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AIRCRAFT PERFORMANCE ON SLIPPERY RUNWAYS IN CROSSWINDS [redacted]

By Jere Cobb and Walter B. Horne, [1964] 12 p refs 2#
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Since 1959 the Civil Aeronautics Board has attributed 30 accidents, or incidents, to aircraft tire hydroplaning. Most of these incidents also occurred under runway crosswind conditions.[1] Thirty such occurrences in the thousands of landings and take-offs made in that same period seem infinitesimally small; however, there were probably numerous additional times when aircraft were partially out of control and in potentially dangerous situations. Since the pilots were able to regain aircraft control, and no damage was done, these latter cases were not reported.

Many articles have been written on the effect of crosswinds on aircraft take-off and landing performance for dry runways. In this article, we will discuss the combined effects of crosswind and slippery runways caused by accumulations of water, snow, ice, and slush on aircraft ground performance.

Runway slipperiness.- Aircraft designers depend upon pneumatic tires to perform three basic functions during aircraft ground operation. These functions are:

(1) To support the weight of the aircraft while at rest or under high-speed rolling (landing or take-off)

(2) To develop high symmetrical or asymmetrical retardation forces (during wheel braking) for stopping or for directional control purposes during landings, aborted take-offs, and taxiing

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[1] CAB Bureau of Safety Pamphlet BOSP 7-4-2, October 1963.

[redacted]

(3) <u>To develop high cornering forces (nose wheel steering) and side forces (on main wheels)</u> to overcome skid-producing external forces acting on the aircraft due to crosswinds or changes in aircraft direction (for example, high-speed turns onto taxiways)

The operational problems connected with the first function are tire failures resulting from foreign-object damage or blowouts from protracted locked wheel skids during wheel braking. The advent of automatic skid control for aircraft wheel braking systems has greatly alleviated the latter problem. The ability of pneumatic tires to perform the 2nd and 3rd functions depends upon the slipperiness of the runway. Some typical runway slipperiness values are shown in figure 1. For example, this figure indicates that snow-covered pavements are, at the least, twice as slippery as dry bituminous or concrete pavements. Ice-covered pavements can be 4 to 16 times as slippery as dry pavements, depending upon the temperature of the ice, with ice near the melting point (32° F) being the most slippery. In contrast to dry, snow-covered, and ice-covered pavements which appear to have little speed effect, water-covered and slush-covered pavements tend to become more slippery (lower friction coefficients) as the aircraft ground speed increases. At high speeds on these deeply flooded pavements, friction coefficients can drop to values as low as those found for icy pavements covered with a water film. Investigations at the NASA Langley Research Center have shown that this condition results from the phenomenon of tire hydroplaning. For this puddled or flooded runway condition, hydrodynamic fluid pressures develop between the tire footprint and pavement. These pressures grow larger as ground speed increases, and at a critical speed called the total hydroplaning speed, the hydrodynamic lift resulting from these pressures equals the weight riding on the tire. Any increase in ground speed above

[redacted]

this critical speed lifts the tire off the pavement, leaving it supported by the fluid alone. (See fig. 2.) Any automobile driver knows about the difficulties he experiences in stopping or maintaining directional control of his vehicle on wet icy pavements. A glance at the comparative friction coefficients for hydroplaning tires in figure 1 shows that similar difficulties will exist when aircraft or automobile tires hydroplane on water or slush-covered pavements.

Tires hydroplane only when certain critical fluid depths are exceeded on runways. These critical depths can range from approximately 0.1 to 0.4 inch, depending upon the character of tire-pavement surfaces. Smooth-tread tires operating on the smoother pavement surfaces require the least fluid depth, whereas rib-tread tires operating on open-textured and transverse-grooved pavement surfaces require the greatest fluid depths. When this critical fluid depth is exceeded for any combination of tire and pavement surface, the critical ground speed (hydroplaning speed) required for total hydroplaning to occur was found to be almost entirely dependent upon tire inflation pressure. This result led to the derivation of the following simple relation for estimating tire hydroplaning speed:

$$V_p = 9\sqrt{p}$$

where V_p is the hydroplaning speed in knots and p is the tire inflation pressure in lb/in.^2.

