MEASUREMENTS OF RUNOFF DEPTHS FROM A GROOVED LABORATORY SLAB

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Abstract

Runoff experiments were conducted indoors on a 30 feet by 15 feet portland cement concrete slab sloping at 1.5 percent along the 30-feet dimension. These laboratory tests were run to verify the concept of a mathematical model developed for grooved runway runoff which was presented at the 1983 Annual Meeting of the Transportation Research Board. Artificial rainfall was applied to the slab by equipment constructed earlier in a separate but cooperating study. The tests essentially consisted of tracing water movement patterns using dye, and measuring small water depths using pressure transducers for rainfall rates of 1.15 and 2.45 inches/hour.

The results indicate that water depths on the upstream surface of the grooved slab are negligible because all of the rainfall is carried in the grooves until, at some point downstream, the grooves fill up and overflow. In addition, the hydraulic roughness coefficient was found to be higher than expected for the pavement surface, and lower than the value used in Phase I for the groove surface. The computer program which solves the analytical model was modified accordingly. Model results were generated and were compared with experimental values. Predicted water depths and their percentage reduction due to grooving were also generated out to a distance of 100 feet for spacings of 5 inches and less under rainfall of 3 inches/hour. The maximum depth reduction due to grooving was about 28 percent at the edge of runway, compared with the Phase 1 estimate of 19 percent over the entire runway. Other runway locations have larger reductions.

Introduction

An important parameter affecting aircraft braking performance is the amount of water on a runway surface. Therefore, it is important to identify, understand, and measure the significant factors that affect surface water depths. To reduce or eliminate hydroplaning, many runway surfaces are grooved normal to the flight path. This practice is known to provide footprint pressure relief which reduces hydroplaning potential. It is not known, however, whether this practice enhances, hinders, or has no appreciable effect on surface drainage relative to ungrooved surfaces. To address this problem, this study was divided into two phases.

In Phase I a mathematical model was solved on a computer. The model included the following parameters: 1) transverse slope of surface, 2) surface texture, 3) groove size and two shapes, 4) groove spacing, and 5) rain rate (uniform). This phase has been reported in References (1) and (2). Phase II, which has been reported in Reference (3), constituted the experimental part of the project and the basis for this paper. This phase incorporated the following elements:

1. Indoor facility using a rain-producing machine developed in a cooperating study sponsored by the Federal Aviation Administration, with storm durations and intensities being restricted to those in that study.
2. Portland cement concrete test slab approximately 15 feet (longitudinal) by 30 feet (transversal), the size being restricted by the rain equipment described in (1).
3. Sampling from the groove spacing and rain parameters listed in Phase 1, for a fixed transverse slope of 1.5 percent and an as-built concrete surface with 1/4-inch-square grooves only.
4. Determination of time to reach steady state under various rain rates.
5. Measurement of water depths and flow rates under steady-state conditions.
6. Modification of the Phase I mathematical model on the basis of experimental results for rectangular grooves, and extrapolation beyond the range of experimental parameters.

Scope of Experimental Work

The project called for the construction of an indoor portland cement concrete slab and the provision of all the necessary equipment for runoff measurements. The slab was built at the Pennsylvania Transportation Research Facility. Rainfall simulation equipment developed in a cooperating study for a 30 feet by 15 feet area and designed to provide routinely a rainfall intensity of about 1 inch per hour, supplied the artificial rain. The slab size of 30 feet by 15 feet was a cost-effective accommodation to the rain equipment. Limitations of laboratory space and rainfall distribution would only permit 30 feet of the 100-feet transverse width of a runway.

The experiments consisted of applying two rainfall rates (approximately 1 inch/hour and 2.5 inches/hour) to each of four surface conditions of the slab (ungrooved, and grooved at spacings of 5 inches, 2.5 inches, and 1.25 inches on centers). The grooves were straight rectangular channels 1/4 inch square, running parallel to the 30-feet dimension. FAA personnel cut the grooves with their equipment at various times during the study. Quantitative work consisted of obtaining water depth data on the untextured surface of the slab using pressure transducers. Qualitative work was also done using dye to trace water movment patterns on the slab for each of the surface conditions.

The groove spacings were selected to be within the spectrum of spacings being studied by the FAA in dynamic tests. See Reference (4) for a discussion of 3-inch spacing versus 1.25-inch spacing.

Relation of the Experiements to the Computer Model of Phase 1

Phase I of this study consisted of the development of an analytical model and a FORTRAN IV computer program to generate overland flow water depths for various rainfall-runoff conditions. The model was based on the concept of kinematic overland flow for the ungrooved surface and kinematic flow in the grooves which have a wetted perimeter of 3/4 inch of solid boundary when filled. The model assumes a planar ungrooved boundary equivalent to the wetted perimeter of a grooved boundary, thereby preserving the flow shear area. For a groove, rain would fall on the middle 1/4-inch segment of the groove, but it would also fall on the connecting 1/4-inch segments as an arbitrary allotment of lateral inflow from adjacent surfaces. The strength of the concept is that solutions of the equations are straightforward and simple, and therefore satisfaction of the principle of conservation of mass is a certainty. The main weakness is that different groove shapes can have vastly different arbitrary allotments of lateral inflow, which should not be the case. However, it was anticipated that this concept in the model would be easy to correct for allotment of lateral inflow, once the experimental results of Phase II became available.

For a uniformly textured planar surface, whether grooved or ungrooved, the model assumed a constant Manning's n (hydraulic resistance coefficient). The value of n chosen depended on the average texture depth of the pavement and was determined from the Reed and Kibler curve (5) for several hypothetical textures. The curve also appears in the Phase I report (1). However, it was believed at the time that the saw-cut grooves would be smoother than the textured experimental slab and hence would have a different value of n. Also, it was thought that the n value of the slab surface obtained by using the median line of the Reed-Kibler graph might not match the value observed during the experiments.

In Phase II of the study, the computer model was adjusted to conform to the experimental observations. It was then used to generate mathematical curves which were compared with plotted experimental data points. In addition, the modified model was used to predict runoff depths beyond the 30-feet range of the slab, i.e., out to the 100-feet edge of the runway.

