Investigation of Limit Design Lateral Ground Maneuver Load Conditions

June 2007

Final Report

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The objective of this project was to instrument a Boeing 747SP aircraft and then develop and compile acceleration, force, and landing gear loads data (as well as aircraft system data) into a database for a variety of ground maneuvers. This information was analyzed to provide landing gear reaction loads during each aircraft maneuver. Relationships describing low- and high-speed exits, S-turns, circle turns, and turns with loss of friction on the inside (main and wing) gear, as well as differential loads between the landing gear, were examined. These relationships provide directly measured information on lateral loads not previously available.
This work was performed under the Federal Aviation Administration (FAA) contracts GS-23F-0106J entitled “B-747SP Ground Maneuver Strain Survey” and DTFACT-04-C-00008 entitled “747SP Ground Loads Testing.” The Program Manager for the FAA was Mr. Thomas DeFiore of the Airworthiness Assurance Branch at the FAA William J. Hughes Technical Center located at the Atlantic City International Airport, New Jersey. Mr. Rick Micklos, Mr. Steve Materio, and Mr. Hank Marek, from the FAA, provided test support. Mr. Emil Finn of Emil Finn & Associates Pty. Limited, conducted test plan development as well as data reduction and analysis. Mr. Richard Gleich, Mr. Mike Szot, Mr. Raymond Saccarelli, and Dr. Kenneth Green of the L-3 Communications, Titan Group, carried out instrumentation, calibration, and all data acquisition. Detailed design and construction of the calibration scale was done by the Emery Winslow Scale Company.
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EXECUTIVE SUMMARY

The Federal Aviation Administration (FAA), Emil Finn & Associates Pty. Limited, and L-3 Communications, Titan Group have undertaken this study to investigate the lateral landing gear loads in ground taxi turn maneuvers on airplanes with multiple (greater than two) main landing gear units for the purpose of better understanding the load distribution among the gear units. Specifically, lateral acceleration and landing gear lateral and vertical loads are recorded during aircraft ground maneuvers at up to 0.35 g’s for different surface conditions.

It has traditionally been assumed that during a ground taxi turn, the side load acting on a main landing gear unit (where a unit can comprise many axles/wheels) is in direct proportion to its vertical ground reaction. This assumption may not be valid in all situations. For example, with gear units on dissimilar surfaces (e.g., wet ice and dry pavement), the lateral load on a gear unit on the dry surface might exceed the expected value. Nevertheless, the assumption is contained in the taxi turn regulation, Title 14 Code of Federal Regulations 25.495, and has generally worked well for airplanes with only two main gear units. In recent times, it has also been applied to airplanes with multiple main gear units. With multiple main gear units, however, apart from the difficulty involved in the determination of redundant vertical reactions, there is reason to doubt that side load will always be in direct proportion to vertical load. The reason is that the different structural characteristics of inner and outer gear units could allow preferential off-loading of the side load on one unit at the expense of the other. Analytic studies, conducted by Emil Finn & Associates for the FAA, have anticipated this effect, predicting that during a steady taxi turn, the outer gear unit will carry less side load, and the inner gear units will carry more than would be expected based on vertical forces alone.

The possibility of gaining access to the FAA’s Boeing 747SP for instrumentation and testing was proposed by the FAA, and the resultant full-scale taxi testing conducted at the FAA William J. Hughes Technical Center is described in this report. The ability to recreate realistic taxi operations has allowed a full investigation of both steady ground turns and dynamic taxi turn entry/exit conditions, among others. The report discusses, in detail, the calibration of the instrumentation on the aircraft, the test procedures for data runs, and the results obtained.

From theoretical investigations, it was expected that the most severe loadings would occur when one or more of the landing gear units were on a reduced friction surface, while other units were on dry pavement. It was therefore necessary to include this scenario into whatever testing was to be undertaken.

In addition, to address both three gear configurations as well as airplanes with four or more landing gear units, the feasibility of elevating the main body gear of the B-747SP was investigated and found to be acceptable with a limited gross weight and an appropriate forward center of gravity. This configuration was also assessed to be most indicative of the predicted lateral load transfer as the airplane encountered dissimilar friction surfaces while performing a high-speed turn.

The test results indicated that for a 0.35-g turn, the lateral load on a highly loaded gear unit can exceed 0.35 of its vertical load. The highest ratio of lateral to vertical for a combination of wet,
ice, and dry pavement in a 0.35-g turn is extrapolated to be 0.584 for the three-gear configuration and 0.488 for the five-gear configuration. For a 0.5-g turn, these ratios are extrapolated to be 0.583 and 0.789 for five- and three-gear configurations, respectively.

The airframe and landing gear unit stiffnesses were found to be of significant influence in the distribution of both vertical and lateral loads during high-speed turning maneuvers for the five-gear configuration.
1. INTRODUCTION.

The investigation of the relationship between lateral accelerations and lateral landing gear loads was triggered by the Federal Aviation Administration (FAA) evaluation of ongoing, in-service lateral acceleration data, which had been collected from various airlines. If any design lateral load factor changes were to be contemplated, then the interaction between lateral load factor and lateral landing gear loads had to be understood.

1.1 MAGNITUDE OF LATERAL LOADS AS DEFINED UNDER 14 CFR 25.495

The current Title 14 Code of Federal Regulations (CFR) 25.495 [1] requires transport category airplanes to be designed to resist the loads imposed by a 0.5-g turn. It further requires the landing gear and supporting structure be designed to resist a lateral load of 0.5 times the vertical load resulting from the 0.5-g turn on each landing gear unit.

1.2 MAGNITUDE OF IN-SERVICE LATERAL ACCELERATIONS

Fleet information collected by the FAA, as well as anecdotal data obtained from airlines, indicate that the maximum expected in-service lateral acceleration experienced during a directed high-speed turn-off would be covered by a reduction in the design lateral acceleration to 0.35 g.

1.3 RELATIONSHIP OF MAXIMUM LATERAL LOADS TO VERTICAL LOAD

The justification or source of the 0.5 design ratio of lateral-to-vertical loads in the current Federal Aviation Regulations is unknown, but has clearly been adequate in safeguarding against landing gear failures when combined with a 0.5-g turn requirement. Rigid airframe analysis results (when considering landing gear units on dissimilar friction surfaces) show that greater than a 0.5 ratio of lateral-to-vertical loads can occur; however, the current design rule appears to adequately cover the lateral load levels generated by in-service conditions.

1.4 JUSTIFICATION FOR TESTING

Initial analytical work by Emil Finn & Associates in 2002 indicated that for a 0.35-g lateral acceleration with landing gear units on dissimilar surfaces (e.g., wet ice and dry pavement), lateral loads would significantly exceed 0.35 g of the resulting vertical loads. These predictions were, however, based on a rigid airframe assumption, so it could not be said to accurately reflect the influences of the flexibility of the various airframe and landing gear components in airplanes with more than two main landing gear units. However, the initial predictions could be said to be applicable for tricycle gear configurations.

Following completion of the initial analytical assessment, the FAA proposed the possibility of gaining access to the FAA’s then recently acquired Boeing 747SP for instrumentation and testing to investigate these phenomena.
2. APPROACH.

The overall approach to the program was to instrument the B-747SP to measure and record strains in critical members of the landing gear as well as oleo pressures. By calibrating the strain and pressure gauges on each bogie with known lateral loads (in all directions), it would be possible to determine the lateral loads on the aircraft as it traversed a predetermined test track by using measured pressure and strain data. An operational test plan was developed to carry out this work and is provided in appendix A.

2.1 FACILITIES.

All tests were conducted at the FAA William J. Hughes Technical Center on the aircraft ramp area at the Atlantic City International Airport in New Jersey. A calibration scale that could apply known lateral loads was designed and constructed in the wash rack area of the ramp. Most testing was done either on the ramp or on a test track that consisted of the ramp and three taxiways that allowed for a rectangular loop (figure 1).

![Figure 1. Overview of FAA Ramp and Taxiways Used for Testing](image)

2.1.1 Test Aircraft.

The test aircraft was a retired B-747SP (originally N-147UA owned by United Airlines). This aircraft was sold to the FAA in 2001 to be used for a variety of test programs. Although the aircraft could be used for taxi testing, it was no longer flight certified and could not be used for flight testing.

2.1.2 Calibration Scale and Horizontal Loading Apparatus.

2.1.2.1 Design.

Design of the calibration system for the testing was one of the major challenges. It was necessary to measure the vertical load (weight) on each bogie in each of the configurations
desired. In addition, lateral and fore-aft loads had to be applied to the wheels at ground level to simulate the actual loads that would be experienced during the taxi tests. Lateral loads were to be up to 50% of the measured vertical load (weight) on the given gear and fore-aft loading up to 80% of the measured vertical load. Finite element simulations of the gear, including tire deflection, were done to estimate surface displacement under these conditions indicated maximum deflections of 6-7 inches. In addition, parasitic displacements in the orthogonal direction, due to gear structure and geometry, were calculated to be approximately 1 inch.

The approach taken for the calibration system was an in-ground, modified truck scale system that would be installed in the wash rack area of the FAA ramp and operations area. The system consisted of two 11’ x 8’ weighbridges to accommodate the landing gear. The lower weighbridge was a scale system for determining the vertical loads. The upper deck was designed to slide on the lower weighbridge with a minimum of friction. This was accomplished using lubricated Fabreeka® pads and highly polished stainless steel surfaces. The system was designed such that the upper surface of the sliding weighbridge was level with the surrounding ramp. Hydraulic rams, integrated into the surrounding steel and concrete pit, would apply the desired horizontal loads. From the center position, the upper slide deck could be deflected 9.5 inches in any direction. The hydraulic system was designed to apply lateral loads up to a maximum of 168,000 lb.

The calibration system was designed and installed by the Emery Winslow Scale Company based on defined design requirements provided by L-3 Communications, Titan Group (figures 2 and 3). An expanded discussion of the calibration scale is provided in appendix B.

![Figure 2. Top and Side View of Calibration Scale](image)
2.1.2.2 Scale Instrumentation.

The calibration system consisted of four hydraulic load cells supporting both the fixed weighbridge and the sliding deck. The hydraulic outputs led to four pressure transducers that were connected to the data acquisition system for measuring loads in the vertical direction. With known areas, the pressure data was converted to load data. A calibration chart was provided by Emery Winslow as part of the scale unit.

The displacement sensors for measuring displacement in the lateral direction consisted of linear string gauges. Displacements of the gear were measured in two directions with respect to the pad surface. This required two gauges. In addition, the displacement and rotation of the pad, with respect to the fixed ramp, was monitored using four linear string gauges. Two gauges were applied to each of two orthogonal sides. All of the displacement gauge outputs were, in turn, inputted into the data acquisition system for monitoring and recording.

Applied loads from the hydraulic rams were measured through the use of pressure transducers located in the hydraulic lines at the rams. Data from these pressure transducers were monitored and recorded by the data acquisition system. Knowing the pressure and the fixed bore diameter of the cylinder, a force reading could be computed and displayed. Figure 4 shows the calibration scale in operation.
2.1.2.3 Calibration of the Scale System.

A series of calibrated weights (up to 40,000 lb) was applied to the scale surface, as a standard procedure by Emery Winslow, to verify the calibration of the hydraulic load cells.

In addition to the vertical, or weight, calibration of the scale, the calibration of the horizontal forces being applied to the landing gear required that an estimate be made of the friction force on the sliding weighbridge as well as the breakaway forces within the hydraulic rams applying the horizontal loads. Since it was not possible to separate these forces, a series of tests were run with test weights applied to the surface of the sliding weighbridge. The pusher heads on the hydraulic rams were fitted with calibrated load cells obtained from the Navy (Naval Air Warfare Center Structures Laboratory at Pax River, MD). The rams were then activated to determine the force required to initiate motion of the weighbridge (static friction) as well as the force required to maintain the motion of the weighbridge (kinetic friction). This was done for several incremental weights. With this information, the actual lateral loads being applied to the landing gear could be determined more accurately by removing the frictional forces.

2.1.3 Test Track.

The test track used for all taxi testing was a loop that included the FAA ramp area, taxiways B, J, and K, which is part of the Atlantic City International Airport (figure 5). Conditions on the track were dry except for specific tests that involved reducing the friction on the inboard (port) main body gear and wing gear. All testing was done in a counterclockwise direction with the aircraft starting on the ramp and then moving to taxiways K, B, and J. Although data was taken throughout the test run, it was the turn from taxiway J back onto the ramp area that specific test conditions were met and data recorded. It was also at this turn (turn 2 in figure 5) that the modified surface was applied. In a few cases, runway 13-31 was used in lieu of taxiway B to provide a higher turn speed at turn 2.
The purpose of this testing was to simulate the loss of friction on the port side wheels of the aircraft due to a wet or icy taxiway. This was accomplished by prepositioning and attaching vinyl sheet flooring to the taxiway. The vinyl was coated with a layer of viscosity modified water, which was then dusted with a very thin layer of bentonite. Bentonite is a powdery clay material used as a lubricant for drilling potable wells and sold under the name of Tru-Bore®. The viscosity modifier (sold under the name of Shur-Mud) was mixed with the water at a concentration of one half of 1 percent by volume. This combination of viscosity modified water and bentonite on the vinyl sheet material produced an extremely slippery surface. The exact location of friction loss during the turn could be easily controlled because the loss of friction only would occur when the wheels were on the sheet vinyl.

The sheet vinyl was purchased in four 12- by 70-ft lengths plus two 12- by 60-ft lengths. The sections were butted together and attached to the ground with a Liquid Nails® outdoor adhesive around the perimeter of each section. Duct tape was used to seal the perimeter edges as well as the butt edges between sections. When completed, it formed an area approximately 36 ft wide by 140 ft long and was positioned on the taxiway turn (turn 2). The outer portion of the vinyl sheet along the 140 ft length was cut to form a curve with a radius of 176 ft. Both ends of the 36-ft length were also cut on the radius such that the wheels would enter and leave the surface at the same time (figure 6).
2.1.4 Calibrated Tow Bar.

The tow bar used for maneuvering the B-747SP at the test site was disassembled, instrumented internally with strain gauges, reassembled, and then calibrated up to 50,000 lb at the Naval Air Warfare Center in Patuxent River. This work was accomplished in preparation for nose gear calibration as well as a separate series of tow tests that would be conducted, where it was necessary to know the loads being applied through the tow bar to the nose gear.

2.2 AIRCRAFT INSTRUMENTATION.

The B-747SP was instrumented with strain gauges, pressure transducers, accelerometers, and data extraction circuitry connected to aircraft systems.