Table I lists hydroplaning speeds and other characteristics including touchdown speeds of typical aircraft types currently being operated in this country.

TABLE I.- HYDROPLANING SPEEDS FOR SOME TYPICAL AIRCRAFT

Aircraft	Maximum take-off gross weight, lb	Tire pressure (main), psi	Touchdown speed, knots	Main wheel hydroplaning speed, knots
Light-Twin Recip.	4,830	50	90	64
Twin Recip. Transport	32,000	58	75	69
Four Eng. Recip.	122,200	125	113	101
Twin Turbo Prop	35,100	120	103	99
Four Eng. Turbo Prop	113,000	140	124	107
Exec. Twin Jet	17,800	165	119	116
Four Eng. Jet	246,000	145	151	109
Service Jet Fighter	30,500	200	161	127

Note that all of these aircraft are susceptible to hydroplaning under the right conditions, since the hydroplaning speed is less than the touchdown speed.

Crosswind.- Crosswinds act over the entire side area of aircraft and produce side forces which tend to push aircraft off the downwind side of runways. These forces are proportional to the square of the crosswind velocity; thus, a 10-knot crosswind would quadruple the side force developed by a 5-knot crosswind on an aircraft. Generally, the center of pressure of this crosswind acts aft of the center of rotation (main landing gear), so that a yawing moment which tends to make the aircraft weather cock, or weather vane, into the wind is usually produced. Exceptions to this behavior may be encountered when the lateral area forward of the center of rotation exceeds that behind it. In this case, the aircraft (for example, the F-102) will yaw downwind.

Combined effects of crosswind and slippery runway.- One of the worst control situations occurs when there is a crosswind in conjunction with water or slush-covered runways, and the conditions that are encountered produce total tire hydroplaning. FAA-NASA tests with a four-engine jet transport in slush demonstrated a loss in directional control and an approximately doubling or tripling of the dry runway stopping distance (without use of reverse thrust) when hydroplaning occurred.

(a) Take-off: During the initial low-speed portion of the take-off roll (see fig. 3(a)), the tire-ground traction is good. The aircraft heading can be maintained by nose-wheel steering, differential braking, differential forward thrust, and rudder; and the resistance to sideways motion can be produced by tire-ground reaction forces. Thus, the aircraft maintains runway heading on runway center line.

As the aircraft approaches tire hydroplaning speed, tire-ground friction forces approach zero, and a point will be reached where the side force from the crosswind overcomes the counteracting tire-ground force. If runway heading is maintained, the aircraft will skid toward the downwind side of the runway. This downwind skid can occur even on a completely dry runway, if the crosswind component is large enough. To prevent drift (see fig. 3(b)), the pilot yaws the aircraft into the wind so that the side component of engine thrust opposes the crosswind component, because tire-ground forces are not available for this puspose.

Aside from the basic aircraft control problem, the following points should be considered:

Slush or standing water on the runway increases take-off distance as a result of the added drag developed by tires displacing the fluid cover from the wheel paths. The FAA has recognized this problem by instituting the $\frac{1}{2}$-inch rule which prevents turbine-powered transport aircraft from taking off or landing on runways covered with slush or standing water exceeding $\frac{1}{2}$ inch in depth. For slush or water depths less than $\frac{1}{2}$ inch, an additional take-off distance, as well as an additional accelerate-stop distance, must be allowed for.

At temperatures near freezing, slush can accumulate around moving components of the aircraft during the take-off roll and freeze after the aircraft becomes airborne. This slush can hinder or even prevent subsequent operation of landing gear, flaps, etc. It is recommended that such devices be cycled before final retraction to minimize the effects of frozen slush or snow in the storage wells.

