LANDING ON
SLIPPERY RUNWAYS

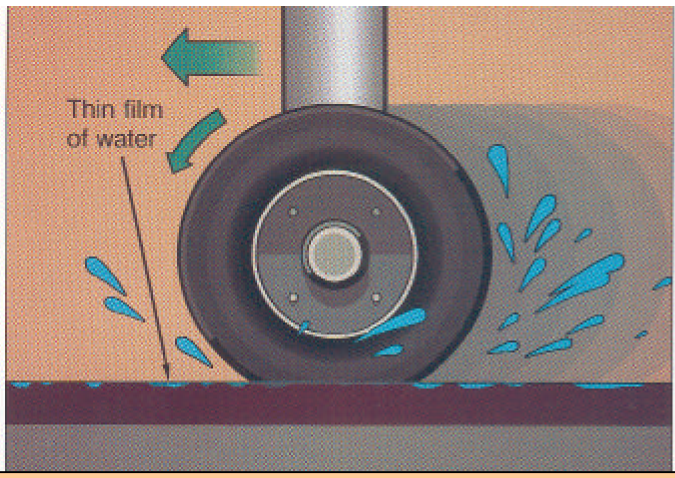
From : Boeing Airliner

This article reviews the principles of tire traction, landing techniques and the use of brakes, speedbrakes and reverse thrust to stop the airplane during landing…

FACTORS AFFECTING WHEEL BRAKING

Wet Runways

As a tire rolls along a wet runway, it is constantly squeezing the water from the tread. This squeezing action generates water pressures which can lift portions of the tire off the runway and reduce the amount of friction the tire can develop. This action is called hydroplaning, so technically, whenever a tire is moving on a wet surface, it is hydroplaning. This results in tire-to-ground friction which can be low at high speeds and improve as speed reduces. There are three types of hydroplaning : *Viscous, Dynamic and Reverted rubber.*



Viscous hydroplaning occurs on all wet runways and is a technical term used to describe the normal slipperiness or lubricating action of the the water (see Figure 1a) - While viscous hydroplaning does reduce the friction it is not to such a low level that the wheel cannot be spun up shortly after touchdown to initiate the antiskid system. Viscous hydroplaning is the most commonly encountered cause of low friction on wet runways, and occurrences are often mistaken for dynamic hydroplaning.

Dynamic hydroplaning is the technical term for what is commonly called *hydroplaning* (see figure 1b). During total dynamic hydroplaning the tire lifts off the pavement and rides on a wedge of water like a water ski. Because the conditions required to initiate and sustain it are extreme, it is a phenomenon that is rarely encountered. However, when dynamic hydroplaning occurs it lifts the tire completely off the runway and causes such a substantial loss of tire friction that wheel spinup may not occur.

The conditions required to cause dynamic hydroplaning are high speed, standing water and poor surface *macrotexture.* These conditions must continue without interruption to keep the tire on its plane. In the absence of any of these conditions, dynamic hydroplaning will either not occur at all or will affect only a portion of the tire footprint.

Reverted rubber hydroplaning can occur whenever a locked tire is skidded along a very wet or icy runway for a time long enough to generate frictional heat in the footprint area (see Figure 1c).

Reverted rubber hydroplaning can be initiated at any speed above about 20 knots and results in tire friction levels comparable to that of icy runways.

Icy Runways

Icy runways, including frost or snow covered runways, can be very slippery at all speeds when the temperature is near freezing. Very cold icy and snow covered runways are capable of generating fairly high friction.

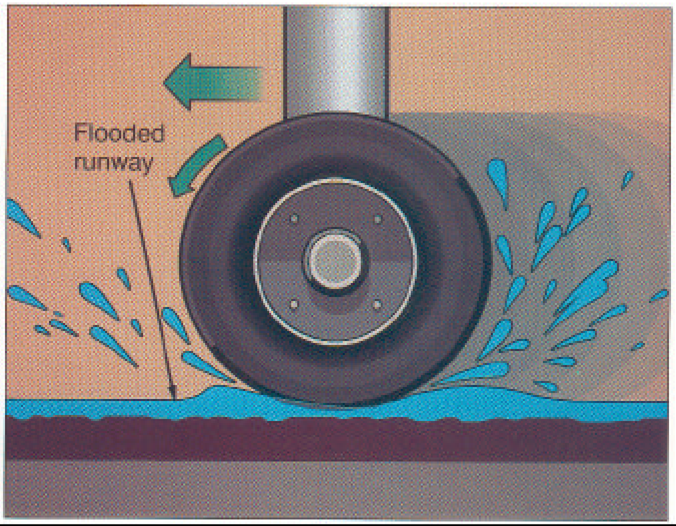


Figure 1b. Dynamic hydroplaning. At high speed the tire planes on deep, standing water. Tire grooves & runway surface macrotexture (stoney or grooved surface) help drain water from the foot print & improve friction.