Data for all sensors was recorded through a Vishay Measurements Group StrainSmart® System 5000 data acquisition system, which is comprised of five 5100 scanners. Each of the 5100 scanners has 20 inputs. The system is set up for a total of 100 channels with a scan rate of 20 inputs per channel per second. Strain gauges, pressure transducers, displacement potentiometers, and other transducers can be intermixed in multiples of 5 by choosing the appropriate sensor card. In the aircraft-related data system configuration, including both the aircraft and the tow bar, there are a total of 48 temperature compensated axial strain gauges, 6 temperature compensated rosette gauges, 5 pressure transducers, 6 accelerometer inputs, and inputs for 4-wheel speed sensors. In addition to the aircraft sensors, inputs to the data acquisition system associated with the calibration scale include pressure transducers for the four load cells and two hydraulic rams for lateral loads as well as six displacement potentiometers.

These inputs are processed by the StrainSmart software package, a Microsoft® Windows®-based software system for acquiring, reducing, presenting, and storing all the measured data from the
System 5000. The data acquisition system was rack mounted within the passenger compartment of the aircraft.

2.2.1 Strain Gauges.

Strain gauges were attached to the primary structural elements of each of the five landing gear systems. In general terms, each primary structural member had two gauges attached to one another at 180°, so that member axial load strains could be determined. Figure 7 shows the location of the axial strain gauges on the main body and wing gears. Drawings are taken from reference 2. Examples of gauge installations are shown in figure 8.

![Figure 7. Location of Axial Strain Gauges on Body and Wing Gear](image)

![Figure 8. Strain Gauge Installations](image)
2.2.2 Pressure Transducers.

Piezoelectric transducer pressure gauges were mounted on each of the five landing gear oleos (see figure 9). The pressure range was from 0-3000 psi with an accuracy of ±0.5 psi, and a response time of 0.01 second. These gauges were monitored and recorded during the gear calibration process and the actual taxi testing with the System 5000 data acquisition unit.

![Oleo Pressure Transducer Installation](image)

Figure 9. Oleo Pressure Transducer Installation

2.2.3 Accelerometers.

A triaxial, orthogonal accelerometer was installed near the airplane center of gravity to measure the accelerations in vertical, fore-aft, and port-starboard senses. The accelerometer was a Motion Pack II, manufactured by the Systron Donner Inertial Division of BEI Technologies, Inc. The system provided 6 degrees of freedom including the axial rotation rates.

2.2.4 Ground Speed.

The pilot was provided a ground speed display from a Garmin™ GPS-V® personal navigator. The GPS system updates speed at a rate of 1 Hz with an accuracy of ±0.09 knots. The pilot used this system to establish target speeds required for each test run just prior to initiating the turn.

2.3 CALIBRATION TESTS.

To interpret the strain and pressure transducer data, it was necessary to apply and measure known loads and record the resulting strains and oleo pressures that were produced by those loadings. Operation of the calibration scale system, for a given aircraft weight and configuration, consisted of aligning a specific gear of the aircraft with the centerline of the calibration system and then towing the aircraft such that the desired gear was centered on the calibration scale pad. The brakes would then be set. All cover plates around the calibration pad were removed to allow the scale to slide freely. Data from the four load cells measuring the
vertical load were taken. This allowed the centerline position of the gear vertical load to be determined. This position information was then used for adjusting the hydraulic rams to minimize any induced rotation during horizontal loading. The sum of the four load cells also provided the total vertical weight on that gear.

In addition to the strain gauges and pressure gauges on the aircraft, displacement sensors were attached to the landing gear on the pad to measure displacement with respect to the pad surface. Displacement sensors on the pad measured displacement with respect to the fixed ramp. All inputs were fed to the data acquisition system and remotely monitored at the calibration scale. In addition, displacements of all the other landing gear (not on the scale) were measured and recorded using threaded rod pointers attached to the front and rear of each bogie during the actual calibration process. Graph paper was positioned under the pointers for each loading condition applied to the gear on the calibration scale.

The hydraulic rams providing the horizontal loads to the scale system were connected to a portable hydraulic pump and control system unit using quick disconnect hoses. Loads being applied by the hydraulic rams were measured with pressure transducers located close to the ram. The outputs of these transducers were fed to the data acquisition system and converted to forces. Loads were then slowly applied by adjusting the hydraulic pressure to the rams to ensure loads remained at the gear centerline. Data was continuously recorded up to the maximum load applied to calibrate the strain gauges with the applied loads.

After completing a given loading direction, the hydraulics were used to recenter the pad and the process was repeated for another direction. This continued until all four directions were calibrated. All displacement sensors were then removed, the cover plates replaced, and the aircraft repositioned such that the next landing gear was on the calibration pad. This process was repeated until all five gear units were calibrated for a given aircraft weight and configuration.

2.3.1 Left Wing Gear Calibration.

The left wing gear was calibrated for vertical, inboard, outboard, forward, and aft loads.

The vertical load increments were achieved by alternately jacking the forward and rear ends of the truck and then placing shims under the forward or aft wheel pairs. When the jacks were lowered and the truck settled onto the shims, the resulting strains, oleo pressures, and displacements were recorded for the left wing gear as well as all other gear units. This process achieved the following average truck elevations in inches: 0.000, 1.094, 2.188, 3.281, and 4.375. A maximum vertical load increment of just over 7000 pounds was achieved for the maximum 4.375-inch jacking height.

The wing gear calibration for inboard, outboard, forward, and aft loading directions was achieved by two horizontal hydraulic rams appropriately placed around the perimeter of the scale. The appropriate proportioning of load for each ram was adjusted to avoid applying excessive torque to the truck. Loads of nominally 20%, 30%, 40%, and 50% of the vertical gear load were applied in each of the referenced directions. The maximum applied load in each
direction was 34,330 pounds. Two additional horizontal hydraulic rams on the opposite side were used to recenter the slide deck after each test.

Truck inboard and outboard skid loads were determined on the scale surface by applying a gradually increasing balanced lateral load until the tires slipped relative to the scale surface.

### 2.3.2 Left Body Gear Calibration

The left body gear was calibrated for vertical, inboard, outboard, forward, and aft loads following the same procedures used for the left wing gear.

A maximum vertical load increment of just over 14,000 pounds was achieved for the maximum 4.375-inch jacking height.

The maximum applied load in each of the inboard, outboard, forward, and aft loading directions was 39,960 pounds.

Truck inboard and outboard skid loads were determined on the scale surface by applying a gradually increasing balanced lateral load until the tires slipped relative to the scale surface.

### 2.3.3 Right Body Gear Calibration

The right body gear was calibrated for vertical, inboard, outboard, forward, and aft loads following the same procedures used for the left wing gear.

A maximum vertical load increment of just over 13,000 pounds was achieved for the maximum 4.375-inch jacking height.

The maximum applied load in each of the inboard, outboard, forward, and aft loading directions was 41,740 pounds.

Truck inboard and outboard skid loads were determined on the scale surface by applying a gradually increasing balanced lateral load until the tires were observed to be slipping relative to the scale surface.

### 2.3.4 Right Wing Gear Calibration

The right wing gear was calibrated for vertical, inboard, outboard, forward, and aft loads following the same procedures used for the left wing gear.

A maximum vertical load increment of just over 7400 pounds was achieved for the maximum 4.375-inch jacking height.

The maximum applied load in each of the inboard, outboard, forward, and aft loading directions was 33,620 pounds.
Truck inboard and outboard skid loads were determined on the scale surface by applying a gradually increasing balanced lateral load until the tires were observed to be slipping relative to the scale surface.

2.3.5 Nose Gear Calibration.

The nose gear was calibrated in the port and starboard directions by placing the nose gear centrally on the calibration scale and then, as in all the other calibration testing, applying known lateral loads using the hydraulics of the calibration scale. In addition, the tow bar was attached to the nose gear while it was on the calibration scale and loads were applied through the calibrated tow bar using the tow tug. Loads were applied at right-hand turning angles of the nose wheels of 0, 20, 40, 60, 65, and 90 degrees (by disabling the nose gear torsion link). The 90 degree position in the left-hand turning direction was also calibrated.

The maximum applied load in each of the port and starboard loading directions was 14,630 pounds. The maximum applied tow bar load was 26,420 pounds.

2.3.6 Friction Assessment of Scale System.

Applying lateral loads to the scale under several vertical load conditions assessed the internal sliding friction of the scale system. The resulting static friction coefficient was determined to be in the range of 0.030 to 0.033, with the sliding friction coefficient in the range of 0.028 to 0.030.

2.3.7 Modified Surface Friction Coefficient Estimate.

Following the right wing gear calibration testing, the aircraft was rolled back off the scale. The scale surface was then modified by the application of the slippery surface. The aircraft was then rolled back onto the surface. The scale was loaded in the starboard direction until the tires began to slip.

The friction coefficient between the tires and the modified surface was calculated to be approximately 0.090. Because of the time delay between stopping the aircraft and initiating tire slippage, it is recognized that the calculated friction coefficient is likely higher than would be experienced had the slippage been achieved sooner. For comparison, the friction coefficients reported in the literature [3] are typically given as an average of 0.050 for tires on wet ice.

2.4 RESOLUTION OF LOADS FROM STRAINS AND PRESSURES.

A matrix solution approach was deemed necessary to model a general set of strains and pressures, which were to be transformed into a prediction of the three orthogonal load components that were applied to the airplane at the tire pavement contact interfaces of each landing gear unit.
2.4.1 Theoretical Basis of Load Resolution.

Based on a consistent set of strains, oleo pressures, and the known applied loads, a matrix solution was derived to correlate a set of selected strain and pressure outputs to applied loads. An explanation and the derivation of the equations for use in theoretically resolving the loads from the recorded test data is set out in appendix C.

2.4.2 Adjustments to the Theoretical Solution to Improve Accuracy.

Theoretical solutions are only as good as their ability to predict future events. In general, one would hope that the errors between a theoretically predicted outcome and individual test results would be acceptably small. Unfortunately, this is not to be expected in a real testing environment. In many instances, the theoretical models have not accounted for all of the influences in the complex systems that one tries to simplify into workable mathematical forms. Hence, the need arises to adjust the theoretical solutions to improve predictive accuracy. The final transformation matrices achieved a load resolution accuracy of ±2000 pounds on each gear unit as well as an overall airplane load resolution of ±10,000 pounds for all five-gear units under each and every calibration loading of the individual gear units.

3. TEST MANEUVERS.

Testing was carried out using several types of maneuvers to investigate the relative lateral load-sharing outcomes for differing control inputs.

3.1 FIVE-GEAR DRY SURFACE 90° TURNS.

Ninety-degree turns were carried out under dry pavement conditions at various speeds turning left from taxiway J onto the FAA ramp at Atlantic City International Airport with body gear steering disabled.

3.2 FIVE-GEAR MODIFIED SURFACE 90° TURNS.

A modified surface was prepared on the inboard side of a 175-ft turn radius on the FAA ramp (figure 6) to accommodate both the B-747SP in its five- and three-gear configurations. In all instances, the intention was to have all port main gear units on the modified (friction reduced) surface for a significant portion of the 90° turn from taxiway J onto the FAA ramp with the body gear steering disabled.

This testing regime was to simulate the situation where one or more main landing gear units are on dry pavement, while others are on a reduced friction surface, such as wet ice.

3.3 THREE-GEAR DRY SURFACE 90° TURNS.

The purpose of the three-gear testing was to address lateral landing gear loadings for the large class of tricycle gear commercial aircraft.
Three-gear testing was conducted at the completion of the five-gear (standard configuration) testing. Raising and supporting the main body gear with straps and chains such that the aircraft was then resting solely on the wing and nose gear units accomplished this. Prior to raising the main body gear, approximately 21,000 pounds of sand bags were placed in the forward cabin on the main deck of the aircraft, as well as the forward cargo compartment, to move the center of gravity sufficiently forward so that the aircraft would have an adequate safety margin against tipping over backwards.

It was felt that the three-gear testing would remove any ambiguities with the lateral load data acquisition and processing techniques used during the five-gear testing. Figure 10 shows the raised body gear in the three-gear test position, approximately 6 inches off the ground.

![Figure 10. View of Body Gear in Raised Position](image)

3.4 THREE-GEAR MODIFIED SURFACE 90° TURNS.

The intention of this testing regime was to simulate the possible situation where one main landing gear unit of a tricycle gear aircraft is on dry pavement, while the other is on a reduced friction surface, such as wet ice. In such a situation, the loss of friction on the reduced friction surface would require that the main gear unit on dry pavement to either take-up the lost friction or further skid if there was insufficient residual capacity on the dry surface.

3.5 FIVE-GEAR CIRCULAR PATH TAXI TESTS.

The proposal to undertake circular path tests was based on maintaining a lateral load level for a longer period of time and hopefully reducing the effects of transient structural response that would surely occur in a 90° turn. Testing was carried out with and without body gear steering.

3.6 FIVE-GEAR S-TURN TESTS.

The S-turn tests were proposed to address exactly the opposite goal of the circular path tests. These tests were intended to excite airplane response modes that would interact and possibly exacerbate the steady-state response that was expected in the circular path tests.
3.7 **FIVE-GEAR BRAKED TURNS.**

The braked turn testing was intended to simulate what was expected during at least some high-speed turnoffs. It was suggested that pilots would often use differential breaking during a high-speed turnoff to reduce their speed and also to facilitate the turn.

4. **DISCUSSION OF TEST RESULTS.**

Test results were assessed using the transformation matrices appropriate to the various landing gear units and the airplane’s configuration. The coordinate system was a right-hand rule system with the +x axis pointing aft, the +y axis pointing to starboard, and the z axis pointing upward, as shown in figure 11. In this coordinate system, it can be seen that a left-hand turn would typically induce negative starboard loads on the main landing gear units and positive loads for a right-hand turn. For this reason, the direction of the turn would generally determine the sign of the lateral-to-vertical load ratio.

![Figure 11. Test Airplane Coordinate System—For Loads Assessment](image)

4.1 **FIVE-GEAR DRY SURFACE 90° TURN RESULTS.**

The five-gear dry surface tests were carried out on 3 December 2004.

All five-gear dry surface 90° turns are left-hand turns onto the FAA ramp from taxiway J, with a nominal turn radius of 175 feet.
The five-gear dry surface tests show that the airframe and landing gear stiffness play a significant role in the distribution of the vertical and lateral loads during a medium- to high-speed turn.

The vertical loads generally follow the assumptions of past design rules, but are affected by the wing flexure and body stiffness. This can be observed in the slight time differences between the body gear and the wing gear initiating vertical load response and in reaching their peak vertical loads.

It is most interesting to observe that the lateral loads are not directly related to the vertical load distribution as might be inferred from 14 CFR 25.495. In fact, they are more directly related to the lateral stiffness of the individual landing gear units. Thus, for the B-747SP in a dry five-gear turn, the highest lateral load always occurs on the body gear on the outer side of the turn. The second highest lateral load occurs on the body gear on the inner side of the turn, with the traditionally assumed highest laterally loaded gear (the outer side wing gear) always coming in third highest.