Water or slush spray thrown up by nose wheels can be ingested into engine intakes, especially on some wing-root or fuselage-mounted engines, and can cause loss of thrust or flame-outs. The innovation of "chine" type nose-wheel tires, which depress nose-wheel spray patterns away from engine intakes, has alleviated this problem in a few cases, and their use is expected to increase.

(b) Landing: The landing is usually more critical than the take-off for the following reason: In the approach, the pilot can be flying solely by instruments and his attention is concentrated entirely within his cockpit. Suddenly he breaks out at "minimums" and must make an instantaneous transition to visual flight; and he must immediately thereafter touch down on a runway of unknown slipperiness. This is one of the worst situations possible, but it can frequently be encountered with slush- or water-covered runways when visibility is poor. This is in contrast to the take-off where the aircraft starts from rest with good tire-ground traction available to the pilot.

Consider the landing shown in figure 3(c), where the aircraft touches down on runway heading and center line. This touchdown is accomplished in a crosswind by either a "wing down" or "crab" correction. Since the touchdown speed is greater than the total hydroplaning speed (see table I), the tire-ground traction is nil. With no pilot corrections, the aircraft will probably weathercock into the wind and drift toward the downwind side of the runway. In this situation, application of reverse thrust increases the drift downwind, since the side component of reverse thrust acts in the same direction as the wind force. (See vector diagram, fig. 3(c).) If this condition is allowed to continue and the crosswind component is large enough, the aircraft will drift off the side of the runway with perhaps thousands of feet of usable runway remaining. Only three alternatives are available to the pilot: (1) he can continue as before and run off the side of the runway, (2) he can apply enough forward thrust to maintain the aircraft in the center of the runway, or (3) he can yaw the aircraft downwind and apply reverse thrust. The first is obviously unacceptable. The second increases the stopping distance appreciably, and the third would seem to be contrary to any maneuver a pilot has attempted before. Fortunately, in most cases, the aircraft can be slowed below the hydroplaning speed before it is pushed off the side of the runway. Then the tires can begin to take part of the load, maintain aircraft control, and help to slow the aircraft. It should be remembered, however, that aircraft braking tests have demonstrated that stopping distances (without reverse thrust) can be increased 60 percent on wet runways without hydroplaning occurring.

The purpose of this article has been to point out some of the problems and principles involved during take-off and landing operations in crosswinds on slippery runways and not to advise experienced pilots on how to control their own familiar aircraft. The strongest and most important fact the pilot should remember is to plan ahead. If the destination has a known crosswind condition, and the conditions to be encountered can possibly cause tire hydroplaning, he should think twice before landing there. In a marginal situation without prior planning there may be insufficient time for the pilot to analyze what is happening and take the proper corrective action. If the landing must be accomplished in these conditions, the pilot should make sure that the approach is not high or fast and that the actions of the aircraft after touchdown are anticipated with subsequent pilot reactions planned. Further information on tire hydroplaning[2,3] can be obtained on request to the NASA Langley Research Center, Langley Station, Hampton, Va.

[2]Hazards of Tire Hydroplaning to Aircraft Operation. Langley film serial No. L-775 (15-minute, 16 mm color film with sound narrative).

