Takeoff Safety - Background Data
### SECTION 4

**Takeoff Safety Background Data**

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Appendix 4-A  NTSB Special Investigation Report SIR-90/02

Appendix 4-B  RTO Accident/Incident List 1959 to 1990

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Appendix 4-D  Reverse Thrust Effectiveness

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Appendix 4-F  Airplane Flight Manual Transition Time Details

Appendix 4-G  Brake Pedal Force Data

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Appendix 4-I  Lineup Distance Charts

Appendix 4-J  The Effect of Procedural Variations On Stopping Distance
4.0 Introduction

The rejected takeoff (RTO) is a maneuver performed at any time during the takeoff roll if the flight crew determines that the takeoff should not be continued. A review of the available data over the history of western-built transport jet operations shows that approximately one in 3000 takeoffs has been rejected. Of these RTO’s about one in 1000 was unsuccessful, resulting in an overrun accident or incident. That is an accident/incident rate of one per 3,000,000 takeoff attempts.

The National Transportation Safety Board (NTSB), in a report on RTO overruns, stated that historical evidence from two decades of RTO-related accidents suggests that pilots faced with unusual or unique situations may perform high-speed RTO’s unnecessarily or may perform them improperly. It is the goal of this Training Aid to reduce the number of RTO related accidents and incidents by improving the pilot’s decision making and associated procedure accomplishment through increased knowledge and awareness of the related factors.

This section provides a thorough review of aspects of the takeoff that affect the Go/No Go decision. It reviews standard operating practices some airlines have adopted to maximize RTO stopping margins. It also reviews training practices that prepare crews to make sound Go/No Go decisions while using effective RTO techniques when an RTO is necessary.

4.1 Objectives

The objective is to reduce the number of RTO accidents and incidents while preserving the excellent record of takeoffs safely continued. Flight crews play a significant role in accomplishing this objective. The RTO begins with a decision by the crew to reject the takeoff and the crew will be responsible for the result. The airline’s responsibility is to establish good standard operating procedures and provide the best possible training. The flight crew’s responsibility is to correctly analyze all the data they receive prior to and during the takeoff roll and perform the “best” procedure for the circumstances.

The material in this section is intended to be a resource for those responsible for policy, procedures and training standards. It can also be used by training department personnel in the development of classroom material and as a resource for answering questions raised in the training process. It is recognized that there is more than one way for an airline to operate safely, therefore this section may not be appropriate for direct release to line pilots due to the requirements of operators to maintain standardization in the cockpit. The underlying message of this section for flight crew members is: be familiar with your airplane’s basic performance characteristics and the margins associated with either continuing or rejecting a takeoff. Know the procedures that will be used for either option, and be prepared to perform them promptly.

Some of the Appendices to this section contain data related to specific airplane models. This data is prepared and delivered by each airplane manufacturer and is the exclusive responsibility of that manufacturer.

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1 Following generally accepted conventions, in this document an accident is defined as an event which involves a fatality and/or serious airframe damage. An incident is defined as an event which results in serious damage to the airplane only, but no fatalities.

2 Appendix 4-A, NTSB/SIR-90/02 Special Investigation Report—Runway Overruns Following High Speed Rejected Takeoffs, 27 February 1990.

3 Appendix 4-F through 4-J contain airplane model specific data.
4.2 "Successful Versus Unsuccessful" Go/No Go Decisions

Any Go/No Go decision can be considered "successful" if it does not result in injury or airplane damage. However, just because it was "successful" by this definition, it does not mean the action was the "best" that could have been taken. The purpose of this section is to point out some of the lessons that have been learned through the RTO experiences of airline crews over the past 30 years, and to recommend ways of avoiding similar experiences by the pilots of today's airline fleet.

4.2.1 An Inservice Perspective On Go/No Go Decisions

Modern jet transport services began in the early 1950's and significantly increased later that decade after introduction of the Boeing 707 and the Douglas DC-8. The western built jet transport fleet accumulated approximately 230 million takeoffs by the end of 1990. The projection for 1995 alone is nearly 18 million takeoffs. That's approximately 34 takeoffs every minute, every day!

Since no comprehensive fleet-wide records are available, it is difficult to identify the total number of RTO's that have occurred throughout the jet era. However, based on those events which have been documented, our best estimate is that one in 3000 takeoff attempts ends with an RTO. At this rate, there will be nearly 6000 RTO's during the year 1995. That means that every day in 1995, 16 flight crews will perform an RTO. Statistically, at the rate of one RTO per 3000 takeoffs, a pilot who flies short-haul routes and makes 80 departures per month, will experience one RTO every three years. At the opposite extreme, the long-haul pilot making only eight departures per month will be faced with only one RTO every 30 years.

The probability that a pilot will ever be required to perform an RTO from high speed is even less, as is shown in Figure 2.

<table>
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<tr>
<td><strong>Takeoffs</strong></td>
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<tr>
<td>Through 1990</td>
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<tr>
<td>Projected 1995</td>
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<tr>
<td>230,000,000</td>
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<td>18,000,000</td>
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<tr>
<td><strong>RTOs (est.)</strong></td>
</tr>
<tr>
<td>76,000</td>
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<tr>
<td>6,000</td>
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<tr>
<td><strong>RTO Overrun Accidents/Incidents</strong></td>
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- 1 RTO per 3,000 takeoffs
- 1 RTO overrun accident/incident per 3,000,000 takeoffs
Available data indicates that over 75% of all RTO's are initiated at speeds of 80 knots or less. These RTO's almost never result in an accident. Inherently, low speed RTO's are safer and less demanding than high speed RTO's. At the other extreme, about 2% of the RTO's are initiated at speeds above 120 knots. Overrun accidents and incidents that occur principally stem from these high speed events.

What should all these statistics tell a pilot? First, RTO's are not a very common event. This speaks well of equipment reliability and the preparation that goes into operating jet transport airplanes. Both are, no doubt, due in large part to the certification and operational standards developed by the aviation community over the thirty plus years of operation. Second, and more important, the infrequency of RTO events may lead to complacency about maintaining sharp decision-making skills and procedural effectiveness. In spite of the equipment reliability, every pilot must be prepared to make the correct Go/No Go decision on every takeoff — just in case.

4.2.2 “Successful” Go/No Go Decisions

As was mentioned at the beginning of Section 4.2, there is more to a “good” Go/No Go decision than the fact that it may not have resulted in any injury or aircraft damage. The following examples illustrate a variety of situations that have been encountered in the past, some of which would fit the description of a “good” decision, and some which are, at least, “questionable”.