The above generalized observations can be seen in figures 12 through 15 for scan session 74. A summary of the peak lateral accelerations, main landing gear peak loads, and their relationships to each other are shown in table 1 for the six test turns documented in appendix D.

![Figure 12. Scan Session 74, Dry Surface Five-Gear Taxi—Vertical Load](image-url)
Figure 13. Scan Session 74, Dry Surface Five-Gear Taxi—Lateral Load

Figure 14. Scan Session 74, Dry Surface Five-Gear Taxi—Load Ratio
During scan session 72, the right body gear can be seen to have the highest lateral load and the highest lateral-to-vertical load ratio (0.416) for a peak lateral load factor of 0.383. Relatively speaking, however, scan session 74 has higher lateral loads in relation to its lower peak lateral load factor of 0.363.

If the test data is extrapolated to a 0.5-g turn condition, a 0.516 lateral-to-vertical load ratio would result, based on a linear best fit to all of the test data points (in table 1) for the right body gear. This ratio is 3.2% above the 14 CFR 25.495 design value of 0.500. As an example, see figure 16.

It is interesting to observe that for the lowest speed turns, (those with the lowest lateral accelerations—scan sessions 69, 70, and 71) almost no lateral load is carried by the wing gear units. As speed increases, however, both wing gear units gradually pick up a more significant portion of the lateral load, even though they never dominate the airplane’s lateral load carrying system.

Figure 15. Scan Session 74, Dry Surface Five-Gear Taxi—Accelerations
<table>
<thead>
<tr>
<th>Scan Session</th>
<th>Peak Lateral Load Factor</th>
<th>LWG Vertical Load (lb)</th>
<th>LWG Starboard Load (lb)</th>
<th>LWG S/V Load Ratio</th>
<th>LBG Vertical Load (lb)</th>
<th>LBG Starboard Load (lb)</th>
<th>LBG S/V Load Ratio</th>
<th>RBG Vertical Load (lb)</th>
<th>RBG Starboard Load (lb)</th>
<th>RBG S/V Load Ratio</th>
<th>RWG Vertical Load (lb)</th>
<th>RWG Starboard Load (lb)</th>
<th>RWG S/V Load Ratio</th>
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<td>69-120304</td>
<td>0.153</td>
<td>61,459</td>
<td>-1,367</td>
<td>-0.022</td>
<td>68,210</td>
<td>-22,646</td>
<td>-0.332</td>
<td>101,666</td>
<td>-25,459</td>
<td>-0.250</td>
<td>109,377</td>
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<td>0.011</td>
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<td>-21,885</td>
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<td>102,643</td>
<td>-25,954</td>
<td>-0.253</td>
<td>114,744</td>
<td>612</td>
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<td>-0.091</td>
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<td>-20,366</td>
<td>-0.311</td>
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<td>-0.412</td>
<td>144,222</td>
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</table>

LWG = Left wing gear
LBG = Left body gear
RBG = Right body gear
RWG = Right wing gear
4.2 FIVE-GEAR MODIFIED SURFACE 90° TURN RESULTS.

The five-gear modified surface tests were carried out on 11 December 2004.

In general, the comments made for the five-gear dry surface testing also apply here. The introduction of the reduced friction surface means that the amount of lateral load that can be carried by any gear unit on the modified surface is significantly reduced and is controlled by the friction coefficient between the individual gear unit and the vertical gear load.

As one would expect, the change in landing gear vertical loads is relatively unaffected by the presence of the modified surface, as it does not affect any gear unit’s ability to sustain vertical load. The lateral loads, on the other hand, are significantly reduced when a gear unit encounters the modified surface. When a gear unit departs the modified surface, it quickly reacquires its previously reduced lateral load capability.

The above generalized observations are shown in figures 17 through 20 for scan session 75 results. A summary of the peak loads and their relationship to each other are tabulated for the four turns in table 2. In addition to the peak load extractions, loads are tabulated at various times through turns to indicate the changes that occur as gear units encounter and depart the surface.
Figure 17. Scan Session 75, Modified Surface Five-Gear Taxi—Vertical Load

Figure 18. Scan Session 75, Modified Surface Five-Gear Taxi—Lateral Load
Figure 19. Scan Session 75, Modified Surface Five-Gear Taxi—Load Ratio

Figure 20. Scan Session 75, Modified Surface Five-Gear Taxi—Accelerations
### Table 2. Five-Gear Vertical and Lateral Load Summary for Modified Surface Turns

<table>
<thead>
<tr>
<th>Scan Session</th>
<th>Current Lateral Load Factor</th>
<th>Elapse Time (seconds)</th>
<th>LWG Vertical Load (lb)</th>
<th>LWG S/V Load Ratio</th>
<th>LBG Vertical Load (lb)</th>
<th>LBG S/V Load Ratio</th>
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<td>222.7</td>
<td>61,282</td>
<td>2,027</td>
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<td>0.009</td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>120,739</td>
<td>-32,103</td>
</tr>
</tbody>
</table>

LWG = Left wing gear  
LBG = Left body gear  
RBG = Right body gear  
RWG = Right wing gear
For the most highly laterally loaded gear unit, it can be seen that the lateral-to-vertical load ratio exceeds the lateral load factor. For scan session 75, for example, a 0.343 peak lateral load factor produces a lateral-to-vertical load ratio of 0.540 in the right body gear. If one then compares the 0.343-lateral load factor to the lateral-to-vertical load ratio of 0.540, instead of the ratio being 1 to 1 (as implied from 14 CFR 25.495), the ratio is 1 to 1.6. For scan session 76, the ratio is 1 to 1.3, for scan session 79, the ratio is 1.8, and for scan session 80, the ratio is 1 to 1.5. The noticeably lower value for scan session 76 is because both body gear were initially on the modified surface, but then both came off the surface during the turn. Result plots for the four test runs shown in table 2 are included in appendix E.

If the five-gear modified surface test data were extrapolated to a 0.5-g turn condition, a 0.583 lateral-to-vertical load ratio would result for the right body gear, based on a linear best fit to the test data shown in table 2. This ratio is 16.6% above the 14 CFR 25.495 design value of 0.500.

4.3 THREE-GEAR DRY SURFACE 90° TURN RESULTS.

All three-gear dry surface 90° turns were left-hand turns of the B-747SP onto the FAA ramp from taxiway J, with a nominal turn radius of 175 feet. All tests were carried out on 13 April 2005.

The three-gear configuration is a nonredundant load system, and the vertical distribution of loads is dependent only on the dimensional layout of the three-gear units and the aircraft’s center of gravity position. It is completely independent of the landing gear and airframe stiffness.

The highest peak lateral load factor experienced during the three-gear dry turn tests was 0.343 for scan session 111, with the right wing gear lateral-to-vertical load ratio being 0.315.

The above generalized observations can be seen in figures 21 through 24 for scan session 111. A summary of the peak lateral accelerations, main landing gear peak loads, and their relationships to each other are shown in table 3 for the five test turns documented in appendix F.
Figure 21. Scan Session 111, Dry Surface Three-Gear Taxi—Vertical Load

Figure 22. Scan Session 111, Dry Surface Three-Gear Taxi—Starboard Loads
Figure 23. Scan Session 111, Dry Surface Three-Gear Taxi—Load Ratios

Figure 24. Scan Session 111, Dry Surface Three-Gear Taxi—Accelerations
Table 3. Three-Gear Vertical and Lateral Load Summary for Dry Surface Turns

<table>
<thead>
<tr>
<th>Scan Session</th>
<th>Peak Lateral Load Factor</th>
<th>LWG Vertical Load (lb)</th>
<th>LWG Starboard Load (lb)</th>
<th>LWG S/V Load Ratio</th>
<th>RWG Vertical Load (lb)</th>
<th>RWG Starboard Load (lb)</th>
<th>RWG S/V Load Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>108-041305</td>
<td>0.153</td>
<td>142,696</td>
<td>-30,713</td>
<td>-0.215</td>
<td>195,171</td>
<td>-34,960</td>
<td>-0.179</td>
</tr>
<tr>
<td>109-041305</td>
<td>0.253</td>
<td>128,798</td>
<td>-47,147</td>
<td>-0.366</td>
<td>203,646</td>
<td>-54,728</td>
<td>-0.269</td>
</tr>
<tr>
<td>110-041305</td>
<td>0.203</td>
<td>139,198</td>
<td>-37,344</td>
<td>-0.268</td>
<td>198,004</td>
<td>-40,529</td>
<td>-0.205</td>
</tr>
<tr>
<td>111-041305</td>
<td>0.343</td>
<td>121,947</td>
<td>-52,930</td>
<td>-0.4334</td>
<td>207,254</td>
<td>-65,245</td>
<td>-0.315</td>
</tr>
<tr>
<td>112-041305</td>
<td>0.213</td>
<td>135,778</td>
<td>-37,645</td>
<td>-0.277</td>
<td>197,202</td>
<td>-37,397</td>
<td>-0.190</td>
</tr>
</tbody>
</table>

Three-gear dry surface taxi test peak loads and ratio results (not occurring simultaneously)

LWG = Left wing gear
LBG = Left body gear
RBG = Right body gear
RWG = Right wing gear

If the three-gear dry surface test data were extrapolated to a 0.5-g turn condition, a 0.439 lateral-to-vertical load ratio would result, based on a linear best fit to the test data for the right wing gear. This ratio is 12.2% below the 14 CFR 25.495 value of 0.500.

4.4 THREE-GEAR MODIFIED SURFACE 90° TURN RESULTS.

All three-gear modified surface 90° turns were left-hand turns of the B-747SP onto the FAA ramp from taxiway J, with a nominal turn radius of 175 feet. All test turns were carried out on 22 April 2005.

The results of this test series clearly demonstrate the loss of lateral load capacity of the gear unit on the modified friction surface and the resultant uptake of lateral load by the main gear unit with reserve capacity on the dry surface. Five test runs are documented in table 4, with the plotted results from scan session 142 shown in figures 25 through 28. A complete set of plots for all five scan sessions are shown in appendix G.
Table 4. Three-Gear Vertical and Lateral Load Summary for Modified Surface Turns

<table>
<thead>
<tr>
<th>Scan Session</th>
<th>Current Lateral Load Factor</th>
<th>Elapsed Time (seconds)</th>
<th>LWG Vertical Load (lb)</th>
<th>LWG Starboard Load (lb)</th>
<th>LWG S/V Load Ratio</th>
<th>RWG Vertical Load (lb)</th>
<th>RWG Starboard Load (lb)</th>
<th>RWG S/V Load Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>135-042205</td>
<td>0.087</td>
<td>291.4</td>
<td>159,703</td>
<td>-2850</td>
<td>-0.018</td>
<td>186,389</td>
<td>-41,897</td>
<td>-0.225</td>
</tr>
<tr>
<td>138-042205</td>
<td>0.173</td>
<td>218.9</td>
<td>148,089</td>
<td>-775</td>
<td>-0.005</td>
<td>191,837</td>
<td>-62,825</td>
<td>-0.327</td>
</tr>
<tr>
<td>141-042205</td>
<td>0.096</td>
<td>216.1</td>
<td>160,014</td>
<td>874</td>
<td>0.005</td>
<td>189,545</td>
<td>-44.527</td>
<td>-0.235</td>
</tr>
<tr>
<td>142-042205</td>
<td>0.153</td>
<td>129.2</td>
<td>147,675</td>
<td>-1618</td>
<td>-0.011</td>
<td>191,955</td>
<td>-64,684</td>
<td>-0.337</td>
</tr>
<tr>
<td>143-042205</td>
<td>0.120</td>
<td>211.8</td>
<td>156,942</td>
<td>-4531</td>
<td>-0.029</td>
<td>189,614</td>
<td>-49,954</td>
<td>-0.263</td>
</tr>
</tbody>
</table>

LWG = Left wing gear  
LBG = Left body gear  
RBG = Right body gear  
RWG = Right wing gear

Figure 25. Scan Session 142, Modified Surface Three-Gear Taxi—Vertical Load
Figure 26. Scan Session 142, Modified Surface Three-Gear Taxi—Starboard Load

Figure 27. Scan Session 142, Modified Surface Three-Gear Taxi—Load Ratio
Inspection of figure 26 clearly indicates when the left wing gear encounters the modified surface and precisely when it departs that surface.

Even though the highest recorded load factor was 0.173, the results clearly point to the result that was forecast in the initial analytical assessment of 2002 (see section 1.4). The main gear unit on the dry surface experiences a lateral load that is markedly greater than the 1:1 ratio referenced in 14 CFR 25.495. In fact, the ratio for the most highly loaded condition in the tests documented in table 4 is for scan session 142, where the ratio is 2.2:1 and as high as 2.6:1 for scan session 135. When the test data is extrapolated to a lateral load factor of 0.350, the expected ratio of lateral-to-vertical load is 1.7:1. When the data is extrapolated to a lateral load factor of 0.500, the expected ratio of lateral-to-vertical load is 1.6:1, or a lateral-to-vertical load ratio of 0.789. This indicates that should a 0.5-g turn take place for a near max gross weight airplane in wet icy conditions, instead of having the intended 50% margin of safety against failure, that margin would be negative for a tricycle gear airplane.

Higher-speed turns were considered using this three-gear configuration, but were rejected because of the aft c.g. position and the risks to personnel on board the airplane.

4.5 FIVE-GEAR CIRCULAR PATH TAXI TEST RESULTS.

Both five-gear dry surface circular path taxi tests were right-hand turns on the FAA ramp and were carried out on 5 May 2005.

