Appendix A Industry Survey

To try to ensure that our work was current and relevant, we made many contacts with industrial and government engineers that work with landing gears. The approach was to conduct a survey. In this section we present the material given to them, and report on what we found. In general, we got the best information in telephone interviews. The questions initiated discussions that were often broader and less focused than the questions themselves. Thus, the discussion of results presented in the following sections follows the broader areas, and does not explicitly summarize individual answers to the questions. In general, the company contacts were not able to give us detailed written material because they considered their expertise proprietary.

The issues we identified that needed to be addressed were: runway compatibility, landing gear integration, landing gear configuration, landing gear weight, advanced technologies, and cost. A list of questions was developed covering these considerations to ask engineers associated with landing gear systems. Using a few suggestions from contacts in industry and government, we started making calls. In some cases, we sent a fax of our questions. Often, we were directed to contact someone else in the organization, or, someone at another company. Eventually, the survey included major airframers, landing gear manufacturers, airlines, and government agencies and technical societies. The list of questions was circulated among the manufacturers for comments and suggestions, while airlines were contacted to obtain operating and maintenance cost information.

A.1. General script for our phone interviews

The landing gear integration issue for advanced aircraft is being investigated under a NASA Ames research grant to Virginia Tech. The project objective is the formulation of a methodology to include landing gear considerations explicitly in the conceptual design stage. In particular, the project addresses the special design considerations associated with the next-generation high-capacity transport with a TOGW exceeding one million pounds. Our landing gear design and integration related issues were defined during the initial background research with heavy reliance on N. S. Currey's *Aircraft Landing Gear Design: Principles and Practices.* We have questions concerning landing gear configuration, aircraft-landing gear integration, runway compatibility, advanced technologies, weight, maintenance, and cost.

A.2 The questions

- What are the design parameters given to the landing gear designer? What is the design envelope you have to work with? Which is the primary design goal, minimum weight, stowage space, or complexity?
- What are the major problems encountered concerning the integration of the landing gear for the ultra high capacity type aircraft currently under study? What kind of special design considerations are required?
- What are some advanced technologies that will change the landing gear configuration of the ultra high capacity type aircraft dramatically in the next decade or two? How will they change the configuration? What kind of weight reduction can be expected with these technologies?
- What method is used to calculated the landing gear ground and landing loads? Which specification is used? Is there a set of equations that can be readily used?
- What method is used to calculate the aircraft flotation requirements? How do you account for multiple main strut configurations? What kind of constraint in gear configuration is imposed by the flotation requirements?
- For a takeoff gross weight outside the experience base are there some "first principles" that can be followed for landing gear weight estimation?
- What will be the most likely landing gear configuration for the ultra high capacity type aircraft? How many main struts can be expected for a takeoff weight exceeding one million pounds? How would you arrange the main assembly if you have six main struts? What is the major advantage/disadvantage of increasing the number of main struts?
- What method is used to produce the initial landing gear weight estimation? What would be the scaling factor if we are to estimate the weight by scaling up current configurations to meet the demand? Can we obtain geometry and weight information on existing landing gears to be used as a design database?

• What method is used for the initial landing gear cost estimate? What are the major cost drivers and the corresponding sensitivities?

A.3. The Contacts

A list of survey participants and their telephone numbers are presented in Table A.1.

A.4. Findings

A.4.1 Runway Compatibility

Due to economic considerations, the ultra high capacity transport, UHCT, must be able to operate out of Class V airports, *e.g.*, the Boeing Model 747 class airports, without requiring extensive runway reinforcement and modification. Flotation requirements can be obtained using the PCA methods for rigid pavement and the CBR method for flexible pavements. Effects of multiple-strut/multiple-wheel landing gear configurations on the pavement bearing strength have yet to be addressed fully by industry. However, preliminary finite element analyses suggest interaction among wheels can be neglected outside a radius of ten footprint radii from the point where the flotation analysis is performed. Based on this information, the number of wheels, *i.e.*, the equivalent number of wheels per strut (ENWS), used to select the proper repetition factor curve (this is the factor that accounts for the number of landings per year on the pavement) becomes the number of wheels found within the circle of ten foot-print radii centered at the strut-truck joint. With current tire inflation pressures, a 20-wheel main assembly is required for a TOGW between 1 and 1.2 million pounds, while a 24-wheel main assembly is required for a TOGW between 1.3 and 1.6 million pounds to produce the desired flotation characteristics. Both numbers include a 20 percent future growth factor.