Tire Braking

Braking is the primary means of stopping the aircraft. When the brakes are applied, the tire is made to roll slower than its *synchronous* or free rolling speed. The result is called slip. A tire generates maximum braking friction when it is slipping approximately 10% slower than synchronous speed. When larger slip values occur, the braking force is reduced.

A vertical load must be placed on the tire in order to generate a braking force. There is no optimum level of vertical load; the more the better. Therefore, actions which quickly place high vertical load on the tires will promote more rapid wheel spinup and higher braking forces. For all Boeing jet transport aircraft at landing flap settings, lowering the nose and raising the speedbrakes places 65% - 100% of the airplane weight onto the tires (Note: for certain models deploying the speedbrakes and lowering the nose will place more than 100% of the airplane weight on its tires due to *negative* lift coefficients being generated at taxi attitudes). Therefore, both actions are considered essential to prompt wheel spinup and the generation of effective braking forces.

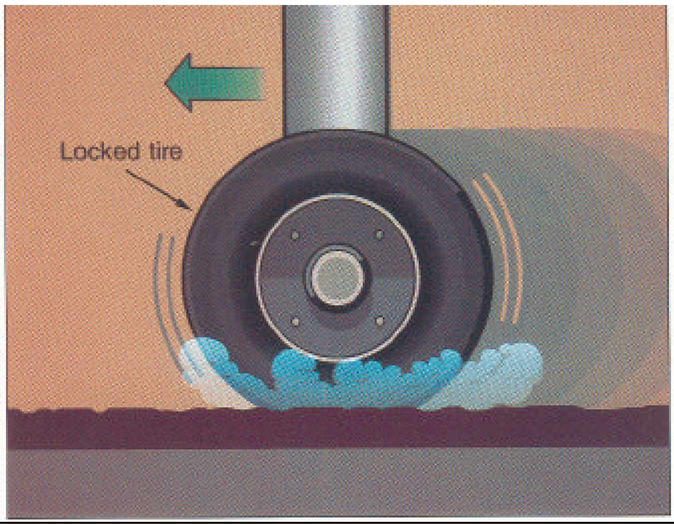


Figure 1c. Reverted rubber hydroplaning. When a tire locks up on a smooth wet or icy surface, the friction heat generates steam. The steam pressure then lifts the tire off the runway; & the steam heat reverts the rubber to a black gummy deposit.

Tire Cornering

The other important function of tire-to-ground friction is the production of cornering forces. Tire cornering forces are the primary means of controlling runway tracking on the ground - even on slippery runways. Cornering forces act perpendicular to the direction of motion of the tire and are generated when a tire is yawed with respect to its actual direction of travel. On slippery runways a tire develops its maximum cornering force at about five degrees of yaw; beyond that point the side force component decreases rapidly. A high vertical load and minimum tire rotational slip also increase the cornering force available.

Combining Cornering and Braking

Tires must often generate both braking and cornering forces simultaneously such as when making crosswind landings. The behavior of the tire under this condition is very complex and difficult to quantify.

Good tire-to-ground friction and high vertical loads help both braking and cornering. The pilot cannot alter the available friction but he can maximize the vertical load on the tires.

Whereas a certain amount of tire rotational slip is necessary to generate braking force, the same slip reduces the tire cornering force. One way of envisioning this is to imagine the total friction force developed by the tire having to be shared between braking and cornering, the result being that, when used together, both suffer to some degree. When combined braking and cornering are required, the degree to which cornering suffers depends upon how much rotational slip is present. As the slip increases, the cornering force reduces. A locked tire generates no cornering force at all. Therefore, spinning the tires up at touchdown is essential to maintain runway tracking capability.

