Rigid				
Ultra-low	18.3/18.6	18.6/18.6	92/96	96/96
Low	16.1/16.4	16.4/16.4	75/79	78/79
Medium	12.9/13.3	13.3/13.3	58/62	62/62
High	10.9/11.5	11.5/11.5	45/50	50/20

Although the location of aircraft *cg* has always played a decisive role in the positioning of the landing gear, instances are possible where design considerations become conclusive in deciding the mounting location, *i.e.*, the landing gear has to be located at a specific location so that desired stability and maneuverability characteristics can be obtained. As shown in Fig. 10.1e, for this particular aircraft-landing gear combination, provided that the location of the main assembly group is fixed, an optimum aircraft *cg* location exists at a short distance aft of the current position where the weight fraction of the landing gear is at its minimum. In such cases, the location of the aircraft *cg* must be maintained at a particular position during takeoff and landing conditions through a controlled loading scheme. Once airborne, the constraints can be relaxed by redistributing the fuel among various fuel tanks.

As shown in Fig. 10.1f, 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. This 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 be extremely difficult. Moving the gear aft could effect takeoff rotation speed and takeoff distance, which has to be checked. Also, brake weight may increase if the rotation speed increases, increasing the deceleration demands for the balanced field length requirement. Finally, the shift may not be feasible due to wing planform constraints, such as the size of the inboard trailing-edge extension (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. The Yehudi also incurs drag and weight penalties that need to be considered.

The repositioning of the wing-mounted assemblies in the lateral direction affects primarily the stability and maneuverability characteristics of the aircraft. As shown in Table 10.8, an outboard movement of the wing-mounted assemblies produces a desired reduction in the sideways turnover angle; however, such a movement shifts the minimum 180-degree turn radius closer to the Class VI 100-foot upper limit [5]. As shown in Fig. 10.1g, the increasing landing gear weight fraction can be associated with the outboard movement of the assemblies. This leads to an increase in the length of the side strut, as well as an 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 10.7 MTOW variations

Subgrade strength	Thickness, in		ACN	
	-10,000 lb (Des./Base)	+ 10,000 lb (Des./Base)	-10,000 lb (Des./Base)	+ 10,000 lb (Des./Base)
Flexible				
Ultra-low	73.2/73.5	73.8/73.5	134/134	136/134
Low	39.0/39.1	39.3/39.1	80/80	81/80
Medium	25.4/25.5	25.6/25.5	59/60	60/60
High	16.0/16.0	16.0/16.0	47/47	47/47
Rigid				
Ultra-low	18.5/18.6	18.7/18.6	95/96	96/96
Low	16.3/16.4	16.5/16.4	78/79	79/79
Medium	13.3/13.3	13.3/13.3	61/62	62/62
High	11.5/11.5	11.5/11.5	50/50	50/50

Table 10.8 Wing-mounted assemblies location variations, lateral

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

Changes in the stability characteristics and ground clearance 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. Both of the above features would require an extension of the strut length to maintain the desired operation angles and nacelle-to-ground clearance. As shown in Table 10.9, the growth-related modifications can result in an increased sideways turnover angle and a reduced permissible pitch angle during takeoff/landing operations. As can be expected and reaffirmed in Fig. 10.1h, an increase in strut length leads to an increase in structural weight, and therefore an increase in the landing gear weight fraction, as well as vice versa. The magnitude of the landing gear weight variation is again similar to the one provided by industry, where a 60-pound increase in weight per strut is anticipated for every inch increase in strut length [App. A].

Changes 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 by Figs 10.1i and 10.1j, an increase in the component length leads to a higher landing gear weight fraction, and vice versa. Data presented in Tables 10.10 and 10.11 show that an increase in either truck beam or axle length will result in a thicker pavement .

Table 10.9 Strut length variations

Design characteristics	-3.0 in	+3.0 in
Sideways turnover angle, deg	40.2	41.1
Available touchdown angle, deg	16.9	16.5
Available takeoff rotation angle, deg	15.3	15.5

Table 10.10 Truck beam length variations

Subgrade strength	Thickness, in		ACN	
	-3.0 in (Des./Base)	+3.0 in (Des./Base)	-3.0 in (Des./Base)	+3.0 in (Des./Base)
Flexible				
Ultra-low	73.1/73.5	73.7/73.5	133/134	135/134
Low	39.1/39.1	39.2/39.1	80/80	80/80
Medium	25.5/25.5	25.5/25.5	60/60	60/60
High	16.0/16.0	16.0/16.0	47/47	47/47
Rigid				
Ultra-low	18.6/18.6	18.6/18.6	96/96	96/96
Low	16.4/16.4	16.4/16.4	78/79	78/79
Medium	13.3/13.3	13.3/13.3	62/62	62/62
High	11.5/11.5	11.5/11.5	50/50	50/50

10.4. Derivatives of the Baseline Aircraft

In today’s highly competitive environment, flexibility in 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 considerations 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 time to place an order, derivatives are considered early on in the conceptual design phase, and more than likely, pursued in parallel with the baseline aircraft.