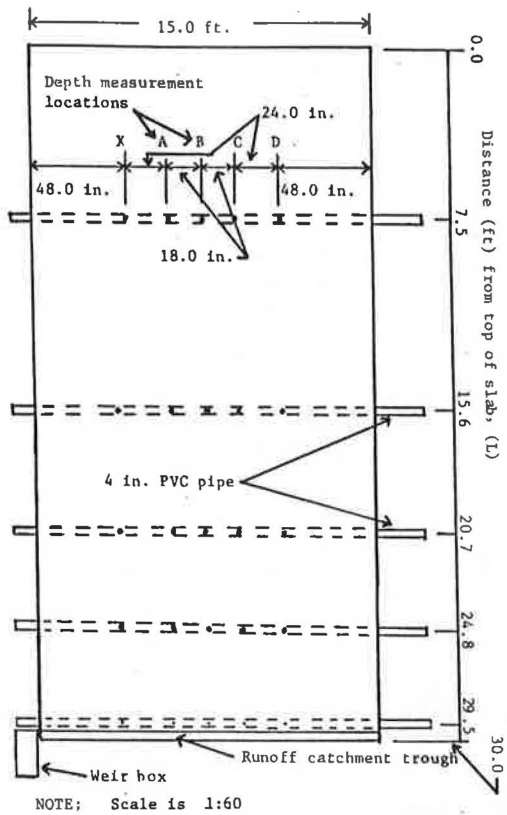
Concrete Slab and Artificial Rainfall

The concrete slab is 4 inches thick with light reinforcing to minimize tension cracks. A plan view is shown in Figure 1. The slab slopes along the 30-feet dimension at 1.5 percent. The slope was set accurately on the concrete forms prior to construction, using precise surveying equipment. It was checked again after the concrete had been poured, typically finished with a stiff broom in the 30-feet direction, and had set. The slab was set on a raised pad of crushed limestone aggregate embedded with PVC (polyvinyl chloride) pipes as shown, with the top of pipes at the aggregate pad surface. The black dots shown over the PVC pipes in Figure 1 are 3/8-inch holes drilled through the slab to the empty PVC pipes in order to accommodate instrumentation tubing beneath the slab. The weir box was used to measure the flow off the downstream edge of the pavement. The runoff trough at the bottom of the slab is used only for collection purposes and is not represented in the computer simulation since flow times are so short. This measurement was used primarily for planning purposes and had no effect on the results.

Figure 2(a) shows a sand-patch test being conducted on the finished ungrooved surface of the slab in order to determine an average texture depth at a given location. Fifteen such tests were performed uniformly on the surface of the slab, and the results showed an average texture depth of 0.026 inch, with a range of 0.022 inch to 0.029 inch. The texture depth used in conjunction with the Reed-Kibler curve mentioned earlier, provided an estimate of the hydraulic roughness coefficient. A special sand-patch test was made near the center of the slab, where a rather severe blemish occurred in the broom finishing of the fresh concrete. The test showed the blemish to have an average texture depth of 0.048 inch. The blemish runs throughout the 15-feet dimension of the slab.

The photograph in Figure 2(b) shows an overall view of the experimental system in operation, with

Figure 1. Plan view of concrete slab showing construction details.

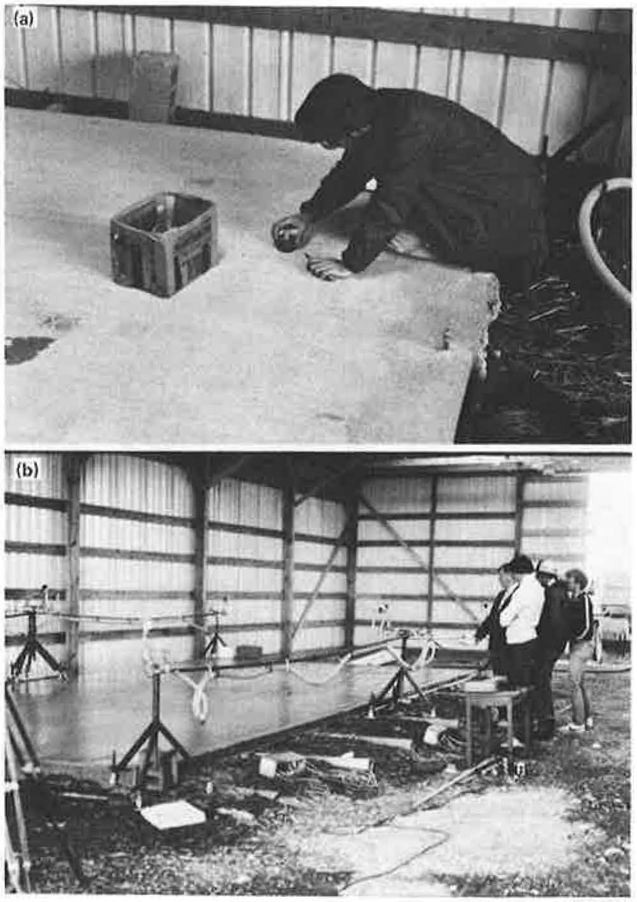


artificial rain falling on the grooved slab. Eight tripods support the spray nozzles, valves, and pressure gages of the rainfall simulation equipment. A 600-gallon tank truck supplies water to the system and, like the rain equipment, belongs to a separate but cooperating study. Tank capacity can be a limiting factor in the duration of rainfall for a test, and the nearest water supply was several miles away.

The rainfall simulation equipment has been documented by Davis (6). To establish an intensity of 1 inch/hour, four nozzles in a predetermined pattern were used, and the pressure gates at the nozzles were regulated to 12 psi. For 2.5 inches/hour, eight nozzles were used, and the pressure gates were set at 20 psi. It should be understood that these rainfall rates are spatial averages and not absolutely uniform. Standard deviations in these averages could be about ±0.3 inch/hour. To insure a closer estimate of the rainfall intensities in this research, collection cup data similar to those taken by Davis (6) were taken in the important flow regions spanned by the sensor holes on the slab. These cups may be seen in Figure 3(a), along with a sensor opening shown at the tip of the pen on the textured slab surface. The collection cup data resulted in more accurately defined rain rates for this study. These rates were 1.15 inches/hour and 2.45 inches/hour. Standard deviations were not determined for these averages, but experience has shown that cup data collected only in the center of a rained-on area are more nearly uniform.

Figure 3(b) is a photograph of the broom-finished surface, showing a rectangular groove and a more discernible 3/8-inch sensor opening. A photograph of the slab being grooved is shown in Figure 4(a).

Figure 2. Concrete test slab and artificial rainfall equipment: (a) sand patch test on dry ungrooved slab; (b) grooved slab under artificial rainfall.



