Field Survey and Analysis of Aircraft Distribution on Airport Pavements

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In the current Federal Aviation Administration design criteria for runway and taxiway pavements, load repetitions are expressed in terms of coverages that represent the number of times a particular point on the pavement is expected to be stressed as a result of a given number of aircraft operations (passes). The coverages resulting from operations of a particular type of aircraft are a function of the number of aircraft passes, the number and spacing of wheels on the aircraft landing gear, the tire-contact area, and the lateral distribution of the aircraft wheel-paths relative to the pavement centerline or guideline markings. The collective effect of these factors is usually expressed in terms of derived pass-to-coverage ratios, based on the observed lateral distribution patterns of aircraft wheel-paths. Fundamental to the current procedure for converting aircraft passes to coverages is the assumption that aircraft wheel-paths for 75 percent of operations are practically uniformly distributed over a certain pavement width. In this study, this procedure was reexamined on the a priori assumption that aircraft wheel-paths conform more nearly to a normal (bell-shaped) than to a uniform distribution. Theoretical normal distribution curves were fitted to the limited number of actual wheel-path distribution data available and found to be more representative of the actual distributions than are the distribution curves based on the uniform distribution assumption. Aircraft pass-to-coverage ratios based on the normal curves were calculated for both military and civil aircraft, although no measured traffic distribution data were available to verify the procedure for civil aircraft.

One of the parameters in the design criteria for airport pavements is the number of load repetitions that the pavement will receive during its design life. However, the incremental detriment to a pavement that will be caused by a particular wheel at a particular location is affected by factors such as the number of wheels, wheel configuration, load on each wheel, tire-contact area, and location of the aircraft on the pavement. In the development of the current Federal Aviation Administration (FAA) design criteria, the collective effect of these factors was evaluated in terms of the concept described as the coverage. The definition of a coverage differs for flexible and rigid pavements. For flexible pavements, a coverage occurs when each point of the pavement within the traffic lane has been subjected to a tire-contact point; for rigid pavements, a coverage occurs when each point of the pavement within the limits of the traffic lane has been subjected to a maximum stress.

The current procedure for converting aircraft passes to coverages uses a traffic width that is based on information developed several years ago by the U.S. Army Corps of Engineers when aircraft traffic flow and volume were considerably different than at present. The current and projected traffic conditions require that this procedure be verified or modified, as a function of the type of aircraft on runways, and the primary aircraft using it, by the use of lateral and longitudinal traffic-distribution measurements.

PURPOSE

The purpose of this study was to develop a simple and effective method of predicting the lateral and longitudinal traffic distributions of aircraft on civil airport runways and taxiways. The study included a selection of particular types of aircraft from among those commonly used for commercial air transportation. Field data were collected and analyzed for specific airports selected to represent reasonable variations in the operating environment. Data on aircraft ground speeds and weather conditions were correlated with observed measured lateral and longitudinal distributions.

SCOPE

Two phases—data collection and data analysis—of the study are summarized here.

The first part of the data-collection phase consisted of the development, assembly, and testing of the necessary instrumentation system for the determination of:

1. The lateral and longitudinal distribution of aircraft on runways,
2. The lateral distribution of aircraft at particular points on taxiways,
3. The aircraft ground speeds on runways and runway exits, and
4. The type of aircraft (by automatic identification or observation and manual recording).

The second part of this phase consisted of the use of the instrumentation system to collect pertinent data at nine selected airports.

SUMMARY OF WORK ACCOMPLISHED

A system of infrared photoelectric sensors was installed in N-shaped and I-shaped arrays on runways and taxiways at selected civil airports to determine aircraft velocities, lateral locations, and longitudinal locations during takeoff, landing, and taxiing operations. Figure 1 shows a schematic diagram of the instrumentation system and a typical arrangement of the light beam arrays. All data were recorded on magnetic tape. The data included such factors as the date, time of day, system parameters, mode (takeoff, landing, or taxiing), and results of calculations (position and velocity).

Aircraft identification was accomplished by measuring the aircraft footprint, as each aircraft of interest had a unique combination of wheelbase, tread, and configuration.