The first of the tests was conducted with body gear steering enabled, and the latter test carried out with the body gear steering disabled. The results of the two tests are summarized in table 5, with plots of the first test shown in figures 29 through 32. Both scan session plots are included in appendix H.
Table 5. Five-Gear Vertical and Lateral Load Summary for Circle Turns

<table>
<thead>
<tr>
<th>Scan Session</th>
<th>Body Gear Steering</th>
<th>Peak Lateral Load Factor (g)</th>
<th>LWG Vertical Load (lb)</th>
<th>LWG Starboard Load (lb)</th>
<th>LWG S/V Load Ratio</th>
<th>LBG Vertical Load (lb)</th>
<th>LBG Starboard Load (lb)</th>
<th>LBG S/V Load Ratio</th>
<th>RBG Vertical Load (lb)</th>
<th>RBG Starboard Load (lb)</th>
<th>RBG S/V Load Ratio</th>
<th>RWG Vertical Load (lb)</th>
<th>RWG Starboard Load (lb)</th>
<th>RWG S/V Load Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>153-050505</td>
<td>On</td>
<td>-0.251</td>
<td>134,778</td>
<td>1930</td>
<td>0.014</td>
<td>88,728</td>
<td>29,359</td>
<td>0.331</td>
<td>57,658</td>
<td>29,364</td>
<td>0.509</td>
<td>62,501</td>
<td>15,220</td>
<td>0.244</td>
</tr>
<tr>
<td>156-050505</td>
<td>Off</td>
<td>-0.278</td>
<td>134,066</td>
<td>-1155</td>
<td>-0.009</td>
<td>86,652</td>
<td>33,785</td>
<td>4</td>
<td>54,235</td>
<td>35,147</td>
<td>0.648</td>
<td>62,743</td>
<td>1,235</td>
<td>0.020</td>
</tr>
</tbody>
</table>

Five gear dry surface circle testing—loads and ratio results (not occurring simultaneously)

LWG = Left wing gear
LBG = Left body gear
RBG = Right body gear
RWG = Right wing gear
Figure 29. Scan Session 153, Five-Gear Circular Path Test—Vertical Loads

Figure 30. Scan Session 153, Five-Gear Circular Path Test—Starboard Loads
As shown in the acceleration plot in figure 31, the acceleration slowly increased during the progress of the test. In general, the results of this testing regime agree with the 90° dry surface turns, but with slightly higher lateral-to-vertical load ratios. There is also an apparent increase in transient airplane dynamic response with body gear steering enabled.
4.6 FIVE-GEAR S-TURN TESTING RESULTS.

All five-gear dry surface S-turns were conducted on 27 May 2005, with relatively low magnitude side-to-side excursions along the FAA ramp with body gear steering disabled.

The results of the six test runs are summarized in table 6, with the plotted results from scan session 251 shown in figures 33 through 36. All scan session plots are in appendix I.

Once again, the results of these tests illustrate the dominance of the main body gear in reacting the lateral loads induced during turn maneuvers. Additionally, the changing phase relationship between the wing and body gear can be observed, indicating their different modal frequencies.
### Table 6. Five-Gear Vertical and Lateral Load Summary for S-Turns

<table>
<thead>
<tr>
<th>Scan Session</th>
<th>Peak Lateral Load Factor for Scan Session (g)</th>
<th>Local Peak Lateral Load Factor (g)</th>
<th>LWG Vertical Load (lb)</th>
<th>LWG Starboard Load (lb)</th>
<th>LWG S/V Load Ratio</th>
<th>LBG Vertical Load (lb)</th>
<th>LBG Starboard Load (lb)</th>
<th>LBG S/V Load Ratio</th>
<th>RBG Vertical Load (lb)</th>
<th>RBG Starboard Load (lb)</th>
<th>RBG S/V Load Ratio</th>
<th>RWG Vertical Load (lb)</th>
<th>RWG Starboard Load (lb)</th>
<th>RWG S/V Load Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>247-052705-A</td>
<td>-0.211</td>
<td>0.165</td>
<td>70,229</td>
<td>3,361</td>
<td>0.048</td>
<td>63,745</td>
<td>-25,282</td>
<td>-0.397</td>
<td>91,462</td>
<td>-26,542</td>
<td>-0.290</td>
<td>96,375</td>
<td>-25,282</td>
<td>-0.290</td>
</tr>
<tr>
<td>247-052705-B</td>
<td>-0.211</td>
<td>-0.195</td>
<td>103,367</td>
<td>1,922</td>
<td>0.019</td>
<td>84,994</td>
<td>18,972</td>
<td>0.223</td>
<td>67,593</td>
<td>22,377</td>
<td>0.331</td>
<td>66,322</td>
<td>6,565</td>
<td>0.099</td>
</tr>
<tr>
<td>248-052705-A</td>
<td>-0.219</td>
<td>0.171</td>
<td>70,210</td>
<td>-2,704</td>
<td>-0.039</td>
<td>63,222</td>
<td>-18,561</td>
<td>-0.294</td>
<td>88,063</td>
<td>-18,633</td>
<td>-0.212</td>
<td>103,145</td>
<td>-3,211</td>
<td>-0.031</td>
</tr>
<tr>
<td>248-052705-B</td>
<td>-0.219</td>
<td>-0.219</td>
<td>107,664</td>
<td>1,910</td>
<td>0.018</td>
<td>83,584</td>
<td>14,994</td>
<td>0.179</td>
<td>67,332</td>
<td>19,063</td>
<td>0.283</td>
<td>64,716</td>
<td>7,029</td>
<td>0.109</td>
</tr>
<tr>
<td>249-052705-A</td>
<td>-0.216</td>
<td>-0.216</td>
<td>103,996</td>
<td>2,146</td>
<td>0.021</td>
<td>82,786</td>
<td>18,005</td>
<td>0.217</td>
<td>67,305</td>
<td>20,307</td>
<td>0.302</td>
<td>69,000</td>
<td>7,454</td>
<td>0.108</td>
</tr>
<tr>
<td>249-052705-B</td>
<td>-0.216</td>
<td>0.074</td>
<td>76,311</td>
<td>7,128</td>
<td>0.093</td>
<td>68,211</td>
<td>-18,296</td>
<td>-0.268</td>
<td>82,993</td>
<td>-19,506</td>
<td>-0.235</td>
<td>91,704</td>
<td>12,058</td>
<td>0.131</td>
</tr>
<tr>
<td>250-052705</td>
<td>0.216</td>
<td>0.083</td>
<td>77,583</td>
<td>6,403</td>
<td>0.083</td>
<td>67,934</td>
<td>-19,389</td>
<td>-0.285</td>
<td>82,549</td>
<td>-21,089</td>
<td>-0.255</td>
<td>88,420</td>
<td>10,667</td>
<td>0.121</td>
</tr>
<tr>
<td>251-052705</td>
<td>-0.278</td>
<td>-0.278</td>
<td>117,900</td>
<td>6,530</td>
<td>0.055</td>
<td>86,377</td>
<td>21,756</td>
<td>0.252</td>
<td>62,231</td>
<td>22,452</td>
<td>0.361</td>
<td>54,066</td>
<td>10,163</td>
<td>0.188</td>
</tr>
<tr>
<td>252-052705</td>
<td>0.393</td>
<td>0.393</td>
<td>53,233</td>
<td>-14,096</td>
<td>-0.265</td>
<td>48,158</td>
<td>-23,378</td>
<td>-0.485</td>
<td>88,807</td>
<td>-34,846</td>
<td>-0.392</td>
<td>127,896</td>
<td>-31,465</td>
<td>-0.246</td>
</tr>
</tbody>
</table>

Five-gear dry surface S-turn testing—loads and ratio results (not occurring simultaneously)

LWG = Left wing gear  
LBG = Left body gear  
RBG = Right body gear  
RWG = Right wing gear
Figure 33. Scan Session 251, Five-Gear S-Turn Test—Vertical Loads

Figure 34. Scan Session 251, Five-Gear S-Turn Test—Starboard Loads
Figure 35. Scan Session 251, Five-Gear S-Turn Test—Load Ratios

Figure 36. Scan Session 251, Five-Gear S-Turn Test—Accelerations
4.7 FIVE-GEAR BRAKED TURN RESULTS.

The five-gear braked turn tests were carried out on dry pavement on 27 May 2005. The turns were performed using differential braking as can be inferred from the aft loads shown in figure 37 and the acceleration plot shown in figure 38.

The five test runs are summarized in table 7, with load and acceleration plots provided for scan session 256 in figures 37 through 41. Plots for all scan sessions are included in appendix J.

The differential braking induces a torsion response on the airframe, which appears to be reacted by a port-starboard couple between the two body gears and the two wing gears. The effect of this condition has amplified the lateral loads on the body gear and takes it to 0.226 of the vertical load in the left body gear in scan session 256 for a lateral load factor of -0.076. Additionally, the breaking reduces the vertical loads on all main gear units.

The airplane response exhibited in the test observations cannot be assumed to be the most severe conditions, since the brake application, duration, and release points appear to be influential in the response. A more detailed study would have to be made to investigate the range of loads that could occur. The phenomenon would also be airplane specific and dependent on gross weight as well as center of gravity and airplane structural response.
<table>
<thead>
<tr>
<th>Scan Session</th>
<th>Peak Lateral Load Factor (g)</th>
<th>Peak Aft Load Factor (g)</th>
<th>LWG Vertical Load (lb)</th>
<th>LWG Starboard Load (lb)</th>
<th>LWG Aft Load (lb)</th>
<th>LWG S/V Load Ratio</th>
<th>LBG Vertical Load (lb)</th>
<th>LBG Starboard Load (lb)</th>
<th>LBG Aft Load (lb)</th>
<th>LBG S/V Load Ratio</th>
<th>RBG Vertical Load (lb)</th>
<th>RBG Starboard Load (lb)</th>
<th>RBG Aft Load (lb)</th>
<th>RBG S/V Load Ratio</th>
<th>RWG Vertical Load (lb)</th>
<th>RWG Starboard Load (lb)</th>
<th>RWG Aft Load (lb)</th>
<th>RWG S/V Load Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>253-052705</td>
<td>-0.051</td>
<td>-0.306</td>
<td>79,652</td>
<td>-8,679</td>
<td>49,428</td>
<td>-0.109</td>
<td>72,994</td>
<td>21,107</td>
<td>40,199</td>
<td>0.289</td>
<td>65,008</td>
<td>21,896</td>
<td>19,480</td>
<td>0.337</td>
<td>80,586</td>
<td>-17,104</td>
<td>21,644</td>
<td>-0.212</td>
</tr>
<tr>
<td>254-052705</td>
<td>0.183</td>
<td>-0.237</td>
<td>72,128</td>
<td>-4,123</td>
<td>33,466</td>
<td>-0.057</td>
<td>57,347</td>
<td>-26,161</td>
<td>32,529</td>
<td>-0.456</td>
<td>87,283</td>
<td>-29,378</td>
<td>7,204</td>
<td>-0.337</td>
<td>93,766</td>
<td>-4,379</td>
<td>7,813</td>
<td>-0.047</td>
</tr>
<tr>
<td>255-052705</td>
<td>0.263</td>
<td>0.273</td>
<td>64,305</td>
<td>-9,075</td>
<td>40,783</td>
<td>-0.141</td>
<td>56,109</td>
<td>-19,047</td>
<td>41,058</td>
<td>-0.339</td>
<td>85,009</td>
<td>-35,289</td>
<td>14,345</td>
<td>-0.415</td>
<td>101,399</td>
<td>-17,432</td>
<td>15,646</td>
<td>-0.172</td>
</tr>
<tr>
<td>256-052705</td>
<td>-0.076</td>
<td>-0.346</td>
<td>80,540</td>
<td>-11,682</td>
<td>45,183</td>
<td>-0.145</td>
<td>63,313</td>
<td>14,334</td>
<td>38,995</td>
<td>0.226</td>
<td>61,983</td>
<td>31,978</td>
<td>27,528</td>
<td>0.516</td>
<td>74,789</td>
<td>-16,014</td>
<td>27,288</td>
<td>-0.214</td>
</tr>
<tr>
<td>257-052705</td>
<td>0.152</td>
<td>-0.328</td>
<td>72,644</td>
<td>21,066</td>
<td>41,615</td>
<td>0.290</td>
<td>57,982</td>
<td>-25,312</td>
<td>39,873</td>
<td>-0.437</td>
<td>82,721</td>
<td>-31,574</td>
<td>24,556</td>
<td>-0.382</td>
<td>86,167</td>
<td>29,053</td>
<td>23,623</td>
<td>0.337</td>
</tr>
</tbody>
</table>

LWG = Left wing gear  
LBG = Left body gear  
RGB = Right body gear  
RWG = Right wing gear
Figure 37. Scan Session 256, Five-Gear Braked Turn Test—Aft Loads

Figure 38. Scan Session 256, Five-Gear Braked Turn Test—Accelerations
Figure 39. Scan Session 256, Five-Gear Braked Turn Test—Vertical Loads

Figure 40. Scan Session 256, Five-Gear Braked Turn Test—Starboard Loads
5. CONCLUSIONS.

The conclusions of this investigation are as follows:

1. For both the five- and three-gear configurations, extrapolations of modified surface test results indicate that a 0.5-g lateral turn will produce lateral loads greater than 0.5 times the peak vertical loads for the stiffest main landing gear units in wet, icy conditions.

2. The existing Title 14 Code of Federal Regulations (CFR) 25.495 has proven to be adequate for existing in-service conditions for large commercial airplanes.

3. The statement in item 2 is not intended to imply that 14 CFR 25.495 is acceptable for the specific bookcase that it sets out. On the contrary, the results of the three-gear modified surface tests demonstrate that should a near maximum gross weight tricycle gear airplane experience a 0.5-g turn condition, it could have a negative margin of safety against failure in wet, icy conditions.

4. Even though the five-gear modified surface test results are not as severe as those for the three-gear configuration, a 0.5-g turn at near maximum gross weight would still produce an unacceptable margin of safety against failure in wet, icy conditions.

5. The predictions of this report are based on least squares fits to the test data and, therefore, do not address an upper bound prediction, which should be used to formulate design criteria.

6. No attempt has been made to determine a lateral load level for which the existing 14 CFR 25.495 would provide an appropriate level of safety. That task is beyond the scope of
this investigation but based on these findings, it could be the subject of a separate study. It is strongly recommended that such a study be undertaken.

6. REFERENCES.


3. FAA Report on Runway Icing and Friction Coefficients.
APPENDIX A—OPERATIONAL TEST PLAN

OPERATIONAL TEST PLAN

INVESTIGATION OF LIMIT DESIGN LATERAL LOAD CONDITIONS UNDER THE FEDERAL AVIATION REGULATIONS AND PROPOSAL FOR TESTING OF THE MAGNITUDE OF LATERAL LANDING GEAR LOADS

22 November 2004

Introduction
The “Ground Loads” design requirements for Part 25 category aircraft are addressed under the Federal Aviation Regulations: FAR 25.471 through 25.519.

This testing is intended to investigate the vertical and lateral loads that are imposed on the landing gear under taxi conditions and to determine if the present limit loading criteria can be safely reduced.

The FAA has obtained an ex-United Airlines Boeing 747SP for testing purposes. It has been decided to carry out testing on this aircraft to investigate the magnitude and distribution of lateral loads resulting from various taxi maneuvers.

The basic airplane geometry and landing gear arrangement for the test aircraft are included in the Attachment to this document.

- After testing the airplane with all five of its landing gear units operative, it is planned to test the aircraft in a tricycle gear configuration by raising both of the main body gear units clear of the pavement. This test will be done at a sufficiently low gross weight, so as not to exceed the main wing gear vertical design loads.