Table A.1. Industry/Government Landing Gear Contact List

		Phone	Fax
Federal Aviation Administration			
John Rice	Airport Standards and Safety	(202) 267-8745	(202) 267-5383
Niel Schalekanp	Aircraft Certification	(206) 227-2112	
Bill Perrella	Aircraft Certification	(206) 227-2116	(206) 227-1320
Wright-Patterson Air Force Base			
Paul Ulrich	Vehicle Equipment	(513) 255-2663	
Henry Pollack		(513) 255-4158	
SAE A-5 Committee			
Richard Vandame		(412) 776-4841	(412) 776-0002
Waterways Experiment Station			
Carlo Gonzalez		(601) 634-2203	
The Tire & Rim Association, Inc.			
Joe Pacuit		(216) 666-8121	
Boeing Commercial Airplane			
Matt Travis	Landing Gear System	(206) 237-7744	
John Potter	Landing Gear System	(206) 237-7745	
Jerry Kileer	Landing Gear System	(206) 965-9775	
Edward Gervais	Airport Technology	(206) 237-0175	
Dave Nielson	Configuration	(206) 342-7577	
Scott Perkins	Structures	(206) 266-7812	
Bob Nielson	Weights	(206) 342-1522	
McDonnell Douglas Aircraft			
Brian Lindley		(310) 496-9129	
Al Kernik		(310) 593-7313	(310) 496-9244
Larry McBee		(310) 496-9949	
Cleveland Pneumatic			
Gene Stuczynski		(216) 429-4213	(216) 883-7153
B.F. Goodrich			
Dave Moser		(513) 440-2206	(513) 339-3813
Paul Snider		(513) 440-2380	(513) 339-4556
Tom Kendall		(513) 440-2205	(513) 339-6811
Dean Peters		(513) 339-3811	(513) 339-6811
Menasco Aerosystem			
Bill Luce		(817) 685-3538	(817) 689-3852
Richard Luu		(818) 847-9208	
Michelin			
Marion DeWitt		(704) 548-2483	
Ron Olds	Director of Sales	(704) 548-2438	
U.S Air			
Norman White	Senior Airframe Engineer	(412) 747-3425	(412) 747-3975
United			
James Gallivan	Landing Gear, B747	(510) 382-8312	(510) 382-8302
Ed Pozzi	Landing Gear, B757	(415) 634-6994	
Northwest			
Jim Baumiller	Landing Gear	(612) 726-3885	
Steve Lydon	Wheels & Brakes	(612) 726-7217	(612) 726-6844

A.4.2 Integration

Aircraft-landing gear integration will be the primary concern for the next-generation high-capacity transports. The location dependency of the wing and the main gear assembly to the aircraft *cg* will play a major role in the integration issue. With the introduction of multiple-strut configurations, the envelope within which the landing gear has to be located to produce the ideal loading and stability characteristics may no longer be large enough to accommodate the increased number of main assembly struts. This phenomenon is known as *location stagnation* by the landing gear community. Modification in design and flotation requirements must be made, if necessary, to accommodate kinematic and stowage constrains such that the landing gear can be deployed and stowed without interference with surrounding structures. A forward-retracting scheme for the fuselage struts is preferred, which allows the gears to be deployed using the slip-stream in case of a hydraulic failure. However, stowage limitations could result in an aft-retracting scheme for the center-line strut located between the wing-mounted struts in a five-plus struts configuration.

A.4.3 Configuration

The number of wheels imposed by the flotation requirement can be accommodated with either a four-, five- or six-strut configuration. One of the centerline struts will be located abreast of the wing-mounted struts for the five-plus main gear struts configurations. With the introduction of the centerline strut(s), a double-keel layout is required, *i.e.*, the stowage space is divided into three compartments with two identical keels placed parallel to each other. The centerline strut(s) will then be mounted and stowed between the keels. The fuselage width of the new aircraft, which will be 20 to 30 inches wider than that of the B747, should be able to accommodate the double-keel layout with relative ease. However, one of the drawbacks is that the structural weight associated with the keels will be doubled, since both keels have to withstand the same buckling load and thus have to be similar in dimension to the one found in the single-keel layout. Another drawback is that a complex deploying/retracting scheme for the landing gear doors must be developed to prevent interference between the doors and the gear itself.

The length of the strut will be dictated by the condition on aircraft ground clearance requirements during cross-wind landings imposed by the large nacelle diameter of the advanced engines. The vertical spacing between the nacelle and the wing, *i.e*., the gully, will be reduced to a minimum, provided that desirable flow characteristics are maintained, before any extension in strut length is made. A main gear steering system will be needed to meet the ground operation requirements, with the most demanding maneuver being the 180-degree turn on existing runways. Options include the fuselage strut steering system found on the B747 and the forward-aft wheel steering system found on the B777.

The wheel truck dimensions of the dual-twin-tandem and triple-dual-tandem configurations will be similar to those of the B747 and B777, respectively. The longitudinal spacing between tires will be maintained at roughly six inches for ease of removal of the wheel plugs, while lateral spacing will be slightly wider in both configurations due to the increased brake size required for the new aircraft. Due to the limited stowage volume, the truck assembly might have to be rotated prior to retraction to minimize the stowage space required.