The water that can be seen on the surface of this slab results from a constant supply to the diamond-tipped saw for cooling and lubrication. Figure 4(b) is a close-up of the grooving machine.

Pressure Transducers

Figure 5(a) shows the flexible tubing connected to the sensor openings, emerging from beneath the slab in the 4-inch-diameter PVC pipe. Figure 5(b) shows one of the tubes being connected to a pressure transducer. Ten of these U.S.-made transducers were purchased for this study because their cost was comparable, without sacrifice of accuracy, to the single one made in Europe and proposed initially for these experiments. In Figure 2(b), the wooden box in which the transducers are mounted can be seen (left center) resting on the floor at the side of the slab. All transducers were placed below the slab surface in order to sense positive pressures, since they were calibrated for positive pressures in this study. The transducers sense small changes of pressure in the tubing (flow depths on the surface of the slab) and send electrical signals to a digital multimeter. A 5 volt DC power supply device in the form of a function generator was used with the system. The multimeter used was Data Precision Model 258, which has an LCD readout to the nearest 0.01 mV.

It was necessary that the calibration coefficient (K) be determined individually for the ten transducers in this study. Figure 6 shows the linear nature of the response for data which determine the maximum and minimum K values (slopes). The transducers were calibrated using a container with a bottom opening to which a transducer could be connected. Water levels in the container were varied, and changes in voltage response by a transducer were recorded against changes in water depth measured by a mechanical point gage accurate to 0.001 feet. As can be seen from Figure 6, the correlations are excellent.

The depth-measuring system using pressure transducers is considered superior to any system that is mounted either above or on the slab surface. Such systems can obstruct in some fashion the very quality they are intended to measure. One of the disadvantages of transducers is that their sensor positions are fixed. Reference (7) describes an excellent above-the-surface system involving a point gage with a variable (x,y) position.

Figure 3. Textured surface of slab showing collection cups, sensor openings, and rectangular groove: (a) collection cups and sensor opening; (b) rectangular groove and sensor opening.

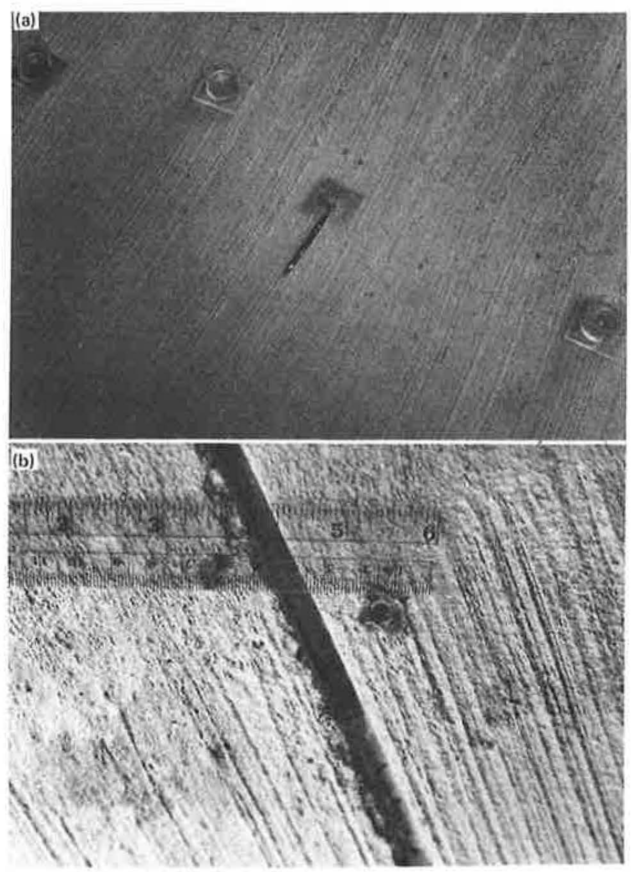


Figure 4. Grooving Machine in Operation: (a) grooving the slab; (b) close-up view of circular saw.

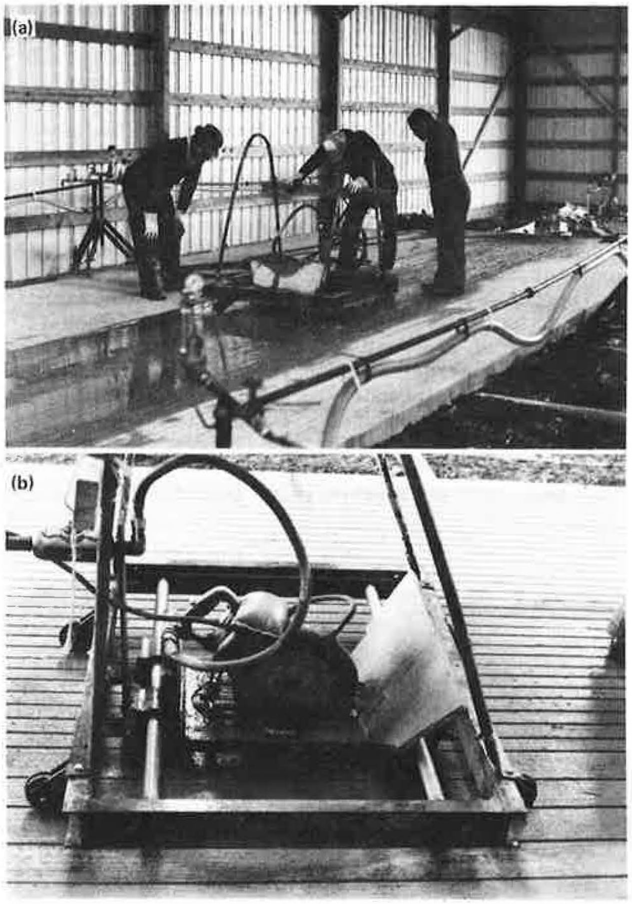


Figure 6. Depth versus voltage curves for pressure transducers.