During antiskid controlled braking, the degradation in tire cornering depends upon the amount of slip the

antiskid system allows. As a general rule, newer antiskid systems allow less slip than older ones and can be expected to have less effect on tire cornering capability. The degradation in cornering during braking is quite small at moderate tire yaw angles. If a lateral skid should develop, immediately releasing the brakes will maximize the tire cornering friction to regain directional control.

AIRCRAFT SYSTEMS

All Boeing commercial jet aircraft are equipped with multiple stopping systems : spoilers/speedbrakes, thrust reversers, and wheel brakes. Knowing how to use each system most effectively is important when landing on a slippery runway.

Speedbrakes

All Boeing jet transports are equipped with wing-mounted spoiler panels which double as on-ground speedbrakes. Deploying the speedbrakes reduces wing lift, thereby placing the aircraft weight onto the tires. Speedbrakes also significantly increase aerodynamic drag, which aids in decelerating the aircraft. On Boeing airplanes, deploying the speedbrakes transfers more than half of the airplane's weight onto the tires at high speed and increases the aerodynamic drag by 50% or more.

Moderately firm touchdowns will promote prompt wheel spinup and shock strut compression, which are key activation signals in 737 airplanes, as is truck untilt in the 747, 757 and 767 models.

Thrust Reversers

Thrust reversers provide a powerful stopping force that is not dependent upon runway friction. On very slippery runways the thrust reversers may be the most effective stopping means available. Since reverse thrust is most effective at high speed, it is important both to initiate reverse early in the landing roll and to increase thrust promptly to the limits recommended for the specific airplane model.

Antiskid Systems

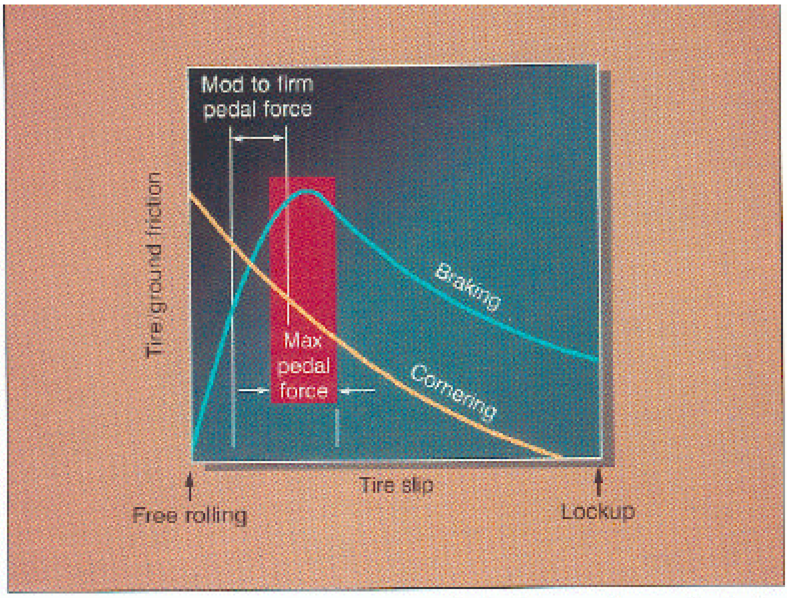


Figure 2 : ANTISKID CONTROLLED BRAKING. During antiskid cycling, a moderate to firm brake pedal application provides good braking effectiveness with a minimal degradation in tire cornering capability. A maximum pedal application optimizes the braking effectiveness but further reduces tire cornering capability

The brakes are the primary means for stopping the aircraft and are applied separately on each side the aircraft by pressing the respective brake pedal. The pedal force applied is transmitted through cables to valves in the wheel well which convert the force to hydraulic fluid pressure. This pressure is then routed to the brakes. Antiskid systems minimize tire skidding and prevent wheel lockups during braking by reducing the pilot's applied brake pressure.
Over the years, these systems have progressed from fairly simple devices, intended to prevent tire blow-outs, to very sophisticated systems which optimize braking effectiveness under all runway conditions. Although many different systems are currently in commercial service, they all share the same design objectives and many common operating principles.

In the antiskid system, the actual speed of the wheel is measured by a transducer in the axle and is compared to a reference wheel speed. if the actual wheel speed drops below the reference, a skid is detected and the antiskid system reduces the brake pressure to allow the tire-to-ground friction to increase the wheel speed. When the antiskid system detects that the skid has been corrected, it allows the brake pressure to increase.