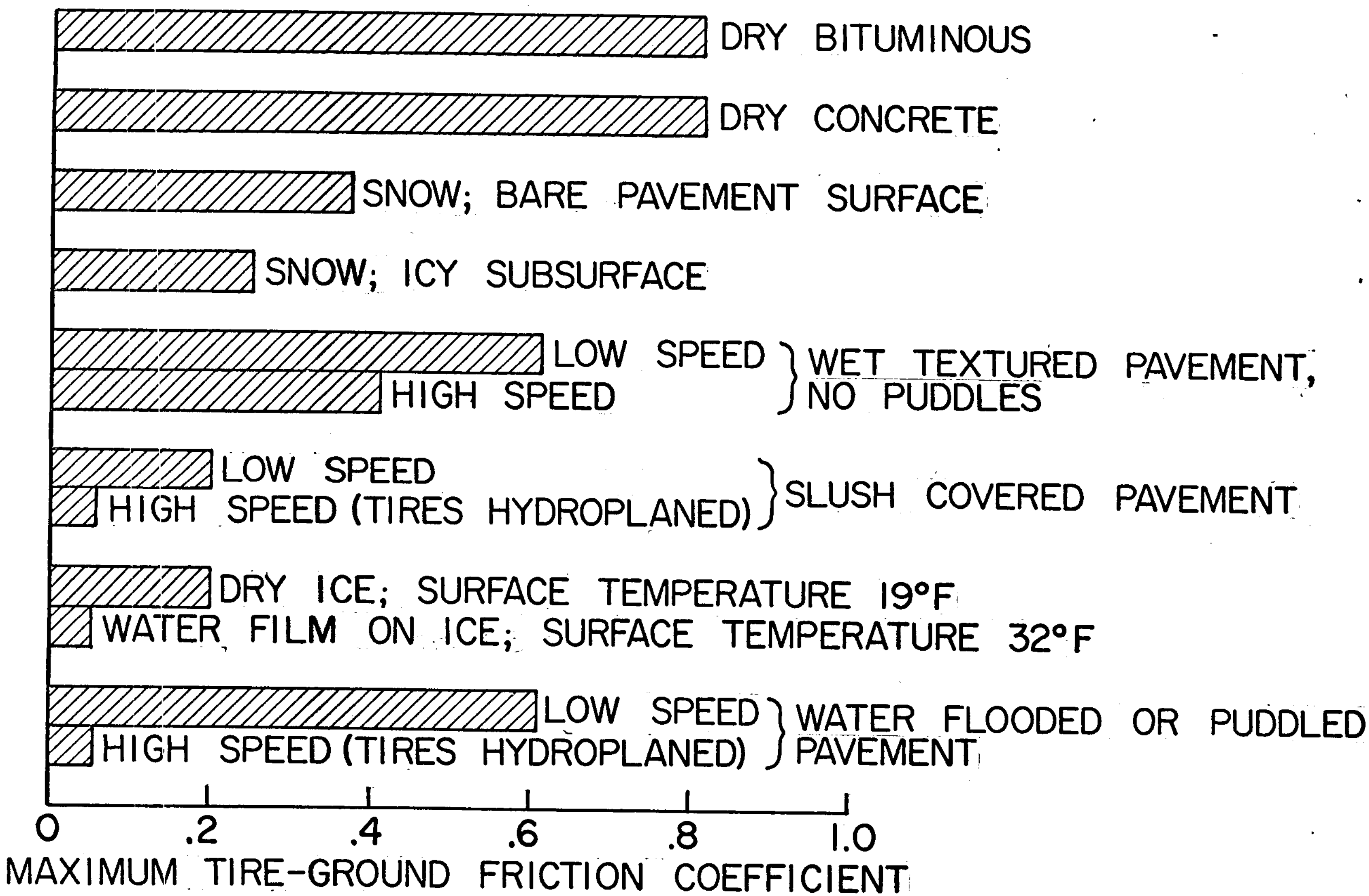
[3]NASA TN D-2056. "Phenomena of Pneumatic Tire Hydroplaning," by Walter B. Horne and Robert C. Dreher.

Figure Tiles for Cobb-Horne Article

Figure 1.- Some typical runway slipperiness values.

Figure 2.- Detachment of aircraft tire footprint from runway surface due to tire hydroplaning.

Figure 3.- Crosswind take-off and landings on flooded runways.