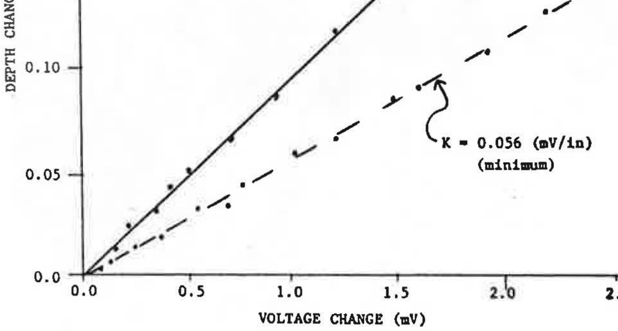
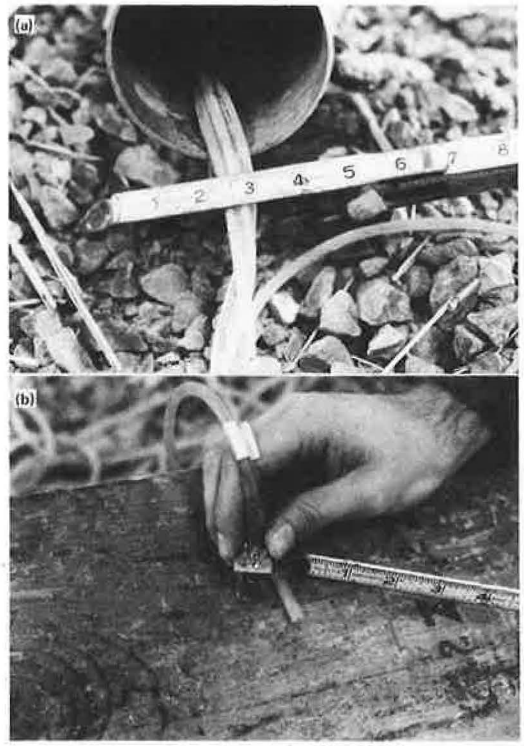


Figure 5. Connection of pressure transducers to openings using flexible tubing; (a) flexible tubing emerging from PVC pipe; (b) pressure transducer connected to sensor tubing.



Equilibrium Water Depth Data

Prior to activation of the artificial rainfall, the tubes connecting the transducers to the slab sensor openings were checked to see whether they were filled with water without air pockets. This procedure is difficult because much of the tubing is concealed in the PVC pipes. It is even more difficult for the upstream row of sensors (L = 7.5 feet in Figure 1) where depths are extremely small and as much as 25 feet of tubing is connected to the sensors. The water level in the sensor openings in the slab was then checked, and a judgment was made as to when the level was at the average texture depth datum. In this process a wetting agent in the form of a mild detergent was placed on the opening with an eye dropper in order to break down surface tension and reduce capillarity effects. When the water levels were judged to be at the proper datum, the transducers were zeroed for this level by recording their output voltage. At this point, the rainfall equipment was prepared for a test.

With the upstream valves for all eight nozzles of the rainfall simulation equipment closed, the centrifugal pump on the tank truck was started, which applied pressure to the system supplying water to the nozzles. The pipes of translucent material were checked for air pockets, which were then purged through small bleed valves with minimum loss of water. Then, one by one, each nozzle was set for the appropriate pressure by opening the valve, adjusting the pressure regulator, and closing the valve. Again, the loss of water was minimized, because this operation takes only a few seconds. When all the nozzles were set, the pump was turned off. The valves to the nozzles were opened, and a small residual spray occurred for a short time due to the release of pressure. Testing then begins when the pump is started and the required intensity sprays forth. For the tests reported herein, the truck capacity provided adequate durations of rainfall, particularly with the conservative startup procedure.

For a given rainfall rate and slab surface condition, voltage readings were taken after equilibrium (steady state) conditions were reached at L - 30 feet. Resulting voltage changes were converted to water depths for each sensor opening, using calibrations as in Figure 6. At least three water depths were recorded per sensor in repeated runs. Eventually, the water depths for the sensors located at a given distance from the top of the slab (L) were averaged to obtain an experimental data point. The data points which resulted from this procedure will appear on graphs later in this paper. No data were recorded for the L - 7.5-feet row of sensors, nor for the X column of sensors in Figure 1. There were no discernible depths for grooved pavement at L - 7.5 feet, and the sensors along the X column were too close to the leg of a rainfall equipment tripod to be considered unobstructed.

Hydraulic Resistance Coefficients

The measured water depths for the ungrooved pavement appeared appreciably larger than the depths obtained from the mathematical model of Phase I. A possible reason for this discrepancy is the uncertainty in the value of the hydraulic resistance coefficient, Manning's n, used in the mathematical model. If the average texture depth of 0.026 inch is used, Manning's n from the Reed and Kibler curve (5) is 0.042 for the median line, and 0.056 for the upper limit line. If the texture depth of 0.048 inch is used for the finishing blemish mentioned earlier, the upper limit line of the curve yields n - 0.081. Of course, the blemish occurs only in one area of the pavement, but it does extend all the way across the slab. It was decided, therefore, to make a dye trace determination of Manning's n prior to grooving the pavement. For this determination the time to reach equilibrium conditions at the downstream edge of the slab is customarily approximated by the travel time of the dye over the entire length of the slab under equilibrium conditions. Thus, Manning's n for the ungrooved slab surface was determined from equation (8) of References (1) and (2):

$$t_{eq} = \frac{56.25\, L^{0.6} n^{0.6}}{i^{0.4} S_o^{\,0.3}}$$

where t_{eq} = equilibrium flow time, seconds

L = length along flow path or width of runway, feet

n = Manning roughness coefficient

i = rainfall intensity, inches/hour

S_o = slope of the plane.

Three travel times were recorded for each of the two rainfall rates. For both rates, the three travel times were very close to each other in value. An arithmetic average of the three was used in the above equation to compute n (353 seconds for 1.15 inches/hour and 260 seconds for 2.45 inches/hour), where L = 30 feet and S_o = 0.015. The data for each intensity yielded identical values of n = 0.096, which seemed rather high. Before these tests were repeated to check n for intermediate values of L, the slab was grooved and no more data were taken. However, for water depths of the order of magnitude in this study, Reference (8) indicates n values between 0.05 and 0.15, with higher values for lower water depths. In addition, in a separate and as yet unpublished study not involving dye, n was determined to vary from 0.03 to 0.10 at a fixed location on the slab surface as the water depth decreased. Hence, the constant value of n used here for the slab surface, whether from the Reed-Kibler curve (0.056) or the dye tests (0.096), is compatible with other studies. Certainly, the higher n values produce higher water depths, which is a conservative posture relative to hydroplaning.