An essential element in the skid control circuit is the reference wheel speed signal. Without this signal, skidding or locked wheels cannot be detected. The reference signal is initially generated at touchdown by spinning up the wheels. On dry runways this occurs almost instantaneously. However, wheel spinup is slower on wet runways. If brake pressure is applied prior to wheel spinup, locked wheels can result.

Airplane tests on very slippery and flooded runways indicate that prompt wheel spinup occurs once sufficient load has been placed on the tires. These tests show that, even on flooded runways, sufficient wheel spinup to establish an antiskid reference for skid detection can be expected to occur by the time the spoilers are raised and the nose is lowered.

Most antiskid systems also employ touchdown protection and locked wheel protection.

Touchdown protection is a feature whereby an artificial skid release signal holds the brakes released for a brief moment after touchdown to ensure wheel spinup. It allows earlier brake application should the wheels spin up sooner and override the feature.

Locked wheel protection allows an antiskid channel that has lost its own reference to *borrow* a reference signal from another rolling wheel to detect its own locked condition.

The antiskid system can detect and correct a skidding condition much

faster than a pilot can. All antiskid systems since the early Model 707 airplanes have been designed to give optimum braking effectiveness when the brake pedals are fully applied. Cycling or pumping the pedals, in an effort to beat the antiskid system, alternately causes excessive wheel skidding and prolonged brake releases, which impairs both braking and cornering effectiveness (see figure 2 above).

In the early days of anti-skid systems, some airlines developed procedures for delaying wheel brake application to 100 knots or less on runways where hydroplaning conditions are suspected. This has presumably been done to ensure wheel spinup prior to brake application so that an antiskid wheel speed reference signal will exist for detecting locked wheels. Boeing strongly recommends against delayed braking techniques, even when hydroplaning is suspected.

In reviewing histories of landing overruns and data from wet runway landing tests, two important facts stand out. First, delayed braking is frequently a contributing cause of overruns. Second, the tire-to-ground friction that can be developed at high speed when landing on wet or flooded runways, although quite small, is still sufficient to spin up the wheels and provide a significant and sometimes necessary braking force for stopping the aircraft short of an overrun. Boeing recommends that braking be initiated as soon as the spoilers have been raised, the nose is down, and the airplane is tracking on the runway. Steady brake pedal pressures should be used.

Autobrakes

Autobrakes operate in parallel with the pilot's brake pedals. At touchdown the brakes apply smoothly and automatically as soon as the main wheels spin up. Even on very slippery runways this can be expected to occur right after spoiler deployment, but may be so smooth as not to be initially felt.

The autobrake system can be of significant value during slippery runway operations by automatically applying smooth, efficient braking as soon as wheel spinup occurs and by freeing the pilot to concentrate on directional control duties during the touchdown and landing roll.

FAR LANDING DISTANCE

The total landing distance is the sum of the air and ground distances. The U.S. Federal Aviation Regulations (FARS) define the minimum dry runway landing field length to be equal to the flight test demonstrated air and ground distance increased by 67 %. The air distance begins at 50 feet over the threshold at the minimum approach speed. The stop is made with spoilers extended and maximum wheel braking but without the use of reverse thrust. Minimum U.S. FAR wet runway landing field length is derived from the dry runway testing by increasing the FAR dry distance by an additional 15%.

Most landings take place on runways that are much longer than the minimum distances established by FARs for dry and wet runways.

FACTORS AFFECTING OVERALL LANDING DISTANCE

Preparation for the stop begins during the approach. A well planned and properly executed approach, flare and touchdown maximizes the runway available for stopping.

Approach Speed

Excess approach speed is a contributing cause in almost every overrun. Excess speed increases the tendency of the airplane to float during the flare and to rebound during touchdown, and increases the stopping distance required once on the runway.

The effect of excess speed on the tendency of an airplane to float during the flare is difficult to describe analytically; some aircraft types are more susceptible to this than others. However, if the touchdown is delayed while 10 knots of speed are bled off in flare, the total landing distance will increase by about 1,400-2,000 feet for airplanes at heavy gross weights.