Listed at the beginning of each of the following examples, is the primary cause or cue which prompted the crew to reject the takeoff:

1. Takeoff Warning Horn: The takeoff warning horn sounded as the takeoff roll commenced. The takeoff was rejected at 5 knots. The aircraft was taxied off the active runway where the captain discovered the stabilizer trim was set at the aft end of the green band. The stabilizer was reset and a second takeoff was completed without further difficulty.
2. Takeoff Warning Horn: The takeoff was rejected at 90 knots when the takeoff warning horn sounded. The crew found the speed brake lever slightly out of the detent. A normal takeoff was made following a delay for brake cooling.

3. Engine Power Setting: The throttles were advanced and \( N_1 \) increased to slightly over 95%. \( N_1 \) eventually stabilized at 94.8% \( N_1 \). The target \( N_1 \) from the FMC Takeoff Page was 96.8% \( N_1 \). The throttles were then moved to the firewall but the \( N_1 \) stayed at 94.8%. The takeoff was rejected due to low \( N_1 \) at 80 knots.

4. Compressor Stall: The takeoff was rejected from 155 knots due to a bird strike and subsequent compressor stall on the number three engine. Most of the tires subsequently deflated due to melted fuse plugs.

5. Nose Gear Shimmy: The crew rejected the takeoff after experiencing a nose landing gear shimmy. Airspeed at the time was approximately \( V_1 \)-10 knots. All four main gear tires subsequently blew during the stop, and fires at the number 3 and 4 tires were extinguished by the fire department.

6. Blown Tire: The takeoff was rejected at 140 knots due to a blown number 3 main gear tire. Number 4 tire blew turning onto the taxiway causing the loss of both A and B hydraulic systems as well as major damage to flaps, spar, and spoilers.

These examples demonstrate the diversity of rejected takeoff causes. All of these RTO’s were “successful”, but some situations came very close to ending differently. By contrast, the large number of takeoffs that are successfully continued with indications of airplane system problems such as caution lights that illuminate at high speed or tires that fail near \( V_1 \), are rarely ever reported outside the airline’s own information system. They may result in diversions and delays but the landings are normally uneventful, and can be completed using standard procedures.

This should not be construed as a blanket recommendation to “Go, no matter what.” The goal of this training aid is to eliminate RTO accidents by reducing the number of improper stop decisions that are made, and to ensure that the correct procedures are accomplished when an RTO is necessary. It is recognized that the kind of situations that occur in line operations are not always the simple problem that the pilot was exposed to in training. Inevitably, the resolution of some situations will only be possible through the good judgment and discretion of the pilot, as is exemplified in the following takeoff event:

After selecting EPR mode to set takeoff thrust, the right thrust lever stuck at 1.21 EPR, while the left thrust lever moved to the target EPR of 1.34. The captain tried to reject the takeoff but the right thrust lever could not be moved to idle. Because the light weight aircraft was accelerating very rapidly, the Captain advanced the thrust on the left engine and continued the takeoff. The right engine was subsequently shut down during the approach, and the flight was concluded with an uneventful single-engine landing.

The failure that this crew experienced was not a standard training scenario. Nor is it included here to encourage pilots to change their mind in the middle of an RTO procedure. It is simply an acknowledgment of the kind of real-world decision making situations that pilots face. It is perhaps more typical of the good judgments that airline crews regularly make, but the world rarely hears about.
4.2.3 RTO Overrun Accidents and Incidents

The one-in-one-thousand RTO’s that became accidents or serious incidents are the ones that we must strive to prevent. As shown in figure 3, at the end of 1990, records show 46 inservice RTO overrun accidents for the western built jet transport fleet. These 46 accidents caused more than 400 fatalities. An additional 28 serious incidents have been identified which likely would have been accidents if the runway overrun areas had been less forgiving. The following are brief accounts of four actual accidents. They are real events. Hopefully, they will not be repeated.

ACCIDENT: At 154 knots, four knots after $V_1$, the copilot’s side window opened, and the takeoff was rejected. The aircraft overrun, hitting a blast fence, tearing open the left wing and catching fire.

ACCIDENT: The takeoff was rejected by the captain when the first officer had difficulty maintaining runway tracking along the 7000 foot wet runway. Initial reports indicate that the airplane slowly accelerated at the start of the takeoff roll due to a delay in setting takeoff thrust. The cockpit voice recorder (CVR) readout indicates there were no speed callouts made during the takeoff attempt. The reject speed was 5 knots above $V_1$. The transition to stopping was slower than expected. This was to have been the last flight in a long day for the crew. Both pilots were relatively inexperienced in their respective positions. The captain had about 140 hours as a captain in this airplane type and the first officer was conducting his first non-supervised line takeoff in this airplane type. The airplane was destroyed when it overran the end of the runway and broke apart against piers which extend off the end of the runway into the river. There were two fatalities. Subsequent investigation revealed that the rudder was trimmed full left prior to the takeoff attempt.

ACCIDENT: A flock of sea gulls was encountered “very near $V_1$.” The airplane reportedly had begun to rotate. The number one engine surged and flamed out and the takeoff was rejected. The airplane overran the end of the wet 6000 foot runway despite a good RTO effort.
ACCIDENT: At 120 knots, the flight crew noted the onset of a vibration. When the vibration increased, the captain elected to reject and assumed control. Four to eight seconds elapsed between the point where the vibration was first noted and when the RTO was initiated (just after $V_1$). Subsequent investigation showed two tires had failed. The maximum speed reached was 158 knots. The airplane overran the end of the runway at a speed of 35 knots and finally stopped with the nose in a swamp. The airplane was destroyed.

These four cases are typical of the 74 reported accidents and incidents. A list of the 74 cases is included in Appendix 4-B as a reference.

4.2.4 Statistics

Studies of the previously mentioned 74 accidents/incidents have revealed some interesting statistics, as shown in Figure 4:

- Fifty-eight percent were initiated at speeds in excess of $V_1$.
- Approximately one-third were reported as having occurred on runways that were wet or contaminated with snow or ice.

Both of these issues will be thoroughly discussed in subsequent sections.

![Figure 4: RTO Initiation Speed](image)

![Figure 5: Runway Condition](image)
An additional, vitally interesting statistic that was observed when the accident records involving Go/No Go decisions were reviewed, was that virtually no revenue flight was found where a "Go" decision was made and the made airplane was incapable of continuing the takeoff. Regardless of the ability to safely continue the takeoff, as will be seen in Section 4.3, virtually any takeoff can be "successfully" rejected, if the reject is initiated early enough and is conducted properly. There is more to the Go/No Go decision than "Stop before V₁" and "Go after V₁." The statistics of the past three decades show that a number of jet transports have experienced circumstances near V₁ that rendered the airplane incapable of being stopped on the runway remaining. It also must be recognized, that catastrophic situations could occur which render the airplane incapable of flight.