Items to be Calculated or Estimated Prior to Testing

- Aircraft gross weight of ex-United Airlines Boeing 747SP (FAA Registration N147UA).
- Aircraft fore-aft center of gravity with gear down.
- Aircraft lateral center of gravity with gear down.
- Aircraft vertical center of gravity with gear down.

Items to be Measured During Testing

It is the aim of the testing program to determine the individual vertical and lateral landing gear loads that occur during taxi conditions and their implications for overall aircraft safety. It is therefore intended to measure and/or accurately estimate as many of the following parameters as is possible during the testing program:

- Individual landing gear static vertical loads (calibration).
- Strain values in all instrumented landing gear support elements due to applied horizontal loads and measured vertical loads (calibration).
- Oleo oil pressures in all instrumented landing gear due to applied horizontal loads and measured vertical loads (calibration).
• Individual vertical, fore-aft and port-starboard movements of the front and rear tow points on each wing and body main landing gear truck due to applied horizontal loads and measured vertical loads (calibration).
• Vertical, fore-aft and port-starboard movements of two reference points on the nose gear truck due to applied horizontal loads and measured vertical loads (calibration).
• Friction coefficients on various runway and taxiway surfaces (calibration).
• Landing gear brace element strains during constant radius turn conditions.
• Oleo oil pressures during constant radius turn conditions.
• Accelerations at the aircraft nominal center of gravity during constant radius turn conditions.
• Differential landing gear vertical loads due to constant radius turn conditions.
• Effects on individual landing gear loads due to differences in individual gear support heights.
• Lateral load distribution among individual landing gear due to airframe and landing gear stiffness.

Test Instrumentation
The proposed location of strain gauges and pressure transducers are shown diagrammatically in Figures A1 through A3, which have been extracted from the Boeing publication, “747 Structures” (Ref. 2). In principle, the gauges are in pairs on opposite sides of components, so that bending can be properly accounted for in the data.

Speed
Taxi speed will be recorded from four of the wheel speed transducers on the main wing gear. The two most outboard wheels on each wing gear truck will be monitored via the anti-skid control circuits. This will allow comparison of the two opposite truck speeds and will be used as a cross check on the turn radii during taxi tests. In addition, a GPS system with a ground speed display will be provided to the pilot for establishing the target speed required for each test.

CG Accelerometers
Three mutually orthogonal accelerometers (alternatively, a three-axis accelerometer) are to be located at the aircraft’s nominal center of gravity. The orientation of the accelerometers should correspond to the aircraft’s structural reference axes. These data will be recorded as $a_{xeg}$, $a_{yeg}$ and $a_{zeg}$.

Wing Main Landing Gear (Left and Right)
Figure A1 shows the general arrangement of the wing gear and nominal instrumentation locations.

Oleo pressure transducer or strut air pressure transducer, $P_{W1}$.

Two strain gauges on side strut (above down lock bungee), $S_{W1}$ and $S_{W2}$.

Two strain gauges on the shock strut (external cylinder), $S_{W3}$ and $S_{W4}$.

Two strain gauges on drag brace, $S_{W5}$ and $S_{W6}$.
Two strain gauges on the torsion link, $S_{W7}$ and $S_{W8}$.

Individual lateral deflections of the two truck tow points using pointers and concentric circular targets.

Vertical movement of the tow-truck tow points by a direct measurement method.

Wheel speed measurement from each of the two outboard wheels by reference to the antiskid control circuits.

**Body Main Landing Gear (Left and Right)**

Figure A2 shows the general arrangement of the body gear and nominal instrumentation locations.

- Oleo pressure transducer or strut air pressure transducer, $P_{B1}$.
- Two strain gauges on drag strut (forward of down lock bungee), $S_{B1}$ and $S_{B2}$.
- Two strain gauges on side brace, $S_{B3}$ and $S_{B4}$.
- Two strain gauges on trunnion, $S_{B5}$ and $S_{B6}$.
- Two strain gauges on the steering torsion link, $S_{B7}$ and $S_{B8}$.

Individual lateral deflections of the two truck tow points using pointers and concentric circular targets.

Vertical movement of the tow-truck tow points by a direct measurement method.

**Nose Landing Gear**

Figure A3 shows the general arrangement of the nose gear and nominal instrumentation locations.

- Oleo pressure transducer or strut air pressure transducer, $P_{N1}$.
- Two strain gauges on left side brace, $S_{N1}$ and $S_{N2}$.
- Two strain gauges on right side brace, $S_{N3}$ and $S_{N4}$.
- Two strain gauges on lower tripod brace or drag strut, $S_{N5}$ and $S_{N6}$.
- Two strain gauges on the upper external cylinder, $S_{N7}$ and $S_{N8}$.
- Two strain gauges on the torsion link, $S_{N9}$ and $S_{N10}$.

Individual lateral deflections of the two truck tow points using pointers and concentric circular targets.
Vertical movement of the tow-truck tow points by a direct measurement method.

**Tow Bar**

Four strain gauges at 90° spacing around the perimeter, at the mid-length of the tow bar, on its outer tubular surface and four additional gauges at 90° spacing around the perimeter on the tow bar’s inner circular shaft.

**Calibration Pad**

Individual vertical load cell digital output.

Individual lateral jack pressure digital output.

Individual lateral deflections of four points using draw wire transducer gauges.

Vertical movement by direct measurement.
Figure A1: Wing Landing Gear Strain Gauge and Pressure Sensor Locations
Figure A2: Body Landing Gear Strain Gauge and Pressure Sensor Locations
Figure A3: Nose Landing Gear Strain Gauge and Pressure Sensor Locations
### Table A1: Maximum Design Loads Based on FAR Requirements and Boeing Data

N. B.: This table is to be revised prior to commencement of testing!!

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tr>
<td>Aircraft Maximum Takeoff Weight</td>
<td>698,670 Lbs</td>
</tr>
<tr>
<td>Aircraft Maximum Taxi Weight</td>
<td>703,000 Lbs</td>
</tr>
<tr>
<td>Aircraft Maximum Landing Weight</td>
<td>450,000 Lbs</td>
</tr>
<tr>
<td>Height of CG above Taxi Surface</td>
<td>192.0 Inches</td>
</tr>
<tr>
<td>Lateral CG offset to Starboard</td>
<td>3.5 Inches</td>
</tr>
<tr>
<td>Nose Gear Body Station - Body Station of Aircraft Nose</td>
<td>305.0 Inches</td>
</tr>
<tr>
<td>Nose Gear Buttock Line</td>
<td>0.0 Inches</td>
</tr>
<tr>
<td>Body Gear Body Station - Body Station of Aircraft Nose</td>
<td>1,173.5 Inches</td>
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<tr>
<td>Body Gear Buttock Line</td>
<td>75.5 Inches</td>
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<tr>
<td>Wing Gear Body Station - Body Station of Aircraft Nose</td>
<td>1,052.5 Inches</td>
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<tr>
<td>Wing Gear Buttock Line</td>
<td>216.5 Inches</td>
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<tr>
<td>Body Station of Leading Edge MAC</td>
<td>1,258.0 inches</td>
</tr>
<tr>
<td>Mean Aerodynamic Cord Length (MAC)</td>
<td>327.8 inches</td>
</tr>
<tr>
<td>Aircraft CG Location (%MAC)</td>
<td>44.0 %</td>
</tr>
<tr>
<td>Aircraft CG Body Station - Body Station of Aircraft Nose</td>
<td>1,113.0 Inches</td>
</tr>
<tr>
<td>B Sta. of Body and Wing Gear Mid-Point - B Sta. of Aircraft Nose</td>
<td>1,113.0 Inches</td>
</tr>
<tr>
<td>Distance of Body Station Datum in front of Aircraft Nose</td>
<td>289.2 Inches</td>
</tr>
<tr>
<td>Max. Wing Gear Static Vertical Load for Aft CG</td>
<td>154,100 Lbs</td>
</tr>
<tr>
<td>Max. Body Gear Static Vertical Load for Aft CG</td>
<td>154,100 Lbs</td>
</tr>
<tr>
<td>Max. Nose Gear Static Vertical Load for Fwd. CG</td>
<td>96,800 Lbs</td>
</tr>
<tr>
<td>Max. Nose Gear Vertical Load for Fwd. CG with Breaking</td>
<td>145,000 Lbs</td>
</tr>
<tr>
<td>Max. Design Nose Gear Vertical Design Load</td>
<td>145,000 Lbs</td>
</tr>
<tr>
<td>Max. Design Wing Gear Vertical Design Load</td>
<td>293,062 Lbs</td>
</tr>
<tr>
<td>Max. Design Body Gear Vertical Design Load</td>
<td>202,560 Lbs</td>
</tr>
<tr>
<td>Max. Design Nose Gear Forward Load</td>
<td>104,801 Lbs</td>
</tr>
<tr>
<td>Max. Design Nose Gear Aft Load</td>
<td>104,801 Lbs</td>
</tr>
<tr>
<td>Max. Design Wing Gear Forward Load</td>
<td>84,755 Lbs</td>
</tr>
<tr>
<td>Max. Design Wing Gear Aft Load</td>
<td>123,280 Lbs</td>
</tr>
<tr>
<td>Max. Design Body Gear Forward Load</td>
<td>84,755 Lbs</td>
</tr>
<tr>
<td>Max. Design Body Gear Aft Load</td>
<td>123,280 Lbs</td>
</tr>
<tr>
<td>Max. Design Nose Gear Side Load</td>
<td>77,440 Lbs</td>
</tr>
<tr>
<td>Max. Design Wing Gear Inboard Load</td>
<td>146,531 Lbs</td>
</tr>
<tr>
<td>Max. Design Wing Gear Outboard Load</td>
<td>146,531 Lbs</td>
</tr>
<tr>
<td>Max. Design Body Gear Inboard Load</td>
<td>101,280 Lbs</td>
</tr>
<tr>
<td>Max. Design Body Gear Outboard Load</td>
<td>101,280 Lbs</td>
</tr>
</tbody>
</table>

### Taxi Tests to be Undertaken

Taxi testing will be undertaken for two different aircraft landing gear configurations in four different categories:

1. Low speed turns.
2. Turns with local taxiway surface treatment.
3. Nose and body gear steering maneuvers.
4. Tow bar maneuvers.
**Test Landing Gear Configurations**

Initial tests will be carried out in the Boeing 747SP normal configuration, with all four main landing gear and the nose gear extended.

A second series of tests will be carried out with both main body gear trucks elevated above the pavement to generate a tricycle landing gear configuration.

**Low Speed Turns**

Low speed turns (less than 30 kts) are intended to be carried out at several lateral acceleration levels, so as to verify the basic vertical load transfer due to center of gravity height above the ground line. They are also intended to indicate the relative lateral load distribution among the various five landing gear units.

![Figure A4: Speed and Turn Radius Effects on Lateral Acceleration](image-url)

Figure A4 shows the relationship of speed, turning radius and resulting lateral acceleration.

The low speed tests will be conducted at the Atlantic City International Airport in New Jersey. Figure A5 shows the layout of the airport, with the low speed turn test track highlighted. Figure A6 shows the test track in more detail, with Figures A7 and A8 showing the details of each turn around the test track as identified in Figure A6. **Note: For some tests, the aircraft will use a section of runway 13-31 between taxiways “J” and “K” in lieu of taxiway “B” as shown in Figure A8.**

The aircraft is intended to traverse the track at constant speed; undertaking uniform radius turns at each of the four corners. Three circuits of the track will be carried out at each speed, all in the counterclockwise direction.
Table A2 sets out the proposed test parameters for the low speed testing on “as is” airport taxiway and FAA apron surfaces. For each test, the surface conditions will be recorded, together with ambient air temperature, wind and weather conditions.

Table A2: Low Speed Taxi Tests, Three Circuits of the Track in Each Direction for the Specified Parameters

<table>
<thead>
<tr>
<th>Speed (Kts)</th>
<th>Nominated Turn Radius (Ft.)</th>
<th>Lateral Acceleration Level (g’s)</th>
<th>Time in Turn (Sec) Turn 1, Turn 2, Turn 3, Turn 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>175</td>
<td>0.114</td>
<td>10.9, 10.9, 10.9, 10.9</td>
</tr>
<tr>
<td>20</td>
<td>175</td>
<td>0.202</td>
<td>8.1, 8.1, 8.1, 8.1</td>
</tr>
<tr>
<td>23</td>
<td>175</td>
<td>0.267</td>
<td>7.1, 7.1, 7.1, 7.1</td>
</tr>
<tr>
<td>27</td>
<td>175</td>
<td>0.369</td>
<td>6.0, 6.0, 6.0, 6.0</td>
</tr>
</tbody>
</table>

The expected nose gear steering angles for these conditions can be obtained from the Boeing plots included in the Attachment to this document and are generally in the range between 20° and 25°. For these nose gear steering angles the body gear steering angle will be negligible if body gear steering were engaged. Body gear steering will be activated for the taxi testing.

**Turns with Taxiway Surface Treatment**

Various surface textural and material differences are not uncommon on runways and taxiways throughout the world. The effects of the differential lateral loads induced by such surface anomalies must be considered in any rigorous investigation of design rules for landing gear lateral loads.

For instance, one or more main landing gear could be on a dry concrete surface, while one or more other gear units could be on ice. Another scenario could have one main gear on very smooth concrete, while the remaining gear units are on a grooved concrete surface. Yet more examples could involve some gear units on a dry surface, while the remaining gear could be on a wet surface. When the above scenarios are combined with breaking and differential thrust, the lateral loading distributions might well turn out to be more complicated than simply related to the vertical gear support load.

This aspect of the test program is intended to obtain an insight into the possible load sharing of lateral loads during situations where lateral load is transferred from one or more gear units (due to reduced surface friction) to other gear units where load reserves exist.