Once the airplane is on the ground and in a stopping mode, the increase in actual distance of 10 knots excess touchdown speed is 200-400 feet on a dry runway or as much as 600-900 feet on a very slippery runway. For a typical slippery runway (wet or very icy), an increase of 500 feet for 10 knots is representative. Thus, decelerating the aircraft on the ground by using spoilers, reversers and brakes is 3 to 10 times more effective than decelerating in an extended flare.

Approach speed wind corrections should not exceed 20 knots and, when properly used, are not considered to be excess speed. This additive provides a necessary and adequate speed margin for anticipated wind conditions during the approach without an excessive increase in stopping distance.

Approach Path Angle

Excess height at the threshold increases the total landing distance by increasing the distance to touchdown. Following a 3° glide slope with the aircraft 50 feet above the normal path increases the distance to touchdown by approximately 1,000 feet. The penalty is even more severe when a shallower glide path is used or when the runway has a downhill slope in the touchdown area. Attempting to correct the threshold height late in the final approach can lead to a hard touchdown, a bounced landing, a short landing or an extended flare. If for any reason the approach path is not maintained, and it is likely that touchdown will occur too short or too far beyond the touchdown zone, a go-around should be initiated.

Flare and Touchdown

The nominal rate of descent during the approach is 500-800 feet-per-minute (8-13 feet-per-second). The flare maneuver arrests the approach rate of descent so that the touchdown sink rate is 2-4 feet-per-second.

It is considered by many that the ideal landing includes a smooth touchdown at the target point. But too often, when trying to *grease it on,* the flare is extended and the airplane touches down far beyond the target zone. An extended flare is most likely to result when the approach speed is excessive and a smooth touchdown is attempted. Planning a moderately firm touchdown helps prevent an extended flare.

Rollout

The stopping forces available are aerodynamic drag, reverse thrust and wheel braking. The total force that can be generated is the sum of these three components and depends upon the aircraft's speed, the prevailing runway condition and pilot technique. Aerodynamic drag and reverse thrust are most effective at high speeds.

A review of overrun accidents indicates that, in many cases, the stopping forces available were not used effectively during the initial and mid-portions of the rollout due to anticipating a turnoff at the far end of the runway. In some cases, the reversers were stowed and the brakes not applied for a time, letting the aircraft roll on the runway that would have produced good braking action. When the aircraft moves onto the final portion of the runway, the crew may suddenly discover poor braking effectiveness caused by moisture on top of rubber deposits on the runway.

An airplane reaching the last 1,500 feet of runway at a speed of 80 knots will need a deceleration of over 6 ft/second/ second (3.5 knots-per-second) in order to stop. If the runway is dry, or wet (but not contaminated) this deceleration rate can be provided by the brakes alone. However, if the runway is icy, wet, and/or contaminated with rubber deposits, brakes alone may not be able to stop this airplane. If the thrust reversers were stowed prior to entering the slippery area, there may not be time to redeploy them and reach sufficient engine speed to produce the force necessary to prevent an overrun.

The best way to avoid this problem is to plan the landing so that hard braking will not be required in the last portion of the runway. If it appears that the aircraft might enter the area at high speed, keep the reversers ready and use them as necessary to complete the stop on the runway.

The total decelerating force available on a dry runway is quite large, approximately .5g deceleration capability. This means the total stopping force available on a 500,000 pound Model 747 is 250,000 pounds, or 45,000 pounds for a 90,000-pound Model 737. At high ground speeds approximately 35%-55% of the total force available is provided by drag and thrust reversers and 45%-65% is provided by the brakes. At lower speeds, the brakes provide 80%-95% of the total decelerating capability.

On wet runways the total stopping force available is less than on dry runways due to the reduced braking effectiveness. The reversers and speedbrakes become more important since they now represent a larger proportion of the total force capability. Wet runway braking capability is smallest at high speeds and increases as speed decreases. with the speedbrakes deployed, the drag and reversers furnish 50%-80% of the high speed stopping force, whereas the brakes furnish 70%-95% of the low speed stopping force. Overall, the wet runway stopping capability is 50%80% of the dry runway capability. Failing to extend the spoilers on a wet runway reduces the stopping capability by an additional 20-30%.

The stopping force that can be generated on icy runways is even smaller. The drag and reverser forces provide 80% of the total at higher speeds. At lower speeds the brakes provide about 50%-70%.

Regarding stopping forces, remember :

- Rapid extension of the spoilers and lowering the nose are essential to developing maximum braking, tracking and drag forces at high speeds.