Reasons why the 74 "unsuccessful" RTO's were initiated are also of interest. As shown in Figure 5, approximately one-fourth were initiated because of engine failures or engine indication warnings. The remaining seventy-six percent were initiated for a variety of reasons which included tire failures, procedural error, malfunction indication or lights, noises and vibrations, directional control difficulties and unbalanced loading situations where the airplane failed to rotate. Some of the events contained multiple factors such as an RTO on a contaminated runway following an engine failure at a speed in excess of V₁. The fact that the majority of the accidents and incidents occurred on airplanes that had full thrust available should figure heavily in future Go/No Go training.

![Figure 5
Reasons for Initiating the 74 RTO Accidents](image)

* Including events "Not reported*
4.2.5 Lessons Learned

Several lessons can be learned from these RTO accidents. First, the crew must always be prepared to make the Go/No Go decision prior to the airplane reaching \( V_1 \) speed. As will be shown in subsequent sections, there may not be enough runway left to successfully stop the airplane if the reject is initiated after \( V_1 \). Second, in order to eliminate unnecessary RTO’s, the crew must differentiate between situations that are detrimental to a safe takeoff, and those that are not. Third, the crew must be prepared to act as a well-coordinated team. A good summarizing statement of these lessons is, as speed approaches \( V_1 \), the successful completion of an RTO becomes increasingly more difficult.

A fourth and final lesson learned from the past 30 years of RTO history is illustrated in Figure 6. Analysis of the available data suggests that of the 74 RTO accidents and incidents, approximately 80% were potentially avoidable through appropriate operational practices. These potentially avoidable accidents can be divided into three categories. Roughly 9% of the RTO accidents of the past were the result of improper preflight planning. Some of these instances were caused by loading errors and others by incorrect preflight procedures. About 16% of the accidents and incidents could be attributed to incorrect pilot techniques or procedures in the stopping effort. Delayed application of the brakes, failure to deploy the speedbrakes, and the failure to make a maximum effort stop until late in the RTO were the chief characteristics of this category.

Review of the data from the 74 RTO accidents and incidents suggests that in approximately 55% of the events, the airplane was capable of continuing the takeoff and either landing at the departure airport or diverting to an alternate. In other words, the decision to reject the takeoff appears to have been improper. It is not possible, however, to predict with total certainty what would have happened in every event if the takeoff had been continued. Nor is it possible for the analyst of the accident data to visualize the events leading up to a particular accident “through the eyes of the crew”, including all the other factors that were vying for their attention at the moment when the “proper” decision could have been made. It is not very difficult to imagine a set of circumstances where the only logical thing for the pilot to do is to reject the takeoff. Encountering a large flock of birds at rotation speed, which then produces loss of thrust on both engines of a two-engine airplane, is a clear example.

Although these are all valid points, debating them here will not move us noticeably closer to the goal of reducing the RTO accident rate. Several industry groups have recently studied this problem. Their conclusions and recommendations agree surprisingly well. The areas identified as most in need of attention are decision making and proficiency in correctly performing the appropriate procedures. These are the same areas highlighted in Figure 6. It would appear then, that an opportunity exists to significantly reduce the number of RTO accidents in the future by improving the pilot’s decision making capability, and the procedure accomplishment through better training.

![Figure 6](image_url)

90% of the RTO accidents and incidents were avoidable.
4.3 Decisions and Procedures -- What Every Pilot Should Know

There are many things that may ultimately affect the outcome of a Go/No Go decision. The goal of the Takeoff Safety Training Aid is to reduce the number of RTO related accidents and incidents by improving the pilot's decision making and associated procedure accomplishment through increased knowledge and awareness of the related factors. This section discusses the rules that define takeoff performance limited weights and the margins that exist when the actual takeoff weight of the airplane is less than the limit weight. The effect of runway surface condition, atmospheric conditions, and airplane configuration variables on Go/No Go performance are discussed, as well as what the pilot can do to make the best use of any excess available runway.

Although the information contained in this section has been reviewed by many major airframe manufacturers and airlines, the incorporation of any of the recommendations made in this section are subject to the approval of each operator's management.

4.3.1 The Takeoff Rules -- The Source of the Data

Let's look at the takeoff from a distance. It may appear that basic common sense would assure a safe conclusion. Common sense will go a long way, but skill and preparedness are necessary also. It is important that all pilots understand the takeoff field length/weight limit criteria and the margins these criteria provide. The rules, in effect, define the window within which the airplane and the pilot must perform in order to achieve the expected results. Misunderstanding the rules and their application to the operational situation could contribute to an incorrect Go/No Go decision.

The U.S. Federal Aviation Regulations (FAR's) have continually been refined so that the details of the rules that are applied to one airplane model may differ from another. However, these differences are minor and have no effect on the basic actions required of the flight crew during the takeoff. Some differences, as discussed in Section 4.3.1.4 and in Appendix 4-C, also occur between FAA certified performance levels and the criteria applied by other regulatory agencies. It is worth noting here, that proposed rule changes currently under consideration by the various regulatory agencies, will probably eliminate any significant differences in the very near future. In general, it is more important for the crew to understand the basic principles rather than the technical variations in certification policies. However, some significant differences exist between commercial airline certification rules and U.S. military rules which can foster misunderstanding by pilots with a background of military flying. These differences are also discussed in Appendix 4-C.

The most recent revision to the FAR's (Amendment 25-42) has only been applied to a limited number of airplanes at this time, and therefore is not discussed in this section. As of July, 1992, there are revisions under consideration to both the FAR's and the JAR's. These revisions are understood to be intended to "harmonize" the two sets of rules (i.e. make them equivalent). The subject areas being revised include the accelerate-stop distance criteria, wet runway accountability, lineup distance accountability, and the effects of worn brakes. However, they are not yet finalized and are therefore not, in general, discussed in this document.
4.3.1.1 The "FAR" Takeoff Field Length

The "FAR" Takeoff Field Length determined from the FAA approved Airplane Flight Manual (AFM) considers the most limiting of each of the following three criteria:

1) All-Engine Go Distance: 115% of the actual distance required to accelerate, liftoff and reach a point 35 feet above the runway with all engines operating (Figure 7).

2) Engine-Out Accelerate-Go Distance: The distance required to accelerate with all engines operating, have one engine fail at $V_{EF}$, at least one second before $V_1$, continue the takeoff, liftoff and reach a point 35 feet above the runway surface at $V_2$ speed (Figure 8).

3) Engine-Out Accelerate-Stop Distance: The distance required to accelerate with all engines operating, have an engine fail at $V_{EF}$ at least one second before $V_1$, recognize the failure, reconfigure for stopping and bring the airplane to a stop using maximum wheel braking with the speedbrakes extended. Reverse thrust is not used to determine the FAR accelerate-stop distance (Figure 9).

The FAR criteria provide accountability for wind, runway slope, clearway and stopway. FAA approved takeoff data are based on the performance demonstrated on a smooth, dry runway. Separate advisory data for wet or contaminated runway conditions are published in the manufacturer's operational documents. These documents are used by many operators to derive wet or contaminated runway takeoff adjustments.