Table 10.11 Axle length variations

Subgrade strength	**Thickness, in**		**ACN**	
	-3.0 in (Des./Base)	**+3.0 in (Des./Base)**	**-3.0 in (Des./Base)**	**+3.0 in (Des./Base)**
Flexible				
Ultra-low	73.4/73.5	73.6/73.5	134/134	135/134
Low	38.7/39.1	39.5/39.1	79/80	82/80
Medium	25.1/25.5	25.8/25.5	58/60	61/60
High	15.7/16.0	16.3/16.0	46/47	48/47
Rigid				
Ultra-low	18.6/18.6	18.6/18.6	96/96	96/96
Low	16.4/16.4	16.4/16.4	78/79	78/79
Medium	13.3/13.3	13.3/13.3	62/62	62/62
High	11.5/11.5	11.5/11.5	50/50	50/50

Two derivatives were envisioned for the baseline UHCT: advanced (high aspect ratio) wing and extended range (8,000 nmi); corresponding configuration characteristics are shown in Table 10.12. 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 10.12 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 Figure 10.2, the advanced wing derivative has the highest landing gear weight fraction of the three configurations, whereas the extended range derivative has the lowest of the three. For identical mission requirements between the baseline and the advanced wing derivative, the baseline aircraft will be the preferred choice if the deciding factor is based on landing gear weight fraction, its lower landing gear weight fraction implies that a greater fraction of the total aircraft weight is made up by revenue-generating payloads. However, if the deciding factor is something other than the landing gear weight faction, *e.g.*, operating cost or runway upgrade cost, the advanced wing configuration will be the preferred choice due to its lower mission fuel requirements and lighter MTOW, respectively. 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 10.13 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.

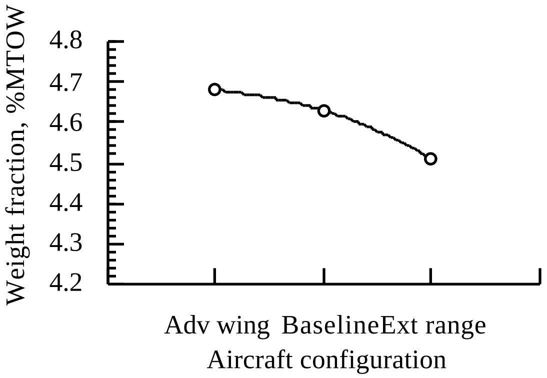


Figure 10.2 Changes in landing gear weight fraction due to aircraft configuration variations

10.5. Landing Gear Weight Trend for Large Aircraft

The baseline aircraft along with its derivatives are used to provide some analytically-based landing gear weight estimates that can be used to help calibrate 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 weight beyond one million pounds, *i.e.*, they are constrained by what has been designed in the past. The 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. 10.3, landing gear weight fractions corresponding to the baseline aircraft and its derivatives suggest that the weight equation used by ACSYNT is likely to produce a more accurate trend than the ones used by Douglas and Torenbeek. In addition, an increase in the number of main assembly struts from four to six did not result in a step increase in the weight fraction as expected. Again, this 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 therefore led to a lighter structure. Note that additional aircraft within the UHCT class must be modeled to extend the database so that the weight trends as observed here may be confirmed.

Table 10.13 Aircraft configuration variations

Subgrade strength	**Thickness, in**		**ACN**	
	Ext. range (Des./Base)	**Adv. wing (Des./Base)**	**Ext. range (Des./Base)**	**Adv. wing (Des./Base)**
Flexible				
Ultra-low	77.1/73.5	70.0/73.5	148/134	90/134
Low	40.8/39.1	37.9/39.1	88/80	75/80
Medium	25.5/25.5	24.6/25.5	61/60	60/60
High	15.6/16.0	15.6/16.0	48/47	50/47
Rigid				
Ultra-low	19.3/18.6	18.2/18.6	104/96	122/96
Low	16.9/16.4	16.1/16.4	84/79	75/79
Medium	13.6/13.3	13.2/13.3	65/62	55/62
High	11.6/11.5	11.6/11.5	52/50	43/50

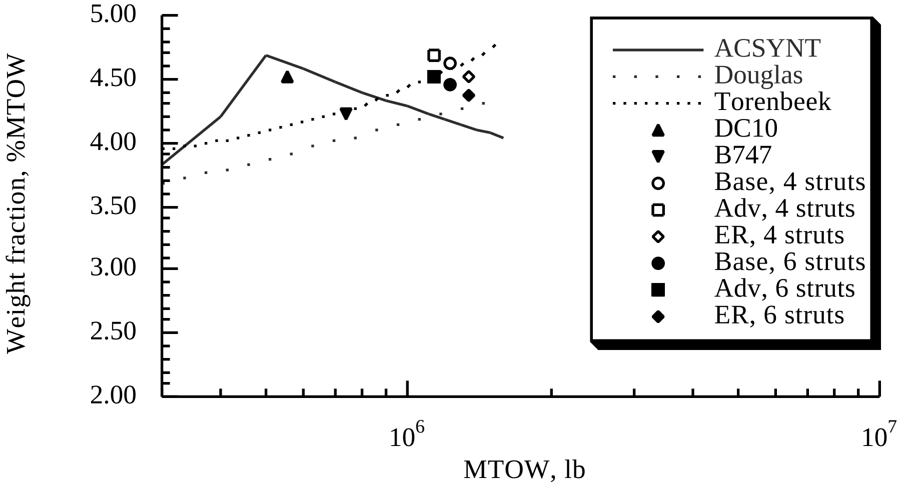


Figure 10.3 Landing gear weight fraction beyond one million pounds MTOW