The saw-cut grooves have a smoother surface than the slab surface. To determine the hydraulic resistance of the groove channels, a flow was created in the grooves from a hose laid on the surface of a grooved slab not subject to rainfall. The flow was adjusted so that reasonably long stretches of the grooves would flow full without overflowing onto the surface. The Manning equation given below, which is shown in Reference (2) for a modeled groove, can be solved for n_g if the flow velocity can be measured. Velocities were measured by timing the movement of a tiny piece of styrofoam moving in the grooves over a distance of 15 feet. The average time for six grooves was 22 seconds. Thus,

$$n_g = \frac{1.49}{V} R^{2/3} S_o^{\,1/2}$$

where n_g = Manning roughness coefficient for grooves

V = velocity of flow in groove, feet per second

R = hydraulic radius of full groove = A/P, feet

A = area of groove = 1/16 square inch

P = wetted perimeter of groove - 3/4 inch

S_o = slope of the plane.

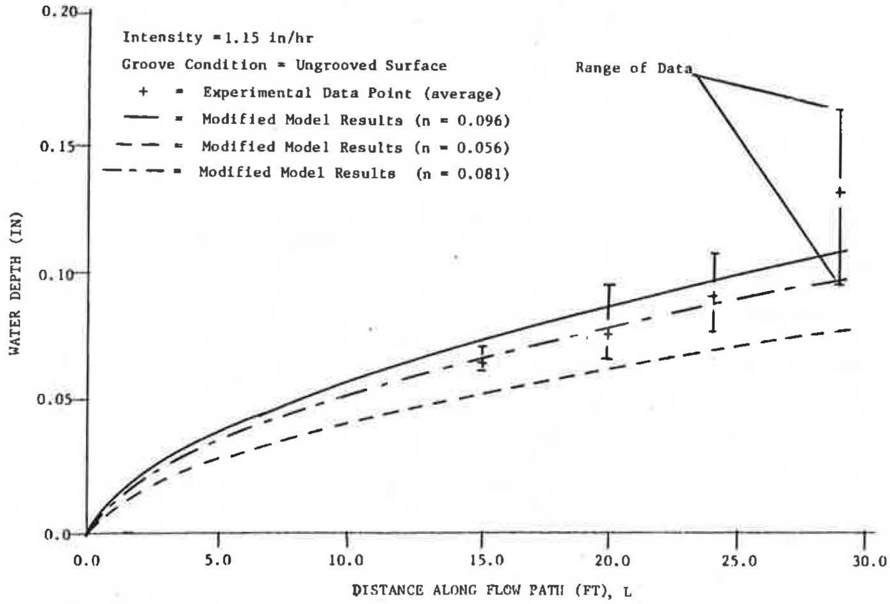
The resulting n_g value of 0.010 is not surprising, since a table lookup for such a smooth surface might show a value of that magnitude.

Qualitative Tests Using Dye

A series of dye tests was undertaken to observe water movement on the grooved slab. Fluorescein sodium salt is a dark-red powder which becomes greenish-yellow when dissolved in water. As a dye, it may be used in dry or liquid form. The most effective observations in this study were made by placing the dry powder along the upper edge of the slab and allowing the rainfall to pick it up and diffuse it downstream.

A large number of color photographs were taken during these tests. The photographs show very clearly that all of the dye is carried in the grooves at the upstream end of the slab. When the grooves become filled, dye comes out of the grooves

Figure 7. Water depth versus distance for ungrooved pavement at 1.15 inches per hour.



and remains on the slab surface for the remaining length of flow. Some interpretation is necessary to identify where this occurs. There are locations where dye comes out of the grooves and then goes back in. Such situations can usually be attributed to some geometric irregularity in the grooves at those locations.

Modification of the Computer Model of Phase I

The FORTRAN IV computer program developed in Phase I was modified to reflect the experience gained from the experiments. Certainly, the Manning's n value used in Phase I for the pavement surface was lower than the experiments indicated, but since it was an input value in the original program, no modification was necessary. However, the program was modified to accept as input a separate Manning's n value (n_g) for grooves. The major modification to the program was based on the concept that all of the rainfall falling at the upstream end of the grooved pavement is carried in the grooves and not on the surface. This condition continues until the grooves fill up at some point downstream. At that point, the pavement surface water depths begin to be computed. The program assumed that all rainfall falling on a spacing of 5 inches or less contributes lateral inflow to a groove. It is uncertain whether this is true for spacing greater than 5 inches. The original computer model used the wetted perimeter of a groove as an arbitrary determination of the rainfall contributing to flow in the groove, but the nature of the model made adjustment to actual conditions easy.

The program was executed on an IBM 370/Model 3033 system to generate the modified model results shown graphically in this paper. The Manning's n values shown on graphs from this point on are those for the grooves value, n_g = 0.01, was fixed for all of the computer runs.

Experimental versus Analytical Water Depths

Figures 7-11 display comparisons of experiemental water depths and analytical curves of water depths generated by the modified computer program. Each of the five graphs represents a specific combination of one of the two rainfall intensities with either the ungrooved or the grooved slab.

Figures 7 and 8 for the ungrooved pavement show three computer model curves, one for each of the three pavement surface n values discussed earlier. The best comparison of data and model appears, surprisingly, to be for n = 0.081, which is the upper limit value from the Reed-Kibler curve using the average texture of the pavement blemish. It would be difficult to conclude, however, that the blemish controls the hydraulic resistance of the entire slab. Figures 9 and 10 clearly show the reduction of water depths as a result of grooving. Figure 11 represents the last set of experimental conditions where non-zero water depths prior to the end of the 30-foot slab are obtained either experimentally or from the computer solution.

A number of errors occurred in this study, which can be divided into two categories: 1) errors which affect the measurement of depth, and 2) those which affect the comparison of the experimental results with the computer model results. The possible sources of error are defined here, but their magnitudes are uncertain.

Several possibilities exist for depth measurement errors. The flexible tubes that extend to the sensor openings in the slab are sealed to the slab using a commercial windshield sealer compound. The holes are so small that uniformity in sealing is not possible. The sealer may be rough and bulge up

Figure 8. Water depth versus distance for ungrooved pavement at 2.45 inches per hour.