Other criteria define the performance weight limits for takeoff climb, obstacle clearance, tire speeds and maximum brake energy capability. Any of these other criteria can be the limiting factor which determines the maximum dispatch weight. However, the Field Length Limit Weight and the amount of runway remaining at $V_1$ will be the primary focus of our discussion here since they more directly relate to preventing RTO overruns.

- 35 feet
- $V_2 + 10$ to 25 knots
- 1 second minimum

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Figure 7
All-engine go distance

Figure 8
Engine-out accelerate-go distance

Figure 9
Engine-out accelerate-stop distance
4.3.1.2 V₁ Speed Defined

What is the proper operational meaning of the key parameter "V₁ speed" with regard to the Go/No Go criteria? This is not such an easy question since the term "V₁ speed" has been redefined several times since commercial jet operations began more than 30 years ago and there is possible ambiguity in the interpretation of the words used to define V₁.

Paragraph 25.107 of the FAA Regulations defines the relationship of the takeoff speeds as published in the Airplane Flight Manual, to various speeds determined in the certification testing of the airplane. Although the terms engine failure speed, decision speed, recognizes, and reacts are all within this "official" definition, for our purposes here, the most important statement within this "official" definition is that V₁ is determined from "...the pilot's application of the first retarding means during the accelerate-stop tests."

One common and misleading way to think of V₁ is to say "V₁ is the decision speed." This is misleading because V₁ is not the point to begin making the operational Go/No Go decision. The decision must have been made by the time the airplane reaches V₁ or the pilot will not have initiated the RTO procedure at V₁. Therefore, by definition, the airplane will be traveling at a speed higher than V₁ when stopping action is initiated, and if the airplane is at a Field Length Limit Weight, an overrun is virtually assured.

Another commonly held misconception: "V₁ is the engine failure recognition speed", suggests that the decision to reject the takeoff following engine failure recognition may begin as late as V₁. Again, the airplane will have accelerated to a speed higher than V₁ before stopping action is initiated. The certified accelerate-stop distance calculation is based on an engine failure at least one second prior to V₁. This standard time allowance³ has been established to allow the line pilot to recognize an engine failure and begin the subsequent sequence of stopping actions.

In an operational Field Length Limited context, the correct definition of V₁ consists of two separate concepts:

First, with respect to the "No-Go" criteria, "V₁ is the maximum speed at which the rejected takeoff maneuver can be initiated and the airplane stopped within the remaining field length under the conditions and procedures defined in the FAR's." It is the latest point in the takeoff roll where a stop can be initiated.

Second, with respect to the "Go" criteria, V₁ is also the earliest point from which an engine out takeoff can be continued and the airplane attain a screen height of 35 feet at the end of the runway. This aspect of V₁ is discussed in Section 4.3.3.

³ The time interval between V₁ and V₁ is the longer of the flight test demonstrated time or one second. Therefore, in determining the scheduled accelerate-stop performance, one second is the minimum time that will exist between the engine failure and the first pilot stopping action.
The Go/No Go decision must be made before reaching \( V_1 \). A "No Go" decision after passing \( V_1 \) will not leave sufficient runway remaining to stop if the takeoff weight is equal to the Field Length Limit Weight. As will be discussed in Section 4.3.4.2, when the airplane actual weight is less than the Field Length Limit Weight, it is possible to calculate the actual maximum speed from which the takeoff could be successfully rejected. However, few operators use such takeoff data presentations. It is therefore recommended that pilots consider \( V_1 \) to be a limit speed: Do not attempt an RTO once the airplane has passed \( V_1 \) unless the pilot has reason to conclude the airplane is unsafe or unable to fly. This recommendation should prevail no matter what runway length appears to remain after \( V_1 \).

4.3.1.3 Balanced Field Defined

The previous two sections established the general relationship between the takeoff performance regulations and \( V_1 \) speed. This section provides a closer examination of how the choice of \( V_1 \) actually affects the takeoff performance in specific situations.

Since it is generally easier to change the weight of an airplane than it is to change the length of a runway, consider the effect of \( V_1 \) on the allowable takeoff weight from a fixed runway length.

The Continued Takeoff -- After an engine failure during the takeoff roll, the airplane must continue to accelerate on the remaining engine(s), liftoff and reach \( V_2 \) speed at 35 feet. The later in the takeoff roll that the engine fails, the heavier the airplane can be and still gain enough speed to meet this requirement. For the engine failure occurring one second prior to \( V_1 \), the relationship of the allowable engine-out go takeoff weight to \( V_1 \) would be as shown by the "Continued Takeoff" line in Figure 10. The higher the \( V_1 \), the heavier the takeoff weight allowed.

The Rejected Takeoff -- On the stop side of the equation, the \( V_1/\text{weight} \) trade has the opposite trend. The lower the \( V_1 \), or the earlier in the takeoff roll the stop is initiated, the heavier the airplane can be, as indicated by the "Rejected Takeoff" line in Figure 10.

The point at which the "Continued and Rejected Takeoff" lines intersect is of special interest. It defines what is called a "Balanced Field Limit" takeoff. The name "Balanced Field" refers to the fact that the accelerate-go performance required is exactly equal to (or "balances") the accelerate-stop performance required. From Figure 10 it can also be seen that at the "Balanced Field" point, the allowable Field Limit Takeoff Weight for a given runway is the maximum. The resulting unique value of \( V_1 \) is referred to as the "Balanced Field Limit \( V_1 \) Speed" and the associated takeoff weight is called the "Balanced Field Weight Limit." This is the \( V_1 \) speed that is typically given to flight crews in handbooks or charts, by onboard computer systems, or by dispatch.

The concept of a balanced field condition is revisited in Section 4.3.4 as it relates to operational takeoff situations.

![Figure 10](image-url)
4.3.1.4 Other Rules Affecting Takeoff Field Length

Some regulatory authorities outside the United States have adopted takeoff rules different from the FAA. For the most part, the differences have minimal effect on takeoff performance and, as a consequence, do not impact the Go/No Go decision. Most significantly, however, some authorities require the effects of a wet runway to be included in the calculation of the maximum allowable takeoff weight. The FAA and several other regulatory agencies currently have similar wet runway requirements under review. The detail considerations of runway surface condition on takeoff safety are discussed in Section 4.3.5.1.

Since the Go/No Go decision made at a speed near V\textsubscript{\text{1}} must be essentially an instinctive reaction based on previous planning and training, a pilot's prior flying experience will play a significant role in the decision process. Ideally, it would be best if the training received on one airplane model was completely applicable when a pilot is transitioning to a different airplane. This ideal situation may be achievable over time at a given airline via thorough standardization, but the attainment of this goal may be hindered if the training program does not recognize some of the biases and preconceptions of the student. Typical areas of potential misunderstanding would be pilots who are hired from another airline, have flown previously under the regulations of a different country, or are transitioning to commercial aviation from a military background.