The accuracy of the data-collection system was verified by a photographic technique. Two synchronized 100-mm, high-speed, high-precision cameras were used to obtain sequenced overlapping pairs of photographs of aircraft passing through an N-array. Several aircraft operations were recorded by both the photographic equipment and the data-collection system. The maximum difference between the offset distances determined by the data-collection system and those determined by the photographic method was 9.1 cm (0.3 ft). Therefore, it was concluded that the data-collection system was adequate.
Data relative to aircraft traffic distribution and speed were collected at the following airports: William B. Hartsfield-Atlanta International Airport, Denver-Stapleton International Airport, Miami International Airport, Seattle-Tacoma International Airport, Greater Buffalo International Airport, Cleveland-Hopkins International Airport, New Orleans International Airport (Moisant Field), Chicago-O'Hare International Airport, and Dallas-Fort Worth Regional Airport. These airports were selected as test sites because of their variations in altitudes, temperatures, and climatological conditions and their individual or collective potential for providing the desired data.

Data were collected for the following types of aircraft: B-707, B-727, B-737, DC-8, DC-9, C-580, B-720, B-747, DC-10, L-1011, C-680, BAC-111, and YS-11. Not all of these aircraft operate at all of the selected airports, and some operate at relatively low frequencies. However, the airports were selected to provide as much data as practicable on all of the aircraft types in general and the first six in particular.

Lateral distributions of aircraft traffic were determined at the following locations of each test site:

1. Runways: (a) for landings—at the approximate point of touchdown or at a point reasonably close thereto, at a point a reasonable distance beyond the point of touchdown and before the start of exit from the runway, and at a point close to the exit from the runway and (b) for takeoffs—at a point near the start of takeoff roll, at the approximate point of rotation or at a point reasonably close thereto, and at a point approximately midway between them and

2. Taxiways: (a) at the exit point on a highway-speed or flat-angled exit taxiway from a runway, (b) at the exit point on a right-angled exit taxiway from a runway, and (c) at a point on the straightaway portion of a taxiway.

Longitudinal distribution of aircraft traffic on runways was collected at the points of touchdown and rotation.

Aircraft ground speeds were determined at the runway observation points for lateral distributions and at the exit points on high-speed exit taxiways.

Data were collected for daytime and nighttime hours of operation at each airport; however, the major portion of the data was for daytime operations.

The following aircraft-traffic-distribution data were collected for each aircraft:

1. Identification of operation (landing, departing, or taxiing) and type of aircraft;
2. Longitudinal location of the point of touchdown relative to the landing end of the runway or displaced-landing threshold for landing aircraft;
3. Longitudinal location of the point of rotation relative to the takeoff end of the runway for takeoff aircraft;
4. Lateral position relative to the runway centerline at the locations described above for both landing and takeoff aircraft;
5. Lateral position relative to the taxiway centerline at the specified taxiway points for taxiing aircraft;
6. Ground speeds at those points for which lateral traffic-distribution data were collected for landing, departing, and taxiing aircraft; and
7. Date and time of day of each event.

Data on the prevailing weather conditions during the collection of the field data were obtained and recorded each hour or whenever significant changes occurred. Data on other conditions that might affect the traffic-distribution characteristics were also observed and recorded.

One runway at each of the nine airports was instrumented such that data could be collected for both operating directions. Two of the runways were 61 m (200 ft) wide; the others were 45.7 m (150 ft) wide. A total of 4359 takeoffs and 5500 landings were recorded. Eight high-speed exits were instrumented, and a total of 697 operations at these exits were recorded. Seven locations on straight taxiways [a 30.5-m (100-ft) wide one and six 22.8-m (75-ft) wide ones] were instrumented, and 590 operations at these locations were recorded.

Procedures based on generally accepted methods of statistical analysis were used to analyze the field survey data. The mean and standard deviations of the lateral distributions and ground operating speeds for each sample—i.e., individual or combined types of aircraft at individual or combined airports—were the two primary statistical parameters used in describing and comparing samples. Frequency distributions (histograms) of the observed aircraft to centerline offsets were plotted in terms of the proportionate occurrences in 0.61-m (2-ft) intervals on either side of the pavement centerline or guideline markings.

Inspection of the histograms, such as the one shown in Figure 2, showed that the lateral distribution of aircraft traffic on runways, runway exits, and taxiways would be much more accurately represented by a theoretical normal distribution function, such as is currently used to derive pass-per-coverage ratios (1), rather than by the modified uniform distribution function that was previously used. This observation was also verified statistically by using the X² goodness-of-fit test.