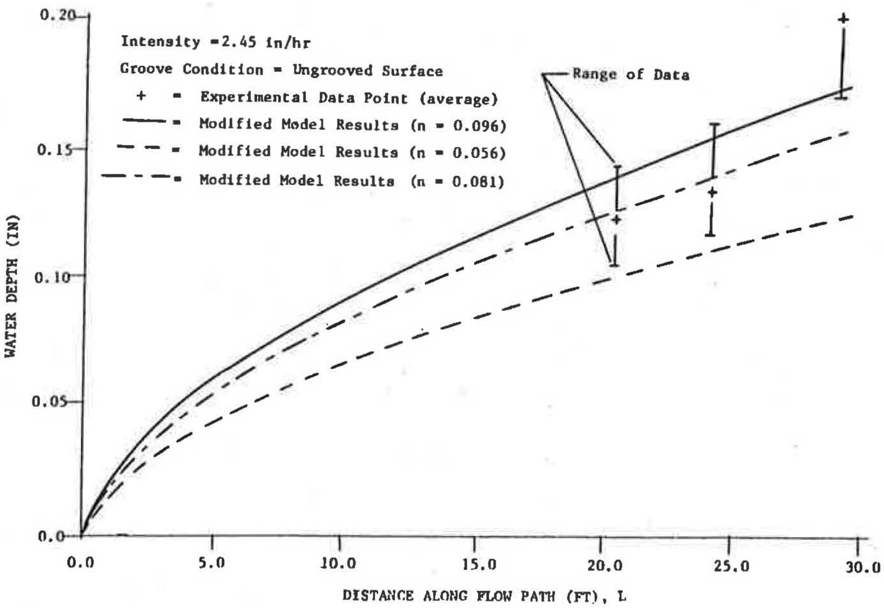
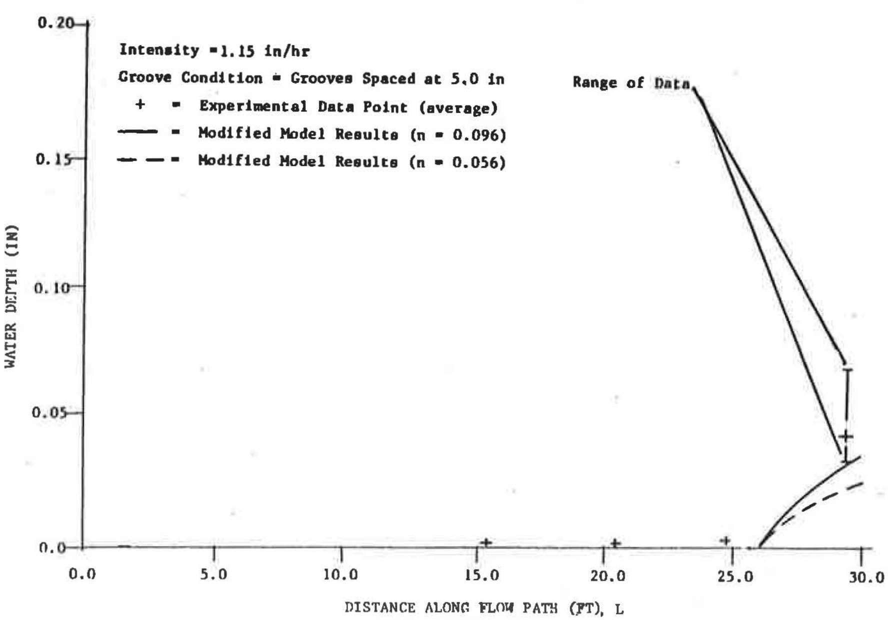


Figure 9. Water depth versus distance for 5-inch groove spacing at 1.15 inches per hour.



slightly around the top edges of the tubing. The setting of the zero water-depth datum for each sensor opening is strictly a judgment made by the research. The effect of capillary action on this setting is uncertain, as is the effect of using a mild detergent as a wetting agent to control this condition by reducing surface tension. Perhaps a better solution in future studies would be to countersink the sensor openings on the slab prior to placing and sealing the tubing.

Another source of error is the possibility of air in the tubing, which could cause a false transmission of water depth pressure to a transducer. Since the tubing beneath the slab is not visible, this condition is difficult to check, let alone control. A system where the transducer is located immediately beneath the slab would probably be more reliable. The calibration of each transducer has been accomplished very well, but not exactly to a 100 percent correlation, to which Figure 6 will attest. Then, too, the fluctuation of voltage readings on the digital multimeter requires judgment on the part of the researcher to record a single reading. Such fluctuations in voltage could be augmented by whether or not a sensor opening is subject to periodic impact from pelting raindrops. Also, in repeated tests the reproducibility of creating exactly the same rain rate and pattern by setting the simulator equipment is uncertain. Furthermore, fluctuations in voltage to the pump supplying the rain are never the same from one run to another. If arbitrary values are given

Figure 10. Water depth versus distance for 5-inch groove spacing at 2.45 inches per hour.

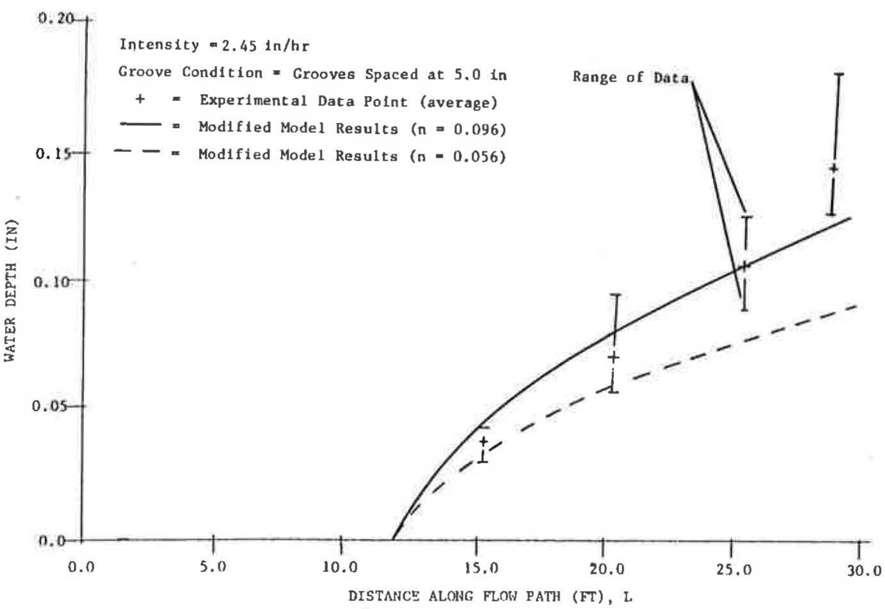


Figure 11. Water depth versus distance for 2.5 inch groove spacing at 2.45 inches per hour.