As an aid to the operator in developing a training program which adequately addresses these concerns, Appendix 4-C contains a discussion of the takeoff rules for other countries and for the U.S. military, as they relate to the Go/No Go decision. It is also intended as a place for operators to include any other regulatory definitions which they feel are pertinent to their particular pilot training program.

4.3.2 Transition to the Stopping Configuration

In establishing the certified accelerate-stop distance, the time required to reconfigure the airplane from the "Go" to the "Stop" mode is referred to as the "transition" segment. This action and the associated time of accomplishment includes applying maximum braking, simultaneously moving the thrust levers to idle and raising the speedbrakes. The transition time demonstrated by flight test pilots during the accelerate-stop testing is used to derive the transition segment times used in the AFM calculations. The relationship between the flight test demonstrated transition times and those finally used in the AFM is another frequently misunderstood area of RTO performance.

4.3.2.1 Flight Test Transitions

Several methods of certification testing that produce comparable results have been found to be acceptable. The following example illustrates the intent of these methods.

During certification testing, the airplane is accelerated to a pre-selected speed, one engine is "failed" by selecting fuel cut-off, and the pilot flying rejects the takeoff. In human factors circles, this is defined as a "simple task" because the test pilot knows in advance that an RTO will be performed. Exact measurements of the time taken by the pilot to apply the brakes, retard the thrust levers to idle, and to deploy the speedbrakes are recorded. Detailed measurements of engine parameters during spooldown are also made so that the thrust actually being generated can be accounted for in the calculation.

The manufacturer's test pilots, and pilots from the regulatory agency, each perform several rejected takeoff test runs. An average of the recorded data from at least six of these RTO's is then used to determine the "demonstrated"
transition times for applying the brakes, retarding the throttles to idle, and extending the speedbrakes. These three actions determine when the forces acting to accelerate (thrust) or decelerate (braking and drag) the airplane take place. It is the integration of these acceleration and deceleration forces that will ultimately determine the runway distance required.

The total flight test "demonstrated" transition time, initial brake application to speedbrakes up, is typically one second or less. However, this is not the total transition time used to establish the certified accelerate-stop distances. The certification regulations require that additional time delays, sometimes referred to as "pads", be included in the calculation of certified takeoff distances.

4.3.2.2 Airplane Flight Manual Transition Times

Although the line pilot must be prepared for an RTO during every takeoff, it is fairly likely that the event or failure prompting the Go/No Go decision will be much less clear-cut than an outright engine failure. It may therefore be unrealistic to expect the average line pilot to perform the transition in as little as one second in an operational environment. Human factors literature describes the line pilot's job as a "complex task" since the pilot does not know when an RTO will occur. In consideration of this "complex task", the flight test transition times are increased to calculate the certified accelerate-stop distances specified in the AFM. These additional time increments are not intended to allow extra time for making the "No Go" decision after passing V1. Their purpose is to allow sufficient time (and distance) for "the average pilot" to transition from the takeoff mode to the stopping mode.

The first adjustment is made to the time required to recognize the need to stop. During the RTO certification flight testing, the pilot knows that the engine will be failed, therefore, his reaction is predictably quick. To account for this, an engine failure recognition time of at least one second has been set as a standard for all jet transport certifications since the late 1960's. V1 is therefore, at least one second after the engine failure. During this recognition time segment, the airplane continues to accelerate with the operating engine(s) continuing to provide full forward thrust. The "failed" engine has begun to spool down, but it is still providing some forward thrust, adding to the airplane's acceleration.

Over the years, the details of establishing the transition time segments after V1 have varied slightly but the overall concept and the resulting transition distances have remained essentially the same. For early jet transport models, an additional one second was added to both the flight test demonstrated throttles-to-idle time and the speedbrakes-up time, as illustrated in Figure 11. The net result is that the flight test demonstrated recognition and transition time of approximately one second has been increased for the purpose of calculating the AFM transition distance.

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4The data in Appendix 4-J, Takeoff Safety Training Aids Human Performance Study, corroborate this statement.

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4.14
In more recent certification programs, the AFM calculation procedure was slightly different. An allowance equal to the distance traveled during two seconds at the speedbrakes-up speed was added to the actual total transition time demonstrated in the flight test to apply brakes, bring the thrust levers to idle and deploy the speedbrakes, as shown in Figure 12. To insure "consistent and repeatable results," retardation forces resulting from brake application and speed brake deployment are not applied during this two second allowance time, i.e. no deceleration credit is taken. This two second distance allowance simplifies the transition distance calculation and accomplishes the same goal as the individual one second "pads" used for older models. Regardless of the method used, the accelerate-stop distance calculated for every takeoff from the AFM is typically 400 to 600 feet longer than the flight test accelerate-stop distance. Details of the certified transition times for specific airplane models is included in Appendix 4-F as a reference for the instructor.

These differences between the past and present methodology are not significant in so far as the operational accelerate-stop distance is concerned. The key point is that the time/distance "pads" used in the AFM transition distance calculation are not intended to allow extra time to make the "No Go" decision. Rather, the "pads" are meant to recognize that executing the "No Go" decision and its subsequent stopping action represent a human factors "complex task." They provide an allowance that assures the pilot has adequate distance to get the airplane into the full stopping configuration, and stop the airplane on the runway.

Regardless of the airplane model, the transition, or reconfiguring of the airplane for a rejected takeoff, demands quick action by the crew to simultaneously initiate maximum braking, retard the thrust levers to idle and then quickly raise the speedbrakes.

4.3.3 Comparing the "Stop" and "Go" Margins

When performing a takeoff at a Field Length Limit Weight determined from the AFM, the pilot is assured that the airplane performance will, at the minimum, conform to the requirements of the FAR's if the assumptions of the calculations are met. This means that following an engine failure at \( V_{FE} \), the takeoff can be rejected at \( V_{1} \) and the airplane stopped at the end of the runway, or if the takeoff is continued, a minimum height of 35 feet will be reached over the end of the runway.

This section discusses the inherent conservatism of these certified calculations, and the margins they provide beyond the required minimum performance.
4.3.3.1 The "Stop" Margins

From the preceding discussion of the certification rules, it has been shown that at a Field Length Limit Weight condition, an RTO initiated at $V_1$ will result in the airplane coming to a stop at the end of the runway. This accelerate-stop distance calculation specifies a smooth, dry runway, an engine failure at $V_{EF}$, the pilot's initiation of the RTO at $V_1$, and the completion of the transition within the time allotted in the AFM. If any of these basic assumptions are not satisfied, the actual accelerate-stop distance may exceed the AFM calculated distance, and an overrun will result.