In general, the aircraft centerline offsets were (a) to the left of the pavement centerline stripe on runways; (b) to the right of the pavement centerline stripe on straight taxiways; and (c) to the left or right of the guideline on high-speed exits, depending on aircraft operational flow pattern and exit configuration. The computed offsets mean for runways, for both landings and takeoffs, generally ranged from 0.15 to 0.48 m (0.5 to 1.5 ft) left of the centerline on 47.5-m-wide pavements and from 0.24 m (0.8 ft) right to 0.76 m (2.5 ft) left of the centerline on 61-m-wide pavements. Wide-body and four-engine aircraft tended to be slightly farther left than two- and three-engine aircraft, but the difference was neither large nor consistent enough to make a distinction among such aircraft groupings.

The shapes of the lateral distribution patterns for takeoffs were generally narrower than those for landings. The computed standard deviations for individual types of aircraft, compared at the various airports, generally varied from 0.91 to 2.4 m (3 to 8 ft) for takeoffs and from 1.2 to 2.7 m (4 to 9 ft) for landings. There was no consistent correlation of the standard deviation with respect to type or size of aircraft.

The standard deviations for takeoffs, for all the airports combined, varied among the individual types of aircraft generally from 1.8 to 2.7 m (6 to 9 ft) in the vicinity of lift-off and from 1.7 to 2.1 m (5.5 to 7 ft) in earlier portions of the takeoff roll. On 61-m-wide runways, the standard deviations in the vicinity of lift-off were about the same as those in the same area on 47.5-m-wide runways, but they were about 47.5 cm wider in earlier portions of the takeoff roll. The normal distribution curves for takeoff operations of all aircraft at all airports are shown in Figure 3.

The standard deviations for landings, for all airports combined, varied among the individual types of aircraft generally from 2.1 to 2.6 m (7 to 8.5 ft), except near the end of landing rolls where, as expected, exit effects intruded. The normal distribution curves for landing operations of all aircraft at all airports are also shown in Figure 3.

Factors such as night operations, crosswinds, and wet pavements had apparent effects on aircraft lateral distributions on runways, but their overall impacts were not significant because these effects were (a) relatively small or generally not consistent, (b) infrequent in occurrence, or (c) compensated for or nullified by other factors in the overall operating conditions.

In general, 90 to 95 percent of touchdowns occurred in the first 0.91 km (3000 ft) from the threshold, 70 to 85 percent occurred in the first 0.61 km (2000 ft), and 15 to 25 percent occurred in the first 0.31 km (1000 ft). A higher percentage of two-engine aircraft touchdowns occurred closer to the threshold in comparison with those of the wide-body and four- and three-engine narrow-body aircraft.

The standard deviations of the observed lateral distributions on high-speed exits were generally greater than those on runways and were affected by aircraft operational flow pattern and exit configuration. The standard deviations ranged from approximately 2.4 to 3.2 m (8 to 10.5 ft), with the upper limit probably more representative of typical exit configurations and their normal use.

The computed offset mean of the lateral distributions on straight taxiway sections was approximately 0.61 m right of the centerline on the 22.8-m-wide taxiways and approximately 0.91 m right of the centerline on the 30.5-m-wide taxiway. The standard deviations of these distributions were much smaller than those on runways, ranging from approximately 0.98 to 1.2 m on the 22.8-m wide taxiways and averaging about 1.8 m on the 30.5-m-wide taxiway. The average taxiing speeds were between 10.6 and 13.7 m/s (35 and 45 ft/s) on both the 22.8 and 30.5-m-wide taxiways.

The analysis of the field survey data leads to the following conclusions:

1. The lateral distribution of aircraft on runways, runway exits, and taxiways is much more nearly represented by a theoretical normal distribution function than by a uniform distribution function;
2. The properties of the aircraft wheel-path distribution (i.e., the aircraft to centerline offset measured relative to the centerline or guideline markings) are as summarized below (1 m = 3.28 ft):

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Effects of Dynamic Loads on Airport Pavements