- Aerodynamic drag (with speedbrakes deployed) and reverse thrust contribute approximately 80% of the high speed stopping force on a slippery runway.

- Although wheel braking on a slippery runway is only 20% of the total force available at high speed, it is a significant force and increases rapidly as speed decreases.

The minimum stopping distance that can be achieved will occur on a dry runway with spoilers extended, thrust reversers and brakes used at their maximum capacity. This minimum distance increases when reduced friction is present and when all of the available stopping forces are not used effectively. For example, failure to use both reversers and spoilers on a wet runway results in a stopping distance that is about 2.5 times the reference dry runway distance.

In addition, approaching with excess speed, touching down far beyond the target zone, and failing to use spoilers, brakes and reversers effectively are particularly costly on wet runways.

RECOMMENDED PROCEDURES

slippery runway landing procedures reviewed below are recommended for all Boeing transports for all runway conditions, slippery or not. These procedures are the result of thorough investigation of the capabilities and limitations of the airplane stopping systems, the environmental problems associated with contaminated runway surfaces and the stopping distance required. They provide some operational margins for unplanned deviations that may be encountered in service, but it must be clearly understood that the maximum safety margins will be available only when the approach, flare and rollout tasks are properly executed.

- **Approach**

Set up the aircraft for landing in the touchdown zone, on centerline, with minimum lateral drift, and without excess speed. This allows the maximum practical runway remaining on which to stop, and minimizes the speed from which the stop is made.

The approach speed should be as low as possible commensurate with landing conditions. Selecting the proper speed additives to account for prevailing approach conditions is very important. The recommended wind additive provides adequate safety margins for both approach and the landing roll.

For most operation situations, planning to touch down 1,000 feet beyond the threshold is optimum. This provides adequate protection against landing short and leaves the maximum practical runway ahead for making the stop.

Arming the automatic SPEEDBRAKE and AUTOBRAKE during approach provides added assurance that the stopping effort will start promptly after touchdown. Verify auto speedbrakes deployment and auto brake application, and deploy/apply manually if necessary.

Typical recommended approach speeds must be adhered to, particularly during adverse weather conditions.

- **Flare and Touchdown**

The landing flare should be performed so that the touchdown is moderately firm. Attempting to achieve a very smooth touchdown *(grease job)* can consume excessive amounts of runway and jeopardize directional control capability by failing to provide wheel spinup to establish runway tracking forces.

Lowering the nose as soon as the main wheels touch down helps *plant* the aircraft on the ground by placing load on the tires. This also helps to spin up the wheels and establish runway tracking capability.

The last chance to initiate a go-around is during the flare. if it appears that the aircraft might not be stopped on the remaining runway, then a go-around should be initiated. Do not attempt a go-around after reverse thrust has been initiated.

- **Rollout**

Deploy the speedbrakes as soon as possible after main gear touchdown to place a high load on the tires. Lowering the nose and deploying the speedbrakes may be done simultaneously. If the landing is made with auto speedbrakes armed, then their deployment should be confirmed (and manually extended if necessary) as soon as possible after touchdown.

if autobrakes are not used, initiate braking as soon as the spoilers have been raised, the nose wheels have contacted the runway, and the aircraft is tracking the runway. Apply the brakes smoothly and symmetrically with moderate to firm steady pedal pressure.

Initiate reverse thrust as soon as possible after main gear touchdown. Since the actions of deploying the speedbrakes and applying reverse thrust must be done one at a time, it is recommended that the speedbrakes be raised first as they have the added benefit of increasing runway tracking capability. Reverse thrust effectiveness at idle is very low, and it is necessary to increase power in order to generate the most effective stopping force.

Close adherence to recommended procedures is especially important when landing on slippery runways. Maintaining the maximum margins to avoid landing overruns requires a well managed, stable approach, touchdown on speed in the touchdown zone, and prompt application of all stopping devices.

LANDING PROCEDURES
(all models / all runways)

APPROACH :
- On speed
- On centerline (no drift)
- On Glide Path

TOUCHDOWN :
- Moderately firm
- On target
- Immediately lower nose

STOPPING :
- Speedbrakes UP
- Brakes when : Nose DOWN, Speedbrakes UP & tracking with prompt application
- Reverse thrust