The most significant factor in these assumptions is the initiation of the RTO no later than $V_1$, yet as was noted previously, in approximately 58% of the RTO accidents the stop was initiated after $V_1$. At heavy weights near $V_1$, the airplane is typically traveling at 200 to 300 feet per second, and accelerating at 3 to 6 knots per second. This means that a delay of only a second or two in initiating the RTO will require several hundred feet of additional runway to successfully complete the stop. If the takeoff was at a Field Limit Weight, and there is no excess runway available, the airplane will reach the end of the runway at a significant speed, as shown in Figure 13.

The horizontal axis of Figure 13 is the incremental speed in knots above $V_1$ at which a maximum effort stop is initiated. The vertical axis shows the minimum speed in knots at which the airplane would cross the end of the runway, assuming the pilot used all of the transition time allowed in the AFM to reconfigure the airplane to the stop configuration, and that a maximum stopping effort was maintained. The data in Figure 13 assumes an engine failure not less than one second prior to $V_1$ and does not include the use of reverse thrust. Therefore, if the pilot performs the transition more quickly than the AFM allotted time, and/or uses reverse thrust, the line labeled "MAXIMUM EFFORT STOP" would be shifted slightly to the right. However, based on the RTO accidents of the past, the shaded area above the line shows what is more likely to occur if a high speed RTO is initiated at or just after $V_1$. This is especially true if the RTO was due to something other than an engine failure, or if the stopping capability of the airplane is otherwise degraded by runway surface contamination, tire failures, or poor technique. The data in Figure 13 are typical of a large, heavy jet transport and would be rotated slightly to the right for the same airplane at a lighter weight.

In the final analysis, although the certified accelerate-stop distance calculations provide sufficient runway for a properly performed RTO on a dry runway, the available margins are fairly small. Most importantly, there are no margins to account for initiation of the RTO after $V_1$ or extenuating circumstances such as runway contamination.
4.3.3.2 The "Go" Option

FAR rules also prescribe minimum performance standards for the "Go" situation. With an engine failed at the most critical point along the takeoff path, the FAR "Go" criteria requires that the airplane be able to continue to accelerate, rotate, liftoff and reach \( V_2 \) speed at a point 35 feet above the end of the runway. The airplane must remain controllable throughout this maneuver and must meet certain minimum climb requirements. These handling characteristics and climb requirements are demonstrated many times throughout the certification flight test program. While a great deal of attention is focused on the engine failure case, it is important to keep in mind that, in nearly three-quarters of the RTO accident cases, full takeoff power was available.

It is likely that each crew member has had a good deal of practice in engine inoperative takeoffs in prior simulator or airplane training. However, it may have been done at relatively light training weights. As a result, the crew may conclude that large control inputs and rapid response typical of conditions near minimum control speeds (Vmcg) are always required in order to maintain directional control. However, at the \( V_1 \) speeds associated with a typical Field Length Limit Weight, the control input requirements are noticeably less than they at lighter weights.

Also, at light gross weights, the airplane’s rate of climb capability with one engine inoperative could nearly equal the all-engine climb performance at typical in-service weights, leading the crew to expect higher performance than the airplane will have if the actual airplane weight is at or near the takeoff Climb Limit Weight. Engine-out rate of climb and acceleration capability at a Climb Limit Weight may appear to be substantially less than the crew anticipates or is familiar with.

The minimum second segment climb gradients required in the regulations vary from 2.4% to 3.0% depending on the number of engines installed. These minimum climb gradients translate into a climb rate of only 350-500 feet per minute at actual climb limit weights and their associated \( V_2 \) speeds, as shown in Figure 14. The takeoff weight computations performed prior to takeoff are required to account for all obstacles in the takeoff flight path. All that is required to achieve the anticipated flight path is adherence by the flight crew to the planned headings and speeds per their pre-departure briefing.

Consider a one-engine-inoperative case where the engine failure occurs earlier than the minimum time before \( V_1 \) specified in the rules. Because engine-out acceleration is less than all-engine acceleration, additional distance is needed to accelerate to \( V_{R} \) and, as a consequence, the liftoff point will be moved further down the runway. The altitude (or “screen height”) achieved at the end of the runway is somewhat reduced depending on how much more than one second before \( V_1 \) the engine failure occurs. On a field length limit runway, the height at the end of the runway may be less than the 35 feet specified in the regulations.

<table>
<thead>
<tr>
<th>Minimum Gradient Required</th>
<th>Typical Rate of Climb</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 engine</td>
<td>3%</td>
</tr>
<tr>
<td></td>
<td>520 FPM at ( V_2 \approx 170 ) knots</td>
</tr>
<tr>
<td>3 engine</td>
<td>2.7%</td>
</tr>
<tr>
<td></td>
<td>440 FPM at ( V_2 \approx 160 ) knots</td>
</tr>
<tr>
<td>2 engine</td>
<td>2.4%</td>
</tr>
<tr>
<td></td>
<td>360 FPM at ( V_2 \approx 150 ) knots</td>
</tr>
</tbody>
</table>

15 degree bank turn will reduce these climb rates by approximately 100 FPM

Figure 14
Rate of Climb at Climb Limit Weight for 1 engine inoperative
Figure 15 graphically summarizes this discussion of “Go” margins. First, let $V_{EF}$ be the speed at which the Airplane Flight Manual calculation assumes the engine to fail, (a minimum of one second before reaching $V_1$). The horizontal axis of Figure 15 shows the number of knots prior to $V_{EF}$ that the engine actually fails instead of the time, and the vertical axis gives the “screen height” achieved at the end of the runway. A typical range of acceleration is 3 to 6 knots per second, so the shaded area shows the range in screen height that might occur if the engine actually failed “one second early”, or approximately two seconds prior to $V_1$. In other words, a “Go” decision made with the engine failure occurring two seconds prior to $V_1$ will result in a screen height of 15 to 30 feet for a Field Length Limit Weight takeoff.

Figure 15 also shows that the “Go” performance margins are strongly influenced by the number of engines. This is again the result of the larger proportion of thrust loss when one engine fails on the two-engine airplane compared to a three or four-engine airplane. On two-engine airplanes, there are still margins but they are not as large, a fact that an operator of several airplane types must be sure to emphasize in training and transition programs.

It should also be kept in mind that the 15 to 30 foot screen heights in the preceding discussion were based on the complete loss of thrust from one engine. If all engines are operating, as was the case in most of the RTO accident cases, the height over the end of the Field Length Limit runway will be approximately 150 feet and speed will be $V_2 + 10$ to 25 knots, depending on airplane type. This is due to the higher acceleration and climb gradient provided when all engines are operating and because the required all-engine takeoff distance is multiplied by 115%. If the “failed” engine is developing partial power, the performance is somewhere between, but definitely above the required engine-out limits.
4.3.4 Operational Takeoff Calculations

As we have seen, the certification flight testing, in accordance with the appropriate government regulations, determines the relationship between the takeoff gross weight and the required runway length which is published in the AFM. By using the data in the AFM, it is then possible to determine, for a given combination of ambient conditions and airplane weight, the required runway length which will comply with the regulations. Operational takeoff calculations, however, have an additional and obviously different limitation. The length of the runway is the Limit Field Length and it is fixed, not variable.