A.4.4 Loads

The dynamic and ground loads are determined in accordance with FAR Part 25. It is unlikely that the new aircraft will be subjected to rough field operating requirements, and thus a single-acting shock absorber will be sufficient to handle the kinetic energy experienced during landing and taxiing. Based on preliminary analysis from industry, the new aircraft will require a shock strut with a 24-inch stroke at the minimum, a piston diameter of 15 inches, and internal oleo pressures between 1,500 and 1,800 psi. Canting of the strut should be avoided, if possible, due to the load path considerations. Active struts will likely be used to provide improved and acceptable ground ride quality. Improvements will probably be internal, e.g., bearings, finishes, and rebound damping, but little difference will be seen in the external configuration.

A.4.5 Weight

The design of the new landing gear must be as simple as possible, since complexity drives up the cost faster than weight. However, weight also appears to be inversely proportional to the level of complexity. With the reduction in the complexity level, *e.g.*, the number of supports, structural members are forced to withstand a higher load, which in term increases the structural weight due to an increase in cross-sectional area. Therefore, a balance must be reached between simplicity and weight, and this can only be accomplished through parametric studies of different landing gear configurations. Note that a step increase in total landing gear weight occurs with each additional strut. Therefore, the number of struts must be kept at a minimum while at the same time meeting the flotation and simplicity requirements. Existing data indicates that fuselage strut weight is roughly 25 to 40 percent less than that of the wing strut, and overall, total gear weight will remain at roughly five percent of the maximum take-off weight.

Structural weight estimation should be obtained using an analytical approach, while the following "rules of thumb" for sensitivities were provided by the industrial contacts. Weight scaling taken to a 1.1 power will give a reasonable estimation for sub-components, *i.e.*, the steering system, up locks, down locks, fittings and miscellaneous items. A landing gear gross weight variation of 5 pounds per 1,000 pounds increase in TOGW for the nose gear was suggested, while a 40-pound variation per 1,000 pounds increase in TOGW for the main gear should be used. Weight variation of 40 pounds per inch increase in strut length per strut was also suggested. The wheel and tire weights will be similar to that of the B747, *i.e*., 190 pounds and 290 pounds, respectively, while the heat sink weight will be heavier, again due to the increased braking energy requirements. A step increase in the landing gear group weight will occur with each additional strut; therefore, the number of struts should be kept at a minimum.

A.4.6 Advanced Technologies

Advanced technologies will play a major role in reducing the weight of the UHCT type landing gears. A five to seven percent weight reduction can be obtained with the use of high strength steel for the landing gear strut and carbon for the brake. Radial-ply tires, although having a higher initial cost, offer a 20 percent weight reduction over bias-ply tires, while at the same time allowing more landings per life-cycle. Further weight reduction can be achieved by the use of a steer-by-wire concept in place of the conventional cable-and-pulley system. Electrical actuation units will be introduced as a way to reduce weight in secondary mechanisms, but the primary actuation method will remain hydraulic.

A 4.7 Cost

The manufacturing cost of the landing gear cannot be treated simply as a function of weight or strut length. Instead, cost estimation must take into account the costs of development, material and processes, certification, marketing, overhaul, refurbishment, and spares. Typical program cost is roughly in the range of $10 to $12 million dollars. The cost of the tire, wheel and brake will remain relatively unchanged. The limiting factor is the size of the tire that can be constructed and tested without a major new investment in the manufacturing and testing facilities. Current hardware limits the maximum diameter to 56 inches for the bias-ply tire and 58 inches for the radial-ply tire. The H49x19.0-22, a 32-bias-ply tire found on both the nose and main gear of the B747, is valued at $2,100. This can be compared to the radial, the 50x20.0-22, which is found on the main gear of the B777 with a 32-ply rating, which is valued at $2,900, and the

42x17.0-18, which is found on the nose gear of the B777 with a 28-ply rating, and is valued at $2,100. Due to its light weight and the increased number of landings allowed per life-cycle, the radial tire has become the preferred choice by airlines even though it costs more. As for the aluminum wheel and carbon-carbon heat sink found on the B747, the unit price is valued at $70,000.

The landing gear overhaul interval varies between 33,000 to 42,000 flight hours. The preferred method is to overhaul the entire set at the same time to minimize the down-time. However, it might be necessary to overhaul the set separately due to schedule, parts and facility constraints. For the B747 type landing gear, the overhaul cost is estimated at $400,000. Replacement of the carbon heat sink occurs every 1,200 to 1,500 landings, while only 300 landings are allowed for the wheel before replacement. The overhaul cost for the wheel and brake is pre-negotiated with the contractors and is known as cost-per-landing. Quoting the B747 figures, the cost for the carbon-carbon brake is estimated at $10 per landing, while the cost for the wheel, including tire, is estimated at $5 per landing.

To conclude, due to the competition among the airframe and landing gear manufacturers, landing gear design procedures, and weight and cost data are considered to be company-proprietary. As a result, the majority of the survey participants were only willing to address the issues in general terms. However, the survey results did provide some useful insights to the design of the landing gear, and reaffirmed design and analysis procedures as previously documented.