Table A3 sets out the defined maneuvers for test data recording. These tests will be carried out for each of the two landing gear configurations. Initial testing will be carried out on the 747’s normal five-gear arrangement. Following completion of that testing, the aircraft will be converted to a three-gear configuration by elevating the two body gear trucks.
### Table A3: Low Speed Taxi Tests with Modified Surface Conditions

<table>
<thead>
<tr>
<th>Speed (Kts)</th>
<th>Estimated Turn Radius (Ft.)</th>
<th>Lateral Acceleration Level (g’s)</th>
<th>Surface Preparation</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>175</td>
<td>0.114</td>
<td>Smooth vinyl sheet flooring, covered with a thin layer of viscosity modified water and a dusting of bentonite</td>
</tr>
<tr>
<td>20</td>
<td>175</td>
<td>0.202</td>
<td>Smooth vinyl sheet flooring, covered with a thin layer of viscosity modified water and a dusting of bentonite</td>
</tr>
<tr>
<td>23</td>
<td>175</td>
<td>0.267</td>
<td>Smooth vinyl sheet flooring, covered with a thin layer of viscosity modified water and a dusting of bentonite</td>
</tr>
<tr>
<td>27</td>
<td>175</td>
<td>0.369</td>
<td>Smooth vinyl sheet flooring, covered with a thin layer of viscosity modified water and a dusting of bentonite</td>
</tr>
</tbody>
</table>
Figure A7: ACY Test Track - Turn 1, from Taxiway “K” onto the FAA Apron, and Turn 4, from Taxiways “B” onto Taxiway “K”
Figure A8: ACY Test Track - Turn 2, from the FAA Apron onto Taxiways “J” and Turn 3, from Taxiways “J” onto Taxiway “B”
**Nose and Body Gear Steering Maneuvers**
The following maneuvers will be carried out for the five-gear configuration only, with and without body gear steering:

1. Collision Avoidance Simulation – Full Lock to Port (Left) at 6 Kts
2. Collision Avoidance Simulation – Full Lock to Starboard (Right) at 6 Kts
3. Collision Avoidance Simulation – Full Lock to Port (Left) at 12 Kts
4. Collision Avoidance Simulation – Full Lock to Starboard (Right) at 12 Kts

**Aircraft Towing Maneuvers**
In order to gain more insight into the effects of multi main gear aircraft bogie interaction, a set of towing maneuvers will be carried out for the five-gear configuration and continuously monitored.

In all instances the push-back and forward pull forces will be such that the nose gear tires will be pulled or pushed in their rolling direction, rather than in the direction of the aircraft axes. In addition to monitoring main gear wheel movements, accelerometers, strain and pressure gauges, the following additional parameters will be continuously recorded during the progress of the aircraft towing maneuvers:

1. Nose gear speed
2. Nose gear steering angle
3. Video imagery of nose and main landing gear units

Table A4 details the maneuver parameters and extent of each test.

**Note:** Although the towing maneuvers were performed as part of the testing, the results will not be reported as part of the current report since it is not directly related to lateral load requirements under FAR 25.495.
Table A4: Aircraft Towing Maneuver Parameter Definitions

<table>
<thead>
<tr>
<th>Direction of Tow</th>
<th>Nose Gear Steering Angle (Degrees)</th>
<th>Nominal Towing Speed (Kts)</th>
<th>Extent of Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forward</td>
<td>0</td>
<td>6</td>
<td>150 Feet</td>
</tr>
<tr>
<td>Backward</td>
<td>0</td>
<td>6</td>
<td>150 Feet</td>
</tr>
<tr>
<td>Forward</td>
<td>20 to Starboard</td>
<td>4</td>
<td>45° Arc</td>
</tr>
<tr>
<td>Forward</td>
<td>40 to Starboard</td>
<td>4</td>
<td>90° Arc</td>
</tr>
<tr>
<td>Forward</td>
<td>55 to Starboard</td>
<td>2</td>
<td>90° Arc</td>
</tr>
<tr>
<td>Forward</td>
<td>65 to Starboard</td>
<td>2</td>
<td>90° Arc</td>
</tr>
<tr>
<td>Forward</td>
<td>90 to Starboard(^1)</td>
<td>2</td>
<td>90° Arc</td>
</tr>
<tr>
<td>Forward</td>
<td>20 to Port</td>
<td>4</td>
<td>45° Arc</td>
</tr>
<tr>
<td>Forward</td>
<td>40 to Port</td>
<td>4</td>
<td>90° Arc</td>
</tr>
<tr>
<td>Forward</td>
<td>55 to Port</td>
<td>2</td>
<td>90° Arc</td>
</tr>
<tr>
<td>Forward</td>
<td>65 to Port</td>
<td>2</td>
<td>90° Arc</td>
</tr>
<tr>
<td>Forward</td>
<td>90 to Port(^1)</td>
<td>2</td>
<td>90° Arc</td>
</tr>
<tr>
<td>Backward</td>
<td>90 to Port(^1)</td>
<td>2</td>
<td>90° Arc</td>
</tr>
</tbody>
</table>

Provision for Additional Maneuvers
The testing program shall make provision for up to ten additional test maneuvers, which will be predicated on the outcome of the testing defined above. These maneuvers may be repeats of previously performed maneuvers or may be completely new definitions, such as multiple S-bends.

\(^1\) The torque links must be disconnected or removed prior to undertaking this maneuver
Operational Test Plan
ATTACHMENT
## BOEING 747SP GENERAL CHARACTERISTICS

### Table: 747SP General Characteristics

<table>
<thead>
<tr>
<th>CHARACTERISTIC</th>
<th>ENGINE UNITS</th>
<th>JT9D-7A, -7F, -7J</th>
<th>RB211-524C2</th>
<th>CF6-45A2/92</th>
<th>JT9D-7A</th>
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</thead>
<tbody>
<tr>
<td>Maximum Ramp Weight</td>
<td>POUNDS</td>
<td>636,000</td>
<td>670,000</td>
<td>669,000</td>
<td>703,000</td>
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<tr>
<td></td>
<td>KILOGRAMS</td>
<td>288,440</td>
<td>306,660</td>
<td>315,600</td>
<td>318,800</td>
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<tr>
<td>Maximum Landing Weight</td>
<td>POUNDS</td>
<td>450,000</td>
<td>450,000</td>
<td>450,000</td>
<td>450,000</td>
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<td>KILOGRAMS</td>
<td>204,100</td>
<td>204,100</td>
<td>204,100</td>
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<tr>
<td>Maximum Takeoff Or Brake Release Weight</td>
<td>POUNDS</td>
<td>630,000</td>
<td>670,000</td>
<td>690,000</td>
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<td></td>
<td>KILOGRAMS</td>
<td>286,700</td>
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<tr>
<td>Operating Empty Weight (Typical—Varies With Engine/Weight Option)</td>
<td>POUNDS</td>
<td>325,660</td>
<td>338,870</td>
<td>331,330</td>
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<td></td>
<td>KILOGRAMS</td>
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<td>POUNDS</td>
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<td>Maximum Structural Payload</td>
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<td>35,680</td>
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<td>Maximum Seating Capacity (Includes 32 Seats on Option-AL Upper Deck)</td>
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<td>Basic Mixed Arrangement 28 First Class, 303 Economy</td>
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<td>Alternate Arrangement 28 FC &amp; 9-Abreast Economy</td>
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<td>Maximum Lower-Lobe Containerized Cargo Volume</td>
<td>CUBIC FEET</td>
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<td>99</td>
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<tr>
<td>Maximum Lower-Lobe Bulk Cargo Volume</td>
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<td>400</td>
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<td></td>
<td>CUBIC METERS</td>
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<td>Usable Fuel Capacity</td>
<td>U.S. GALLONS</td>
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<td>49,960</td>
<td>48,780</td>
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<td>POUNDS</td>
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<td>337,410</td>
<td>334,870</td>
<td>326,625</td>
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<tr>
<td></td>
<td>KILOGRAMS</td>
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<td>153,020</td>
<td>151,870</td>
<td>148,130</td>
</tr>
<tr>
<td>Engine Injection Water Capacity</td>
<td>U.S. GALLONS</td>
<td>600</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>LITERS</td>
<td>2,270</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

1. Typical engine/weight combinations shown. See Sec. 1.3 for other combinations available.
2. Add 5,000 lb (2,270 kg) to JT9D-7AW and JT9D-7FW.
3. Optional landing weight of 465,000 lb (210,860 kg) is available.
4. Add 650 lb (295 kg) for -7AW and -7FW.
5. Optional zero fuel weight of 425,000 lb (192,740 kg) is available.
6. Deduct 650 lb (295 kg) for -7AW and -7FW.
7. Extended range fuel (1,576 gal/5,965 L) is available with OEW increase of 90 lb (40 kg).
8. JT9D-7AW and JT9D-7FW.
BOEING 747SP LANDING GEAR FOOTPRINT
BOEING 747SP VIEW OF ALL LANDING GEAR UNITS FROM AFT
### Boeing 747 SP Base Data from Various Sources

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Take-Off Weight (lbs.)</td>
<td>793,206</td>
</tr>
<tr>
<td>Maximum Take-off Weights (lbs.)</td>
<td>793,206</td>
</tr>
<tr>
<td>Maximum Landing Weight (lbs.)</td>
<td>450,000</td>
</tr>
<tr>
<td>Useful Fuel Capacity (lbs.)</td>
<td>320,256</td>
</tr>
<tr>
<td>Zero Fuel Weight, FSW (lbs.)</td>
<td>410,000</td>
</tr>
<tr>
<td>Maximum Landing Angle</td>
<td>69°</td>
</tr>
<tr>
<td>Minimum Pavement Width for a 180° Turn</td>
<td>43' - 4'</td>
</tr>
<tr>
<td>Lateral Distance between Main Body Gear Posts</td>
<td>26 - 1'</td>
</tr>
<tr>
<td>Lateral Distance between Main Wing Gear Posts</td>
<td>12 - 7'</td>
</tr>
<tr>
<td>Fore-Alt Distance between Nose Gear and Wing Gear Posts</td>
<td>62 - 3.5'</td>
</tr>
<tr>
<td>Fore-Alt Distance between Nose Gear and Body Gear Posts</td>
<td>72 - 4.5'</td>
</tr>
<tr>
<td>Fore-Alt Distance between Aircraft Nose and Nose Gear Post</td>
<td>15 - 2'</td>
</tr>
<tr>
<td>Passenger Capacity (Typical)</td>
<td>391</td>
</tr>
<tr>
<td>Wing Span</td>
<td>155' - 8'</td>
</tr>
<tr>
<td>Total Aircraft Length (to top of vertical stabilizer)</td>
<td>184' - 9'</td>
</tr>
<tr>
<td>Horizontal Stabilizer Span</td>
<td>82' - 5'</td>
</tr>
<tr>
<td>Height of Top of Tail (above pavement)</td>
<td>69' - 6'</td>
</tr>
<tr>
<td>Height of Top of Fuselage (above pavement)</td>
<td>56' - 2'</td>
</tr>
</tbody>
</table>

#### Geometry Definition for Various Landing Gear Bogeys/Tracks

<table>
<thead>
<tr>
<th>Landing Gear Bogle</th>
<th>Number of Wheels on Bogle</th>
<th>Bogle Type</th>
<th>Tyre Size</th>
<th>Fore-Alt Spacing of Wheels within Bogle</th>
<th>Lateral Spacing of Wheels within Bogle</th>
<th>Tyre Pressure (PSI)</th>
<th>Typical Bogle Load (% SWL)</th>
<th>Rated Load Per Tyre (lbs.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nose Landing Gear</td>
<td>2</td>
<td>Twin</td>
<td>49 x 17</td>
<td>N/A</td>
<td>2.6'</td>
<td>106-108</td>
<td>16</td>
<td>4450</td>
</tr>
<tr>
<td>Main Wing Landing Gear</td>
<td>4</td>
<td>Twin Tandem</td>
<td>66 x 16</td>
<td>4.10'</td>
<td>2.6'</td>
<td>108-213</td>
<td>10</td>
<td>4450</td>
</tr>
<tr>
<td>Main Body Landing Gear</td>
<td>4</td>
<td>Twin Tandem</td>
<td>66 x 16</td>
<td>4.10'</td>
<td>3.5'</td>
<td>108-213</td>
<td>15</td>
<td>4450</td>
</tr>
</tbody>
</table>

#### Tyre Manufacturer for United Airlines Boeing 747 SP Registration N447UA

<table>
<thead>
<tr>
<th>Landing Gear Bogle</th>
<th>Tyre 1</th>
<th>Tyre 2</th>
<th>Tyre 3</th>
<th>Tyre 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nose Gear</td>
<td>M</td>
<td>M</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Starboard Main Wing Landing Gear</td>
<td>B/RF</td>
<td>B/RF</td>
<td>B/RF</td>
<td>B/RF</td>
</tr>
<tr>
<td>Port Main Wing Landing Gear</td>
<td>R/B</td>
<td>R/B</td>
<td>R/B</td>
<td>R/B</td>
</tr>
<tr>
<td>Starboard Main Body Landing Gear</td>
<td>R/B</td>
<td>R/B</td>
<td>R/B</td>
<td>R/B</td>
</tr>
<tr>
<td>Port Main Body Landing Gear</td>
<td>R/B</td>
<td>R/B</td>
<td>R/B</td>
<td>R/B</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Michelin</td>
<td>M</td>
</tr>
<tr>
<td>B.F. Goodrich</td>
<td>RF</td>
</tr>
<tr>
<td>Bridgestone</td>
<td>B/RF</td>
</tr>
<tr>
<td>Aitken (by Michelin)</td>
<td>A/VR</td>
</tr>
</tbody>
</table>

---

**BOEING 747 BASE DATA FROM VARIOUS SOURCES**
Note: The maximum nose wheel steering angle is restricted to 65° for the 747SP.