4.3.4.1 The Field Length Limit Weight

Instead of solving for the required runway length, the first step in an operational takeoff calculation is to determine the maximum airplane weight which meets the rules for the fixed runway length available. In other words, what is the limit weight at which the airplane:

1) will achieve 35 ft altitude with all engines operating with a margin of 15% of the actual distance used remaining;

2) will achieve 35 ft altitude with the critical engine failed prior to \( V_1 \);

3) will stop with an engine failed prior to \( V_1 \) and the reject initiated at \( V_1 \);

...all within the existing runway length available.

The result of this calculation is three allowable weights. These three weights may or may not be the same, but the lowest of the three becomes the Field Length Limit Weight for that takeoff.

An interesting observation can be made at this point as to which of these three criteria will typically determine the Takeoff Field Limit Weight for a given airplane type. Two-engine airplanes lose one-half their total thrust when an engine fails. As a result, the Field Length Limit Weight for two-engine airplanes is usually determined by one of the engine-out distance criteria. If it is limited by the accelerate-stop distance, there will be some margin in both the all-engine and accelerate-go distances. If the limit is the accelerate-go distance, some margin would be available for the all-engine-go and engine-out-stop cases.

By comparison, four-engine airplanes only lose one-fourth of their takeoff thrust when an engine fails so they are rarely limited by engine-out go performance. The Field Length Limit Weight for a four-engine airplane is typically limited by the 115% all-engine distance criteria or occasionally by the engine-out stop case. As a result, a slight margin frequently exists in both of the engine-out distances on four-engine airplanes.

Three-engine airplanes may be limited by engine out performance or for some models, by a more complex criterion wherein the rotation speed \( V_R \) becomes the limiting factor. Since the regulations prohibit \( V_1 \) from exceeding \( V_R \), some trijets frequently have \( V_1 = V_R \), and a small margin may therefore exist in the accelerate-stop distance. Two-engine airplanes may occasionally be limited by this \( V_1 = V_R \) criterion also.

The possible combinations of airport pressure altitude, temperature, wind, runway slope, clearway and stopway are endless. Regardless of airplane type, they can easily combine to make any one of the three previously discussed takeoff field length limits apply. Flight crews have no convenient method to determine which of the three criteria is limiting for a particular takeoff, and from a practical point of view, it really doesn't matter. The slight differences that may exist are rarely significant. Most RTO overrun accidents have occurred on runways where the airplane was not at a limit takeoff weight. That is, the accidents occurred on runways that were longer than required for the actual takeoff weight. Combining this historical evidence with the demanding nature of the high speed rejected takeoff, it would seem prudent that the crew should always assume the takeoff is limited by the accelerate-stop criteria when the takeoff weight is Field Length Limited.
4.3.4.2 Actual Weight Less Than Limit Weight

Returning to the operational takeoff calculation, the second step is to then compare the actual airplane weight to the Field Length Limit Weight. There are only two possible outcomes of this check:

1) The actual airplane weight could equal or exceed the Field Length Limit Weight, or

2) The actual airplane weight is less than the Field Length Limit Weight.

The first case is relatively straightforward, the airplane weight cannot be greater than the limit weight and must be reduced. The result is a takeoff at a Field Length Limit Weight as we have just discussed. The second case, which is typical of most of jet transport operations, is worthy of further consideration.

By far, the most likely takeoff scenario for the line pilot is the case where the actual airplane weight is less than any limit weight, especially the Field Length Limit Weight. It also is possibly the most easily misunderstood area of takeoff performance since the fact that the airplane is not at a limit weight is about all the flight crew can determine from the data usually available on the flight deck. Currently, few operators provide any information that will let the crew determine how much excess runway is available; what it means in terms of the $V_1$ speed they are using; or how to best maximize the potential safety margins represented by the excess runway. Later on, in Section 4.3.6.8, we will work an example takeoff weight problem which will show how one major U.S. operator uses this “excess” runway. In this section, however, the discussion is aimed more at the technical definitions side of what it means when the actual airplane weight is less than the Field Length Limit Weight.

As a preface to this discussion, it should be kept in mind that the use of any $V_1$ adjustment procedure by a flight crew must be contingent on the implementation of a standard operating procedure by an operator which will take into account all the appropriate variables. Unless this data has been provided to the flight crew by their operations department, there is simply no way the crew can make the judgment of how much before $V_1$ they could lose an engine and still have adequate “Go” performance. Neither do they have any way to estimate with sufficient accuracy, how far beyond $V_1$, a successful “No Go” maneuver can be initiated. Therefore, we can only recommend that if adjustment information is provided to the crew, the value of $V_1$ given in their standard takeoff analysis should be treated as a “limit speed” for rejecting the takeoff.

Let’s look again at the figure used in discussing the definition of a Balanced Field condition, only this time, the actual airplane weight is less than the Field Limit Weight for the runway. As a result, it is not necessary to show the Balanced Field Limit $V_1$ Speed, since it does not apply to the lower actual weight of our example. Figure 16 shows that for a given runway length, if the actual weight is less than the limit weight, there is actually a range of speeds which could be called “$V_1$.” The minimum $V_1$ speed still satisfies the continued takeoff criteria and the maximum $V_1$ speed meets the rejected takeoff requirements. Of interest here is that any
speed between these two limit speeds would actually provide performance in excess of that specified by the continued or rejected takeoff criteria.

In this situation the operator can choose from several possible courses of action:

Choice 4. Conduct a reduced thrust takeoff, either using a Fixed Derate and/or the Assumed Temperature method, to reduce engine stresses and maintenance costs. Reducing the takeoff thrust causes both the “Stop” and “Go” distances to increase since it takes more distance to accelerate to \( V_1 \). Using the typical takeoff analysis data to accomplish this produces a new “Balanced Field” condition at the lower thrust setting.

Unless the fixed derate chosen exactly matches the thrust required by the actual weight/runway combination, there is still a margin remaining in the “Stop” and “Go” distances, but the original margin is reduced.

Using the Assumed Temperature method of reducing thrust results in margins in both the “Stop” and “Go” distance requirements, even when the maximum assumed temperature is used. This is primarily due to the True Airspeed effects inherent to this method of reducing thrust. Both the fixed derate and assumed temperature methods of reducing thrust are discussed in Section 4.3.5.7.

Choice 5. A combination of reduced thrust with either choice 2 or 3 is possible. Since the primary emphasis here is to maximize the “Stop” margins, the combination of Choice 2, a lower \( V_1 \), with reduced thrust, Choice 4 is recommended.