DRY BITUMINOUS
DRY CONCRETE
SNOW; BARE PAVEMENT SURFACE
SNOW; ICY SUBSURFACE
LOW SPEED
HIGH SPEED
WET TEXTURED PAVEMENT, NO PUDDLES
LOW SPEED
HIGH SPEED (TIRES HYDROPLANED)
SLUSH COVERED PAVEMENT
DRY ICE; SURFACE TEMPERATURE 19°F
WATER FILM ON ICE; SURFACE TEMPERATURE 32°F
LOW SPEED
HIGH SPEED (TIRES HYDROPLANED)
WATER FLOODED OR PUDDLED PAVEMENT
0
.2
.4
.6
.8
1.0
MAXIMUM TIRE-GROUND FRICTION COEFFICIENT

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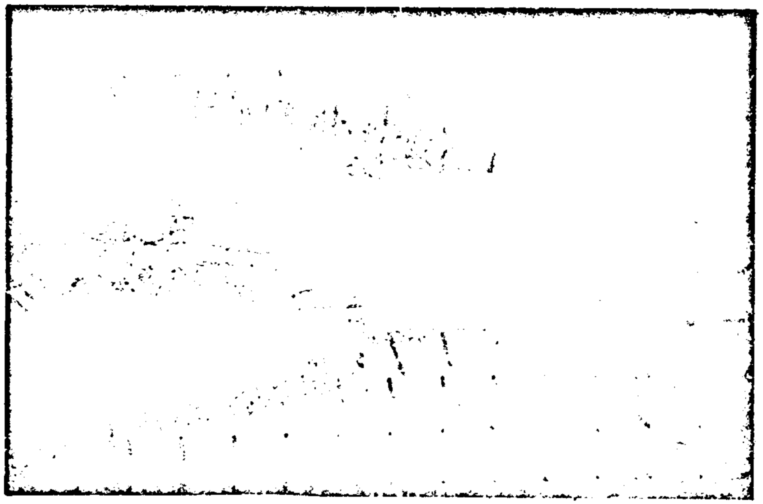
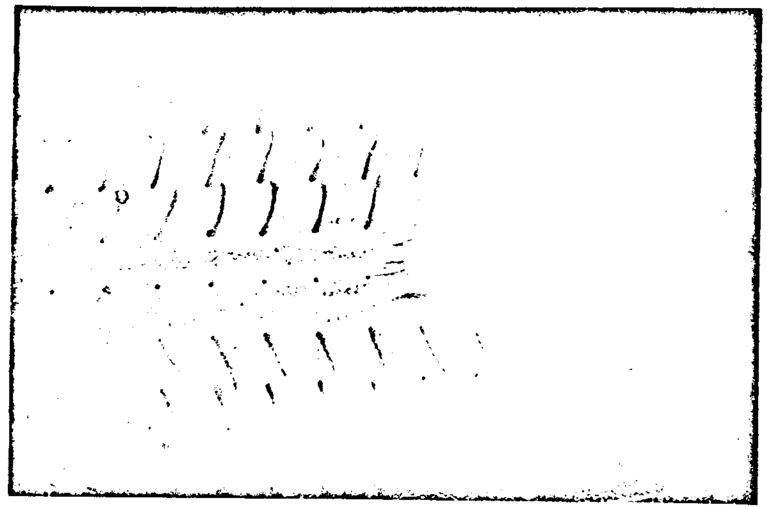
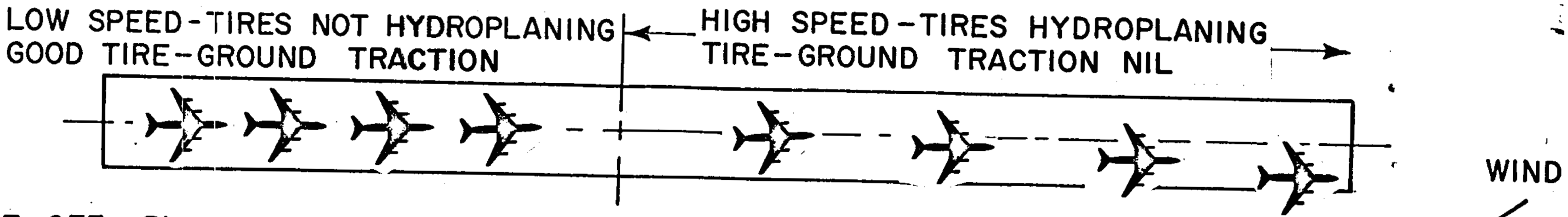