### 4.1.1 GENERAL INFORMATION BODY GEAR STEERING SYSTEM

**MODEL 747**

GENERAL INFORMATION BODY GEAR STEERING SYSTEM

Note: The maximum nose wheel steering angle is restricted to 65° for the 747SP.
NOTES:

- 747-100 AIRPLANE AT 430,000 LB (195,220 KG) (C.G. 27% MAC) AND 600,000 LB (272,400 KG) (C.G. 30% MAC)
- 747-200 AIRPLANE AT 800,000 LB (363,200 KG) (C.G. 15% MAC)
- 747SP AIRPLANE AT 600,000 LB (272,400 KG) (C.G. 15% MAC)
- LOW SPEED 7-25 FT (2.1-7.6 M) PER SEC.
- NO DIFFERENTIAL BRAKING
- DRY CONCRETE PAVEMENT
- 747-300 AIRPLANE AT SAME WEIGHT AND C.G. AS ABOVE -100 OR -200 AIRPLANE

TURNING RADIUS "X":

1. OPERATING RANGE DEPENDENT ON:
   - WEIGHT AND C.G. LOCATION
   - PILOT TECHNIQUE

2. TURNING RADIUS IS THE DISTANCE BETWEEN AIRPLANE CENTERLINE AND TURN CENTER.

TURNING RADII – WITH BODY GEAR STEERING – SYMMETRICAL THRUST
NOTES:
- 747-100 AIRPLANE AT 430,000 LB (195,220 KG) (C.G. 27% MAC) AND 600,000 LB (272,400 KG) (C.G. 30% MAC)
- 747-200 AIRPLANE AT 800,000 LB (360,200 KG) (C.G. 15% MAC)
- 747SP AIRPLANE AT 600,000 LB (272,400 KG) (C.G. 15% MAC)
- LOW SPEED 7-25 FT (2.1-7.9 M) PER SEC.
- NO DIFFERENTIAL BRAKING
- DRY CONCRETE PAVEMENT
- 747-300 AIRPLANE AT SAME WEIGHT AND C.G. AS ABOVE -100 OR -200 AIRPLANE
BOEING 747 PREDICTED TOWING FORCES AND PNEUMATIC TIRE FRICTION COEFFICIENTS
### Boeing 747SP Maximum Pavement Loads Definition (Highlighted)

- **$V_{NG}$** = Maximum vertical nose-gear ground load at most forward CG
- **$V_{MG}$** = Maximum vertical main-gear ground load at most aft CG
- **H** = Maximum horizontal ground load from braking

![Diagram showing the definitions of $V_{NG}$, $V_{MG}$, and H]

<table>
<thead>
<tr>
<th>Model</th>
<th>Maximum Gross Weight</th>
<th>$V_{NG}$ Static at Most Forward CG</th>
<th>$V_{MG}$ Static Plus Force Due to Braking at Most Forward CG</th>
<th>$V_{NG}$ Per Strut (4) Max Load Occurring at Static Aft CG</th>
<th>H Per Strut (4) Max Load at Steady Braking Deceleration</th>
<th>Max Load at Instantaneous Braking (Coef of Friction + 0.8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-100B</td>
<td>523,000</td>
<td>55,100</td>
<td>26,600</td>
<td>126,000</td>
<td>40,600</td>
<td>100,800</td>
</tr>
<tr>
<td>SR/200</td>
<td>573,000</td>
<td>58,600</td>
<td>28,600</td>
<td>138,000</td>
<td>44,500</td>
<td>110,400</td>
</tr>
<tr>
<td>SR/300</td>
<td>623,000</td>
<td>63,200</td>
<td>32,600</td>
<td>145,200</td>
<td>46,800</td>
<td>116,200</td>
</tr>
<tr>
<td>SR/300</td>
<td>613,000</td>
<td>64,200</td>
<td>29,100</td>
<td>147,700</td>
<td>47,600</td>
<td>118,200</td>
</tr>
<tr>
<td>SR/300</td>
<td>713,000</td>
<td>74,200</td>
<td>33,500</td>
<td>166,500</td>
<td>55,400</td>
<td>123,200</td>
</tr>
<tr>
<td>SP</td>
<td>738,000</td>
<td>77,400</td>
<td>36,100</td>
<td>170,600</td>
<td>57,300</td>
<td>136,600</td>
</tr>
<tr>
<td>SP</td>
<td>753,000</td>
<td>78,900</td>
<td>35,800</td>
<td>174,000</td>
<td>58,500</td>
<td>139,200</td>
</tr>
<tr>
<td>SP</td>
<td>636,000</td>
<td>69,900</td>
<td>41,200</td>
<td>147,200</td>
<td>49,400</td>
<td>117,800</td>
</tr>
<tr>
<td>SP</td>
<td>666,000</td>
<td>75,200</td>
<td>43,200</td>
<td>152,200</td>
<td>51,100</td>
<td>121,700</td>
</tr>
<tr>
<td>SP</td>
<td>676,000</td>
<td>76,800</td>
<td>43,800</td>
<td>152,800</td>
<td>52,500</td>
<td>122,300</td>
</tr>
<tr>
<td>SP</td>
<td>696,000</td>
<td>77,400</td>
<td>43,800</td>
<td>153,600</td>
<td>54,000</td>
<td>122,900</td>
</tr>
<tr>
<td>SP</td>
<td>703,000</td>
<td>80,800</td>
<td>43,900</td>
<td>154,100</td>
<td>54,600</td>
<td>123,300</td>
</tr>
</tbody>
</table>

Note: The highlighted values indicate the maximum pavement loads for different models of the Boeing 747SP.
7.4.5 LANDING GEAR LOADING ON PAVEMENT
MODEL 747SP

NOTE: UNSHADED AREAS REPRESENT OPERATIONAL LIMITS.

PERCENT MAC
0 10 20 30

MAXIMUM DESIGN TAXI WEIGHT
703,000 LB (318,000 KG)
676,000 LB (302,000 KG)
666,000 LB (300,000 KG)
656,000 LB (295,500 KG)

CENT OF WEIGHT ON MAIN GEAR

WEIGHT ON MAIN LANDING GEAR
1,000 POUNDS

PERCENT OF WEIGHT ON MAIN GEAR

RAMP WEIGHT
(1,000 KILOGRAMS)

BOEING 747SP PERCENTAGE OF WEIGHT ON MAIN GEAR—PAVEMENT LOADS
Aircraft Ground Loads Calibration Scale

In support of an aircraft ground loads testing requirement, a unique in-ground calibration scale was installed at the Federal Aviation Administration (FAA) William J. Hughes Technical Center, Atlantic City International Airport, New Jersey. The scale is shown in Figure B1 below.

The scale was used to calibrate landing gear loads for a strain survey conducted on the landing gear of an out-of-service B-747SP airplane. This survey was conducted to determine the interrelationship between the lateral and vertical sharing of load by the wing and body gear during taxi operations. This study was part of an FAA review of the applicability of the current regulations for wide-body aircraft with multiple main gear configurations. The research task was one of the FAA’s Operational Loads Monitoring activities under the FAA Aging Aircraft Research Program.

The Aviation and Maritime Services Sector of L-3 Communications, Titan Group, Warminster, Pennsylvania, managed the overall testing program. The actual scale design and installation was subcontracted to Emery Winslow Scale Company of Seymour, Connecticut, and Advanced Scale Inc., Lindenwold, New Jersey. Emil Finn & Associates Pty. Limited, Mosman, New South Wales, Australia, provided engineering consultant services for the project.

Figure B1. Aircraft in fully raised position during the vertical calibration procedure. Wood shims are placed under the tires during the jacking procedure.
The measurement of operational landing gear loads on an aircraft with multiple main landing gear units was complex. A series of strain gauges were installed on the aircraft’s landing gear components to monitor landing gear loads during taxi maneuvers. These gauges monitored the strain on the landing gear shock struts, side struts, drag braces, and torsion links. The gauges were calibrated against applied loads to allow the strains measured during aircraft turning maneuvers to be converted into derived loads. The FAA’s William J. Hughes Technical Center in-ground scale was the tool that permitted the calibration of the installed strain gauges.

Several factors complicated the analysis of gear loads on aircraft with multiple main landing gear configurations. The load transfer among the individual landing gear struts is controlled by the aircraft’s structural stiffness. The load stroke relationships may not be the same for the inboard and outboard main landing gear units. This relation also varies with differences in strut servicing. Strut deflections can vary independently under particular aircraft loading conditions. The loads carried by the individual landing gear can be modified by inertial loads applied during a turn as well as stroke changes as the aircraft traverses uneven surfaces. The loads also vary with changes in the aircraft’s center of gravity position. To monitor these changes, an accurate load versus measured strain relationship must be established. This was done through a static calibration procedure using the specially designed in-ground scale system. The scale, in its closed position, is flush with the airfield surface, which is visible in the foreground of Figure B2. The red access plates are located above the mounting locations for horizontal hydraulic cylinders that are used to apply lateral loads to the upper sliding deck of the scale system. The gray plates are removable for accessing the underground scale components and, when in place, permit the aircraft to be moved onto and off of the scale. The concrete area surrounded by the gray access plates is the actual upper surface of the in-ground scale. The tow vehicle driver used the colored lines on the ramp surface to properly position the aircraft.

![Figure B2. The FAA Boeing 747SP ground test vehicle being moved onto the in-ground calibration scale. Temporary cover plates are installed to permit the landing gear to roll onto the scale.](image)
As shown in Figure B3 below, the temporary cover plates have been removed from the scale exposing a gap between the scale pit and the platform. Jackscrews, located between the lower fixed and upper sliding weighbridges stabilized the upper platform when the aircraft was moved onto the scale. Horizontal load hydraulic cylinders, installed at the aft end of the scale platform, are also visible in the figure. Three linear displacement transducers are positioned on the platform; two are in the foreground (off the platform) to monitor horizontal motion during loading. The temporary wiring, visible in Figure B3, connected the scale’s load cells and the position transducers to a data collection system on the aircraft. The scale output data was recorded by the same data collection system that was used to collect the strain gauge data.

The initial use of the in-ground calibration scale was in preparation for taxi testing of a retired Boeing 747SP aircraft. The scale dimensions were specified to support the load of a single truck of a fully loaded B-747SP. Four load cells were located under the lower weighbridge scale platform, each with a rated capacity of 200,000 pounds. A computer monitored the individual load on each of the load cells as well as the total load on the scale. Each of the aircraft’s main landing gear units were calibrated separately with the aircraft at a constant weight and center of gravity location. The calibration scale platform measures 11 ft long by 8 ft wide and was designed to support a maximum vertical load of 200,000 lbs distributed on the platform in the pattern applied by the tires of a B-747SP landing gear. The scale measurement accuracies were ±0.15% for the applied vertical loads. The displacement accuracy of the scale using linear string gauges was ±0.10 inch in both horizontal directions. Figure B3 shows the port main body gear of the test B-747SP aircraft on the scale platform that is level with the surrounding ramp area.

Figure B3. Side view of the B747SP aircraft’s port main body gear on the in-ground scale platform.
The in-ground calibration scale system allowed direct measurement of the applied load on the landing gear and permitted the applied load to then be plotted against strain gauge output. By jacking the landing gear vertically while it was on the scale, several data points on the load versus strain curves were collected. A tire-changing jack was used to raise the landing gear and temporary shims were installed to support the tires as they are lifted during the jacking procedure. This process was repeated for all the landing gear struts individually. Figure B1 shows the shims installed under the landing gear tires during the calibration procedure. Figure B4 shows the jacking procedure in progress as well as the computer data collection system.

A unique feature of the in-ground calibration scale was its ability to apply measurable lateral loads to the scale platform and, thus, to the landing gear on the scale’s platform. The scale’s sliding deck was designed for lateral and longitudinal loads up to 120,000 lbs. The key design feature that allows this measurement capability was the concrete-reinforced steel frame around the scale pit.

The frame provided multiple mounting locations for hydraulic cylinders. Two hydraulic cylinders can be installed along each edge of the pit. Hydraulic cylinders were installed on opposite sides of the pit to load the platform and then re-center the platform after load application. The hydraulic system that applies the lateral loads consisted of a 15-horsepower motor driving an 8-gpm, 3000-psi hydraulic pump. The hydraulic cylinders had a 6-inch bore, a 20-inch stroke, and were rated at 5000psi. The system included the necessary hydraulic hoses, valves, and fittings. Pressure transducers were installed on the hydraulic cylinders to monitor the load applied to the platform.
Another key design feature in providing the lateral load capability was the design of the scale platform itself. The platform was split into two sections. The upper sliding deck rested on four lubricated Fabreeka bearing pads with highly polished stainless steel plates that produced extremely low coefficients of friction, allowing the upper section of the platform to freely slide horizontally over the lower platform. Displacements of up to 9 inches in any direction could be obtained from the center position of the sliding deck. Fabreeka International, Inc. of Boston, Massachusetts manufactured the slide bearing pads.

In addition, similar sliding bearing pads were installed at the ends of the horizontal hydraulic rams to minimize any side loading on the ram as it pushed on the sliding deck during the testing procedures.

During the calibration procedure, the horizontal displacements of the landing gear, as well as changes to the main strut pressure were monitored and recorded for each applied load. The gear’s horizontal position was monitored automatically for the gear on the scale. The information for the other gears was collected manually. Shifts in the aircraft’s angular deviation from level were also monitored manually during the calibration procedures, following standard weight and balance monitoring procedures.

As shown in Figure B5, a limited capability to apply torque to the landing gear strut was also available. The ability to skew the platform with respect to the pit walls was restricted to 5 degrees. Testing to determine tire friction under different surface conditions, such as ice and snow, were also performed. In these friction tests, a low friction surface treatment (see Section 2.1.3.1 of the report) was applied to the platform, the aircraft was moved onto the scale, and then a lateral load applied to the platform.

Figure B5. View looking down into the scale pit during application of horizontal torque to the B-747SP’s right wing gear. The low-friction Fabreeka bearing pad and plate is visible on the end of the hydraulic ram and side of the slide deck.
The ability to calibrate strain gauges using the in-ground calibration scale was and continues to be a significant addition to the testing facilities of the FAA William J. Hughes Technical Center. While the scale was designed for a specific ground load test program, it should be flexible enough to support strain gauge calibration activities for all current aircraft landing gear configurations.

The aircraft ground loads in-ground calibration scale is available to support research activities by contacting Mr. Tom DeFiore (609) 485-5009 (e-mail Thomas.DeFiore@faa.gov), Airport and Aircraft Safety R&D Division, Operational Loads Monitoring Research at the FAA William J. Hughes Technical Center.
APPENDIX C—DERIVATION OF MATRIX RESOLUTION OF STRAINS AND PRESSURES INTO INDIVIDUAL GEAR UNIT LOADS

Introduction
In order to interpret the strains and pressures recorded during calibration and operational conditions of the Boeing 747SP it was necessary to determine the relationships between measured parameters and the applied load.

The 747SP landing gear load carrying components are effectively hinged on each end for retraction purposes. This allows the loads applied to each landing gear truck to be determined by reference only to the axial loads in each structural element. For this reason pairs of strain gauges were installed on opposite sides of each structural element. By taking the average of the output of the two strain gauges, any bending due to eccentric loading was eliminated and the axial strain was isolated.

Oleo pressures are recorded as the prime indicator of vertical load being transferred hydraulically to the exposed surfaces of the inner cylinder. It is, however, not the sole mechanism of vertical load transfer. The friction between the inner and outer cylinders also forms a load path for vertical forces. Once loads enter the outer cylinder via friction, those loads are distributed among the inner cylinder, the drag brace and the side brace. The distribution is, of course, based on the vertical load stiffness of each of the components.

When we don’t know what the loads are but we do know that the strains and pressures are, the question becomes “How do we sort it out?” The answer to that question is that by applying known loads to each landing gear unit we can obtain information about the interplay of the loads and the strains and pressures that they generate.

A load in any direction generates changes in all of the strain gauges as well as the oleo pressure. If we can isolate the effect of a given load on each strain gage and the oleo pressure, then we can solve a set of simultaneous equations to determine the applied loads that result in any combination of strains and pressure.

Nomenclature
The aircraft frame of reference has the vertical axis pointing upward, the positive port-starboard axis pointing starboard and the positive fore-aft axis pointing aft. For this reason, loads will be referred to as positive vertical when acting upward and negative when acting downward. Positive starboard loads act in the starboard direction and negative starboard loads act in the port direction. Positive aft loads act in the aft direction and negative aft loads act in the forward direction.