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A study of the responses of typical flexible and rigid airport pavements to static and dynamic loading is summarized. Two series of full-scale tests using instrumented aircraft and runways were made. Among the results were that (a) both types of pavements exhibited both elastic and inelastic responses; (b) these types of responses must be separated to interpret the data; (c) two different types of displacement responses (inertial and noninertial) are present; (d) bow waves and elastic vertical expansions about the wheels occur in both types of pavements; (e) the vertical pressures in both types of pavements are totally recoverable and elastic; (f) no basic aircraft ground operating mode induces pavement responses greater than those occurring for static load conditions, although under unusual conditions, such responses might occur; (g) pavement thicknesses can be reduced in the interiors of runways, but the pavement in exit areas of flexible runways should be stronger than that of main runways; (h) inelastic behavior is highly dependent on temperature, rate of load application, and load history; (i) in the velocity range of static load to low-speed taxi, inelastic displacements can be larger than elastic ones; and (j) the elastic behavior of stiff pavements is almost constant. Because the elastic and inelastic displacement behavior of pavements correlates to the behavior of the Waterways Experiment Station pavements test sections under simulated aircraft loads and wheel configurations and distributed traffic to the behavior of actual pavements under actual aircraft operations, further investigations of dynamic load effects can probably be conducted on pavement test sections of limited size.

Because of reports of pavement distress resulting from current commercial aircraft loads and growing concern over the possibility of further detrimental aircraft dynamic-load effects on airport pavements, the Federal Aviation Administration has sponsored a study of this problem. The study consisted of a literature survey, computer analyses to determine aircraft-loads and pavement responses, scaled pavement tests, and correlations between experimental and analytical data. In general, it was concluded that aircraft dynamic wheel loads have had a significant effect on portions of airport pavements. Specifically, the study showed that the primary effects that influence pavement response to dynamic loads are

1. The increased magnitudes of aircraft wheel loads that result from aircraft modes of operation, pavement unevenness, and aircraft structural characteristics during moving ground operations and
2. The dynamic load phenomena associated with the materials used in the construction of both rigid and flexible pavements.

For a given aircraft and level of pavement unevenness, the loads imposed on a runway can be accurately defined for various ground operations. On the other hand, there has been a serious lack of the information necessary to obtain an accurate description of pavement response to dynamic loads.

PURPOSE

The study was undertaken to provide experimental pavement-response data so that the significance of dynamic loads on airport pavements could be evaluated. Specifically, the basic purpose of the study was to determine the relations between the responses of typical flexible and rigid runway pavements and static and dynamic loads. The magnitudes of the dynamic loads and the depths to which pavement structures are affected by both static and dynamic loads were determined, and the relation between aircraft ground speeds and dynamic loads were investigated.

SCOPE

Two series of full-scale tests using instrumented aircraft and both flexible and rigid instrumented runways were conducted to provide the data needed. One series of tests was conducted during the winter of 1972 when the average temperature of the top pavement layer was between 1.7 and 12.8°C (35 to 55°F), while the second series was conducted (on the flexible pavement only) during the summer of 1974 when the average temperature of the top pavement layer was between 28.9 and 46.3°C (84 to 116°F). Instrumentation systems were installed aboard aircraft to measure and record the three components of force of each of the main-gear assemblies. Instrumentation systems were also installed at various elevations in the pavements to measure the pavement responses to aircraft loads as relative displacements and pressures. The key element in this experimental approach was the recording of a common time base for the aircraft-load and the pavement-response measurements. This control provided a means of correlating the responses of the aircraft and pavement structures to within 1 ms. The locations of the instrumented pavement test sites were

<table>
<thead>
<tr>
<th>Type of Pavement</th>
<th>Width of Pavement (m)</th>
<th>Average Offset (m)</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Runway Landings</td>
<td>45.7</td>
<td>0.27 to 0.48 left</td>
<td>2.1 to 3.1</td>
</tr>
<tr>
<td></td>
<td>61.0</td>
<td>0.24 right to 0.70 left</td>
<td>2.7 to 3.4</td>
</tr>
<tr>
<td>Takeoffs</td>
<td>45.7</td>
<td>0.15 to 0.37 left</td>
<td>1.8 to 2.5</td>
</tr>
<tr>
<td></td>
<td>61</td>
<td>0.70 to 0.76 left</td>
<td>2.3 to 2.5</td>
</tr>
<tr>
<td>Straight taxiway</td>
<td>22.8</td>
<td>0.64 right</td>
<td>0.76 to 1.2</td>
</tr>
<tr>
<td></td>
<td>30.5</td>
<td>0.97 right</td>
<td>1.8</td>
</tr>
<tr>
<td>High-speed runway exit</td>
<td>Variable</td>
<td></td>
<td>2.4 to 3.2</td>
</tr>
</tbody>
</table>

3. The overall impact of such factors as night operations, crosswinds, and wet pavements is not a significant influence on the distribution of aircraft traffic.