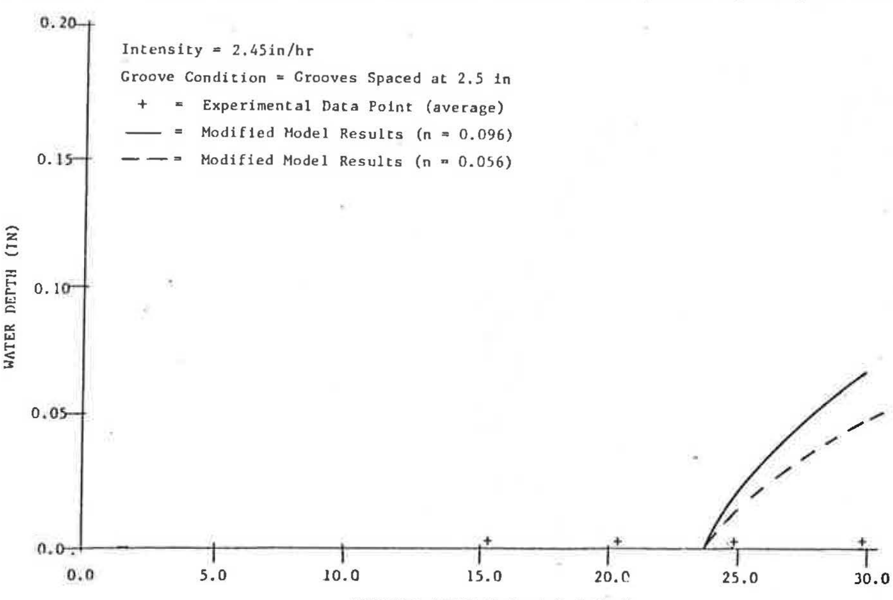
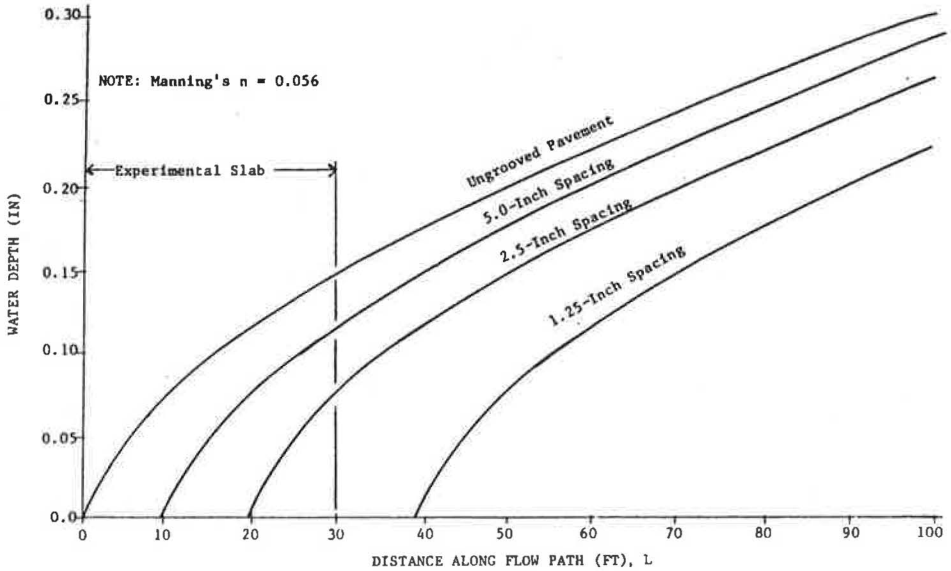


Figure 12. Predicted water depths for various groove spacings at 3.00 inches per hour.



to the sources of errors, it is estimated that any depth measurement could be subject to an error of perhaps ±0.04 inches.

In comparing the model results with the measured water depths, differences between what the computer assumes in its solution and what actually occurs in the experimental system become sources of error. The computer model assumes an absolutely perfect plane sloping at 1.5 percent with texture depth, Manning's n, and rainfall intensity perfectly uniform. The slab was constructed within forms set accurately to 1.5 percent slope. The surface finishing of the concrete was accomplished as carefully as cost would permit, but some slight ponding was evident during tests. The blemish is the primary example of the texture not being uniform. Also, the slab may have settled slightly since construction, perhaps nonuniformly, since a small tension crack was visible on the surface. The rainfall simulation equipment does not generate absolutely uniform rainfall rates: there are spatial variations in rainfall intensities. In the development of the equipment these variations were minimized. Still, standard deviations of the spatial average intensities in this study may be of the order of ±0.3 inch/hour. The spatial variations would affect not only the depths down the slab, but also the lateral average depths. Certainly the experimental errors in measuring depths also affect the comparison.

It does not seem logical to absorb all the errors of experimentation into an adjusted value of Manning's n, but numerous other studies have done so. The question is whether an n value can be accurately predicted for a given real situation, or whether it must be measured.

Although laboratory conditions did not achieve complete control of the experiments, it is clear that the experimental errors associated with surface texture and rainfall distribution are small compared with those found in the field.

Prediction of Water Depths For Runway Lanes

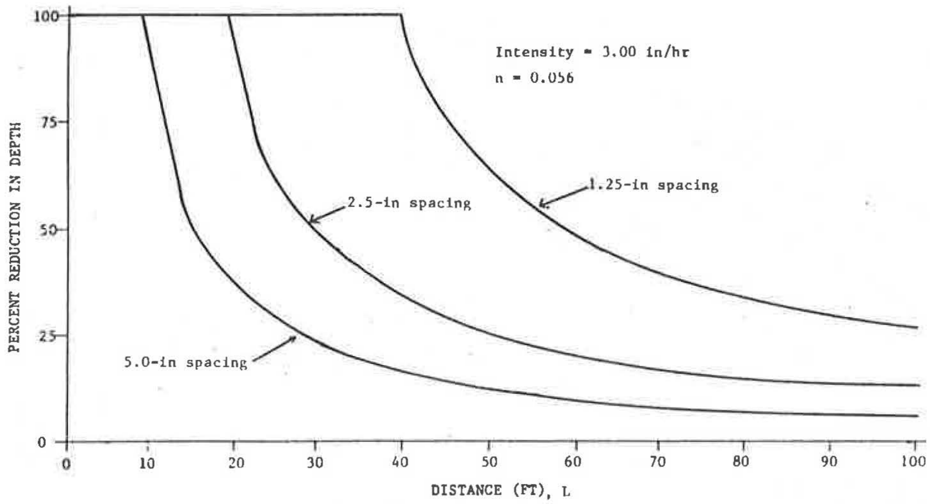
The modified computer program was used to predict equilibrium water depths out to a width of runway lane of 100 feet. The Manning's n value of 0.056 for these computer runs was selected from the upper limit of the Reed-Kibler curve using an average texture depth of 0.026 inch. The rainfall rate selected was 3 inches/hour, the next highest integer value beyond the maximum used in the experiments and near the maximum achievable by the rain simulator. The output for these computer runs is summarized graphically in Figure 12. Note that the equilibrium time at the 100-feet edge is 360 seconds for all four pavement conditions. This seems reasonable at the given value of n since the equilibrium flow rate off the edge of the pavement is the same for all four cases at the given rain rate of 3 inches/hour. Hence, conservation of mass is satisfied.