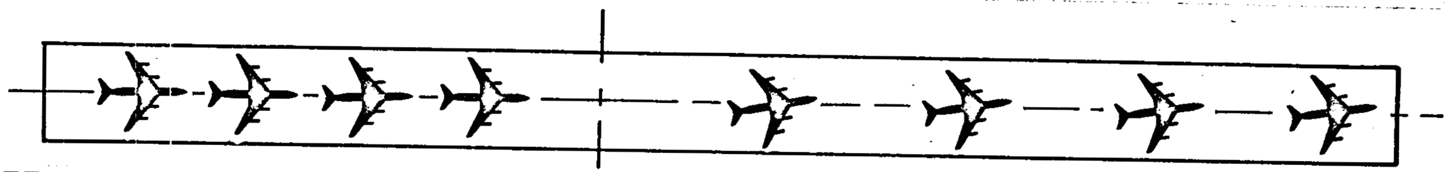
(a) BELOW HYDROPLANING SPEED



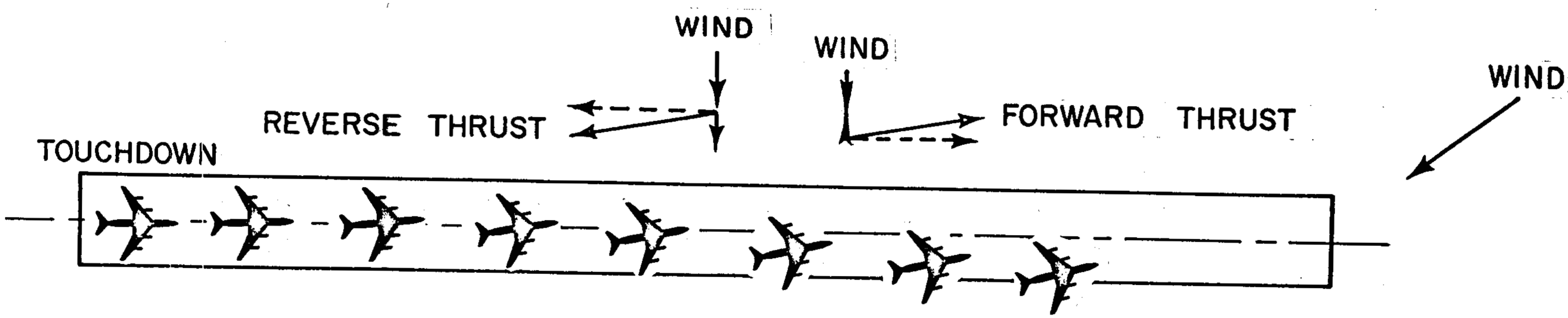
(b) ABOVE HYDROPLANING SPEED



(A) TAKE-OFF: PILOT MAINTAINS HEADING DOWN RUNWAY. LACK OF TIRE-GROUND TRACTION AT HIGH GROUND SPEED ALLOWS WIND FORCE TO DRIFT AIRCRAFT OFF RIGHT SIDE OF RUNWAY.



(B) TAKE-OFF: AT THE HIGHER GROUND SPEEDS, PILOT YAWS AIRCRAFT SO THAT SIDE COMPONENT OF ENGINE THRUST CANCELS SIDE THRUST ON AIRCRAFT DUE TO WIND. AIRCRAFT THEN PROCEEDS STRAIGHT DOWN RUNWAY.



(C) LANDING: AT THE HIGH TOUCHDOWN SPEEDS, TIRE-GROUND TRACTION IS NIL (TIRES HYDROPLANING). AFTER TOUCHDOWN, AIRCRAFT WEATHER VANES INTO WIND. WIND FORCE TENDS TO DRIFT AIRCRAFT OFF RIGHT SIDE OF RUNWAY.

~~Figure 2~~ 3

W. Horne