If we take the oleo pressure to be just another recorded parameter, we can treat it in the same way that we treat strains. For the purposes of the derivation of the generalized solution of recorded parameters into applied loads, we will refer to any recorded parameter (direct or averaged) as “e.”
Matrix Solution for Resolving Strains and Pressure into Three Orthogonal Applied Loads

We know that the total value of any recorded parameter is made up of the component due to vertical load plus the component due to starboard load plus the component due to aft load. We then have:

\[ e_{\text{Total}} = e_{\text{Vertical}} + e_{\text{Starboard}} + e_{\text{Aft}} \]

During calibration testing of the Boeing 747SP, we were able to determine the effect on each recorded parameter due to a series of applied vertical, starboard and aft loadings. In order to have a predictive tool, the relationship between recorded parameters and the applied load was fitted with a least squares linear curve fit. The curve fitting produced a series of relationships as shown below:

\[
F_{\text{Vertical}} = b_{0V} + b_{1V}e_{V} \\
F_{\text{Starboard}} = b_{0S} + b_{1S}e_{S} \\
F_{\text{Aft}} = b_{0A} + b_{1A}e_{A}
\]

These relationships can now be rearranged to give the dependence of the strain on the force as follows:

\[
e_{V} = (F_{\text{Vertical}} - b_{0V})/b_{1V} \\
e_{S} = (F_{\text{Starboard}} - b_{0S})/b_{1S} \\
e_{A} = (F_{\text{Aft}} - b_{0A})/b_{1A}
\]

Now we can set up a set of simultaneous equations for any combination of three recorded parameters. The formulation is as follows:

\[
e_{\text{Total},i} = (F_{\text{Vertical}} - b_{0Vi})/b_{1Vi} + (F_{\text{Starboard}} - b_{0Si})/b_{1Si} + (F_{\text{Aft}} - b_{0Ai})/b_{1Ai} \\
e_{\text{Total},j} = (F_{\text{Vertical}} - b_{0Vj})/b_{1Vj} + (F_{\text{Starboard}} - b_{0Sj})/b_{1Sj} + (F_{\text{Aft}} - b_{0Aj})/b_{1Aj} \\
e_{\text{Total},k} = (F_{\text{Vertical}} - b_{0Vk})/b_{1Vk} + (F_{\text{Starboard}} - b_{0Sk})/b_{1Sk} + (F_{\text{Aft}} - b_{0Ak})/b_{1Ak}
\]
This set of simultaneous equations can now be represented in their matrix format as:

\[
\begin{bmatrix}
\mathbf{e}_{\text{Total } i} \\
\mathbf{e}_{\text{Total } j} \\
\mathbf{e}_{\text{Total } k}
\end{bmatrix} =
\begin{bmatrix}
F_{\text{Vertical}}/b_{1Vi} + F_{\text{Starboard}}/b_{1Si} + F_{\text{Aft}}/b_{1A1} \\
F_{\text{Vertical}}/b_{1Vj} + F_{\text{Starboard}}/b_{1Sj} + F_{\text{Aft}}/b_{1Aj} \\
F_{\text{Vertical}}/b_{1Vk} + F_{\text{Starboard}}/b_{1Sk} + F_{\text{Aft}}/b_{1Ak}
\end{bmatrix}
\begin{bmatrix}
b_{0Vi}/b_{1Vi} + b_{0Si}/b_{1Si} + b_{0Ai}/b_{1A1} \\
b_{0Vj}/b_{1Vj} + b_{0Sj}/b_{1Sj} + b_{0Aj}/b_{1Aj} \\
b_{0Vk}/b_{1Vk} + b_{0Sk}/b_{1Sk} + b_{0Ak}/b_{1Ak}
\end{bmatrix}
\]

We can now rearrange the matrix equation and obtain the following relationship:

\[
\begin{bmatrix}
\mathbf{e}_{\text{Total } i} \\
\mathbf{e}_{\text{Total } j} \\
\mathbf{e}_{\text{Total } k}
\end{bmatrix}
+ \begin{bmatrix}
b_{0Vi}/b_{1Vi} + b_{0Si}/b_{1Si} + b_{0Ai}/b_{1A1} \\
b_{0Vj}/b_{1Vj} + b_{0Sj}/b_{1Sj} + b_{0Aj}/b_{1Aj} \\
b_{0Vk}/b_{1Vk} + b_{0Sk}/b_{1Sk} + b_{0Ak}/b_{1Ak}
\end{bmatrix}
= \begin{bmatrix}
1/b_{1Vi} & 1/b_{1Si} & 1/b_{1A1} \\
1/b_{1Vj} & 1/b_{1Sj} & 1/b_{1Aj} \\
1/b_{1Vk} & 1/b_{1Sk} & 1/b_{1Ak}
\end{bmatrix}
\begin{bmatrix}
F_{\text{Vertical}} \\
F_{\text{Starboard}} \\
F_{\text{Aft}}
\end{bmatrix}
\]

If we now solve for the applied orthogonal loads we obtain:

\[
\begin{bmatrix}
1/b_{1Vi} & 1/b_{1Si} & 1/b_{1A1} \\
1/b_{1Vj} & 1/b_{1Sj} & 1/b_{1Aj} \\
1/b_{1Vk} & 1/b_{1Sk} & 1/b_{1Ak}
\end{bmatrix}^{-1}
\begin{bmatrix}
\mathbf{e}_{\text{Total } i} \\
\mathbf{e}_{\text{Total } j} \\
\mathbf{e}_{\text{Total } k}
\end{bmatrix}
+ \begin{bmatrix}
b_{0Vi}/b_{1Vi} + b_{0Si}/b_{1Si} + b_{0Ai}/b_{1A1} \\
b_{0Vj}/b_{1Vj} + b_{0Sj}/b_{1Sj} + b_{0Aj}/b_{1Aj} \\
b_{0Vk}/b_{1Vk} + b_{0Sk}/b_{1Sk} + b_{0Ak}/b_{1Ak}
\end{bmatrix}
= \begin{bmatrix}
1/b_{1Vi} & 1/b_{1Si} & 1/b_{1A1} \\
1/b_{1Vj} & 1/b_{1Sj} & 1/b_{1Aj} \\
1/b_{1Vk} & 1/b_{1Sk} & 1/b_{1Ak}
\end{bmatrix}
\begin{bmatrix}
F_{\text{Vertical}} \\
F_{\text{Starboard}} \\
F_{\text{Aft}}
\end{bmatrix}
\]

Since more than three parameters are recorded for each landing gear unit, we can obtain multiple solutions by resolving the loads using different groups of three parameters.

It should be noted that some combinations of recorded parameters will not give the most accurate solution for all three of the applied loads. By way of an example, the use of differential torque link strains, drag brace average strain and oleo pressure would be expected to give a very poor definition of starboard load.
APPENDIX D—TEST PLOTS OF FIVE-GEAR DRY SURFACE 90° TURNS: ACCELERATIONS, VERTICAL LOAD, STARBOARD LOAD, AND VERTICAL-TO-STARBOARD LOAD RATIOS

Measured Individual Gear Vertical Loads vs. Elapsed Time
Scan Session #69 - Dry Surface 5-Gear 120304

Measured Individual Gear Starboard Loads vs. Elapsed Time
Scan Session #69 - Dry Surface 5-Gear 120304
Starboard to Vertical Gear Load Ratio vs Elapsed Time
Scan Session #69 - Dry Surface 5-Gear 120304

Elapsed Time (Seconds)

Ratio of Starboard to Vertical Load (%)

Left Wing Gear
Left Body Gear
Right Body Gear
Right Wing Gear

Accelerations vs. Elapsed Time
Scan Session #69 - Dry Surface 5-Gear 120304

Elapsed Time (Seconds)

Accelerations (g)

Corrected Vertical Acceleration
Corrected Starboard Acceleration
Corrected Aft Acceleration

D-2
Starboard to Vertical Gear Load Ratio vs Elapsed Time
Scan Session #72 - Dry Surface 5-Gear 120304

Accelarations vs. Elapsed Time
Scan Session #72 - Dry Surface 5-Gear 120304
Figures 4.1.22: Scan Session 74 – Dry Surface 5-Gear Taxi – Lateral Load
APPENDIX E—TEST PLOTS OF FIVE-GEAR MODIFIED SURFACE 90° TURNS: ACCELERATIONS, VERTICAL LOAD, STARBOARD LOAD, AND VERTICAL-TO-STARBOARD LOAD RATIOS

Measured Individual Gear Vertical Loads vs. Elapsed Time
Scan Session #75 - Modified Surface 5-Gear 121104

Measured Individual Gear Starboard Loads vs. Elapsed Time
Scan Session #75 - Modified Surface 5-Gear 121104
Measured Individual Gear Vertical Loads vs. Elapsed Time
Scan Session #76 - Modified Surface 5-Gear 121104

Measured Individual Gear Starboard Loads vs. Elapsed Time
Scan Session #76 - Modified Surface 5-Gear 121104
Measured Individual Gear Vertical Loads vs. Elapsed Time
Scan Session #80 - Modified Surface 5-Gear 121104

Measured Individual Gear Starboard Loads vs. Elapsed Time
Scan Session #80 - Modified Surface 5-Gear 121104
Starboard to Vertical Gear Load Ratio vs Elapsed Time
Scan Session #80 - Modified Surface 5-Gear 121104

Accelerations vs. Elapsed Time
Scan Session #80 - Modified Surface 5-Gear 121104
APPENDIX F—TEST PLOTS OF THREE-GEAR DRY SURFACE 90° TURNS: ACCELERATIONS, VERTICAL LOAD, STARBOARD LOAD, AND VERTICAL-TO-STARBORD LOAD RATIOS

Measured Individual Gear Vertical Loads vs. Elapsed Time
Scan Session #108 - Dry Surface 3-Gear 041305

Measured Individual Gear Starboard Loads vs. Elapsed Time
Scan Session #108 - Dry Surface 3-Gear 041305
Starboard to Vertical Gear Load Ratio vs Elapsed Time
Scan Session #111 - Dry Surface 3-Gear 041305

Accelerations vs. Elapsed Time
Scan Session #111 - Dry Surface 3-Gear 041305
APPENDIX G—TEST PLOTS OF THREE-GEAR MODIFIED SURFACE 90° TURNS: ACCELERATIONS, VERTICAL LOAD, STARBOARD LOAD, AND VERTICAL-TO-STARBOARD LOAD RATIOS

Measured Individual Gear Vertical Loads vs. Elapsed Time
Scan Session #135 - Modified Surface 3-Gear 042205
APPENDIX H—TEST PLOTS OF FIVE-GEAR CIRCULAR PATH TURNS: ACCELERATIONS, VERTICAL LOAD, STARBOARD LOAD, AND VERTICAL-TO-STARBOARD LOAD RATIO

Measured Individual Gear Vertical Loads vs. Elapsed Time
Scan Session #153 - 5-Gear Circle Test - Body Gear Steering "On" 050505

![Graph showing vertical loads vs. elapsed time for different gears.](image-url)
Measured Individual Gear Starboard Loads vs. Elapsed Time
Scan Session #153 - 5-Gear Circle Test - Body Gear Steering "On" 050505

Starboard to Vertical Gear Load Ratio vs Elapsed Time
Scan Session #153 - 5-Gear Circle Test - Body Gear Steering "On" 050505
Accelerations vs. Elapsed Time
Scan Session #156 - 5-Gear Circle Test - Body Gear Steering "Off" 050505

Elapsed Time (Seconds)

Corrected Vertical Acceleration
Corrected Starboard Acceleration
Corrected Aft Acceleration

H-5/H-6
APPENDIX I—TEST PLOTS OF FIVE-GEAR S-TURNS: ACCELERATIONS, VERTICAL LOAD, STARBOARD LOAD, AND VERTICAL-TO-STARBOARD LOAD RATIOS

Measured Individual Gear Vertical Loads vs. Elapsed Time
Scan Session #247 - 5-Gear S-Turn Test 052705
Accelerations vs. Elapsed Time
Scan Session #247 - 5-Gear S-Turn Test 052705

Measured Individual Gear Vertical Loads vs. Elapsed Time
Scan Session #248 - 5-Gear S-Turn Test 052705
Measured Individual Gear Starboard Loads vs. Elapsed Time
Scan Session #250 - 5-Gear S-Turn Test 052705

Starboard to Vertical Gear Load Ratio vs Elapsed Time
Scan Session #250 - 5-Gear S-Turn Test 052705
Accelerations vs. Elapsed Time
Scan Session #251 - 5-Gear S-Turn Test 052705

Corrected Vertical Acceleration
Corrected Starboard Acceleration
Corrected Aft Acceleration

Measured Individual Gear Vertical Loads vs. Elapsed Time
Scan Session #252 - 5-Gear S-Turn Test 052705

Left Wing Gear
Left Body Gear
Right Body Gear
Right Wing Gear
APPENDIX J—TEST PLOTS OF 5-GEAR BRAKED TURNS: ACCELERATIONS, VERTICAL LOAD, STARBOARD LOAD, AFT LOAD, AND VERTICAL-TO-STARBOARD LOAD RATIOS

Measured Individual Gear Vertical Loads vs. Elapsed Time
Scan Session #253 - 5-Gear Brake During Turn Test 052705
Accelerations vs. Elapsed Time
Scan Session #254 - 5-Gear Brake During Turn Test 052705

Corrected Vertical Acceleration
Corrected Starboard Acceleration
Corrected Aft Acceleration
Starboard to Vertical Gear Load Ratio vs Elapsed Time
Scan Session #256 - 5-Gear Brake During Turn Test 052705

Elapsed Time (Seconds)

Ratio of Starboard to Vertical Load (%)

-30
-20
-10
0
10
20
30
40
50
60

51 0

Accelerations vs. Elapsed Time
Scan Session #256 - 5-Gear Brake During Turn Test 052705

Elapsed Time (Seconds)

Accelerations (g)

-1.100
-1.000
-0.900
-0.800
-0.700
-0.600
-0.500
-0.400
-0.300
-0.200
-0.100
0.000
0.100
0.200
0.300
0.400

51 0

Corrected Vertical Acceleration
Corrected Starboard Acceleration
Corrected Aft Acceleration
Measured Individual Gear Vertical Loads vs. Elapsed Time
Scan Session #257 - 5-Gear Brake During Turn Test 052705

Measured Individual Gear Starboard Loads vs. Elapsed Time
Scan Session #257 - 5-Gear Brake During Turn Test 052705
Measured Individual Gear Aft Loads vs. Elapsed Time
Scan Session #257 - 5-Gear Brake During Turn Test 052705

Starboard to Vertical Gear Load Ratio vs Elapsed Time
Scan Session #257 - 5-Gear Brake During Turn Test 052705
Accelerations vs. Elapsed Time
Scan Session #257 - 5-Gear Brake During Turn Test 052705

Corrected Vertical Acceleration
Corrected Starboard Acceleration
Corrected Aft Acceleration