From Figure 13, it can be observed that the predicted maximum reduction in water depths due to grooving is 100 percent for spacing at 1.25 inches and distances up to 39 feet. This reduction amounts to about 0.18 inches at L=39 feet, as seen in Figure 12. Figure 12 shows a linear relation between the distance at which grooves fill up and groove spacing. It is believed that if the distance axis values on the graphs of Figure 12 and Figure 13 were multiplied by groove spacing, the curves would collapse into a single curve on each one. It was elected not to do this, since a clearer relation among the variables is believed to exist on the graphs in their present form.

Conclusions

From the equilibrium water depth data obtained in this study and the dye tests conducted, the following conclusions can be drawn:

Figure 13. Predicted percent reduction in depth versus distance for various groove spacings at 3.00 inches per hour.



1. Water depths increase downstream, as expected.

2. Depths increase with rainfall rate, as expected.

3. All rain falling on a segment of the upstream end of the pavement has been observed to enter all grooves spaced at 5 inches or less and is carried downstream.

4. Grooving renders depths over much of the upstream part of the pavement negligible.

5. Depths begin to build up, however, on the pavement surface at a downstream point where grooves are filled and overflow.

6. Grooving, overall, reduces depths on a pavement surface.

7. Water moves faster in saw-cut grooves than on the surface, due to a lower hydraulic resistance of the polished groove surface.

From the modification of the computer model and the comparison of its results with those from the experiments, the following observations can be made:

8. It was not difficult to modify the computer model of Phase I to take into account the experience gained from the experiments.

9. Correlation of the model's output with data can be excellent if the appropriate Manning's n value is chosen.

10. The Manning's n value can be used to absorb the effects of nonuniformity in pavement surface alignment, surface texture depth, and spatial rainfall rate.

In using the computer model to predict water depths for a 100-feet-wide runway, the following is noted:

11. From Figure 12, the maximum reduction in depth is 0.18 inch, which occurs at a distance of about 39 feet for grooves spaced at 1.25 inches.

12. From Figure 13, the maximum percent reduction in depth is 100 percent overall, and 28 percent at the edge of the runway, for grooves spaced at 1.25 inches.

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MODEL FOR ASSESSING AIRPORT COMMUNITY NOISE IMPACT

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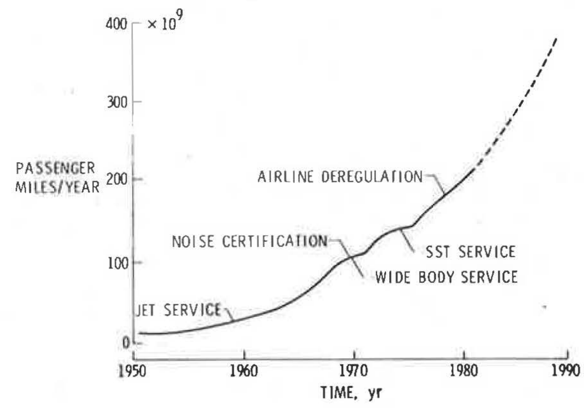
Abstract

A model is described which has been designed to predict aircraft noise impact in an airport community. The model explicitly takes into account community noise levels, population distributions, and human subjective response to noise. Algorithms upon which the model is based are described, as is the computer implementation of the model. A number of examples are given which illustrate how the model has been applied to quantitatively assess the reductions in noise impact associated with such candidate countermeasures as runway re-orientation, population-minimal ground tracks, and soundproofing of homes in the airport community.

Introduction

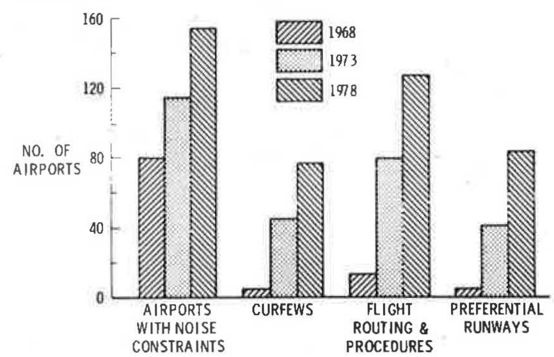
This paper describes an airport community noise impact model which has been developed at the National Aeronautics and Space Administration (NASA) Langley Research Center. The model is designed to quantify the noise impact in the airport community associated with aircraft operations for a given operating scenario. Figure 1 provides some background, by indicating the growth of the U.S. air carrier service in the last decade to the present extrapolated into the next decade. A number of milestones are identified in this figure which are considered to be important with respect to community noise impact. The most recent of these is airline deregulation. It is difficult to determine exactly what effect this will have on the overall trend, but to the extent that it does affect the trend, some accelerating effect would be expected. In any case, it can be anticipated that the United States air

Figure 1. Growth in U.S. air carrier service.



transportation system is going to continue to grow into the next decade. Because of the sustained growth in the air transportation industry in the United States, a number of airport communities have taken steps to deal with the noise problems that are associated with that growth. This is indicated in Figure 2 which shows that in the ten year period from 1968 to 1978, the number of airports with some sort of noise constraints has essentially doubled. These constraints take different forms, some of which are indicated in Figure 2. Curfews,

Figure 2. Noise constraints at major world airports.



noise minimal near-terminal routing, alternative take-off and approach procedures, and preferential runway systems, all of these noise countermeasures have one thing in common, namely a severe impact on the air transportation system which makes them all very costly in one form or another.

Many of these noise countermeasures are applied in a way which does not bring a great deal of technology to bear on the noise problem. It is generally difficult to determine exactly how much noise relief is associated with a particular preferential runway scheme, for example. It is very easy to quantify the cost associated with these countermeasures, but not nearly so easy to quantify the corresponding benefits in noise relief. To address this problem, a model was developed at NASA Langley in an attempt to clearly quantify the benefits of noise countermeasure options. The approach employed was to make use of as much existing technology as possible. The three major