The next two sections will discuss some of the major factors and physical conditions which affect RTO stopping margins and some general recommendations on how stopping margins are maximized by control of these factors. The example takeoff problem worked in Section 4.3.6.8 provides an easy way to get a feel for the magnitude of the potential margins.

### 4.3.5 Factors that Affect Takeoff and RTO Performance

The airplane rolls onto the active runway and the power is applied immediately. The airplane quickly accelerates along the smooth dry runway, rotates and climbs briskly into the clear blue sky. You may have done this
many times and seen it happen many more while waiting for your turn for takeoff. It is a truly majestic sight and makes you proud to be in aviation.

In reality, you know that a lot of preparation went into that seemingly simple maneuver. The ground crew checked and serviced the airplane. Dispatch assembled the flight plan, weather briefing, load and trim sheet, and the takeoff performance data. ATC assigned a slot for your departure. The flight crew configured the airplane and are prepared to work as an effective team.

With all the preparation that goes into making a flight, it is not difficult to imagine that most of the thought energy is directed toward completing the flight uneventfully, not encountering a significant difficulty. The passengers, as well as the flight crew are anxious to reach their destination.

It is an abnormal situation when something goes wrong requiring an air turnback or a rejected takeoff. It cancels all of the hard preparation work done by so many and it can result in expensive delays. In the case of a takeoff performed at a limit weight, it can require the crew to use the maximum performance capability of the airplane to successfully complete whichever course of action they choose.

Both the continued and the rejected takeoff performance are directly affected by atmospheric conditions, airplane configuration, runway characteristics, engine thrust available, and by human performance factors. The following sections review the effects of these variables on airplane performance. The purpose is not to make this a complete treatise on airplane performance. Rather, it is to emphasize that changes in these variables can have a significant impact on a successful Go/No Go decision, and in many instances, the flight crew has a degree of direct control over these changes.

4.3.5.1 Runway Surface Condition

The condition of the runway surface can have a significant effect on takeoff performance, since it can affect both the acceleration and deceleration capability of the airplane. The actual surface condition can vary from perfectly dry to a damp, wet, heavy rain, snow, or slush covered runway in a very short time. The entire length of the runway may not have the same stopping potential due to a variety of factors. Obviously, a 10,000 foot runway with the first 7,000 feet bare and dry, but the last 3,000 feet a sheet of ice, does not present a very good situation for a high speed RTO. On the other hand, there are also specially constructed runways with a grooved or Porous Friction Coat (PFC) surface which can offer improved braking under adverse conditions. The crews cannot control the weather like they can the airplane’s configuration or thrust. Therefore, to maximize both the “Go” and “Stop” margins, they must rely on judiciously applying their company’s wet or contaminated runway policies as well as their own understanding of how the performance of their airplane may be affected by a particular runway surface condition.

Certification testing is performed on a smooth, ungrooved, dry runway. Therefore, any contamination which reduces the available friction between the tire and the runway surface will increase the required stopping distance for an RTO. Runway contaminants such as slush or standing water can also affect the continued takeoff performance due to “displacement and impingement drag” associated with the spray from the tires striking the airplane. Some manufacturers provide advisory data for adjustment of takeoff weight and/or $V_f$ when the runway is wet or contaminated. Many operators use this data to provide flight crews with a method of determining the limit weights for slippery runways. As was discussed in Section 4.3.1.4, British CAA operators are required to adjust their takeoff performance if the runway is wet. It is also anticipated that a soon to be released FAA proposal will include wet runway takeoff requirements which are similar to the U.K. CAA rules. Factors that make a runway slippery and how it affects the stopping maneuver are included here for reference.
4.3.5.1.1 Hydroplaning

Hydroplaning is an interesting subject since most pilots have either heard of or experienced instances of extremely poor braking action on wet runways during landing. The phenomenon is highly sensitive to speed which makes it an especially important consideration for RTO situations.

As a tire rolls on a wet runway, its forward motion tends to displace water from the tread contact area. While this isn’t any problem at low speeds, at high speeds this displacement action can generate water pressures sufficient to lift and separate part of the tire contact area from the runway surface. The resulting tire-to-ground friction can be very low at high speeds but fortunately improves as speed decreases.

Dynamic hydroplaning is the term used to describe the reduction of tire tread contact area due to induced water pressure. At high speeds on runways with significant water, the forward motion of the wheel generates a wedge of high pressure water at the leading edge of the contact area, as shown in Figure 17A. Depending on the speed, depth of water, and certain tire parameters, the portion of the tire tread that can maintain contact with the runway varies significantly. As the tread contact area is reduced, the available braking friction is also reduced. This is the predominant factor leading to reduced friction on runways that have either slush, standing water or significant water depth due to heavy rain activity. In the extreme case, total dynamic hydroplaning can occur where the tire to runway contact area vanishes, the tire lifts off the runway and rides on the wedge of water like a water-ski. Since the conditions required to initiate and sustain total dynamic hydroplaning are unusual, it is rarely encountered. When it does occur, such as during an extremely heavy rain storm, it virtually eliminates any tire braking or cornering capability at high speeds.

Another form of hydroplaning can occur where there is some tread contact with the runway surface but the wheel is either locked or rotating slowly (compared to the actual airplane speed). The friction produced by the skidding tire causes the tread material to become extremely hot. As indicated in Figure 17B, the resulting heat generates steam in the contact area which tends to provide additional upward pressure on the tire. The hot steam also starts reversing the vulcanizing process used in manufacturing the rubber tread material. The affected surface tread rubber becomes irregular in appearance, somewhat gummy in nature, and usually has a light gray color. This “reverted” rubber hydroplaning results in very low friction levels, approximately equal to icy runway friction when the temperature is near the melting point. An occurrence of reverted rubber hydroplaning is rare and usually results from some kind of antiskid system or brake malfunction which prevented the wheel from rotating at the proper speed.

In the last several years, many runways throughout the world have been grooved, thereby greatly improving the potential wet runway friction capability. As a result, the number of hydroplaning incidents has decreased considerably. Flight tests of one manu-

![Image 17A](Dynamic_Hydroplaning)

![Image 17B](Reverted_Rubber_Hydroplaning)
facturers airplane on a well maintained grooved runway, which was thoroughly drenched with water, showed that the stopping forces were approximately 90% of the forces that could be developed on a dry runway. Continued efforts to groove additional runways or the use of other equivalent treatments such as porous friction overlays, will significantly enhance the overall safety of takeoff operations.

The important thing to remember about wet or contaminated runway conditions is that for smooth runway surfaces there is a pronounced effect of forward ground speed on friction capability — aggravated by the depth of water. For properly maintained grooved or specially treated surfaces, the friction capability is markedly improved.

4.3.5.1.2 The Final Stop

A review of overrun accidents indicates that, in many cases, the stopping forces available were not used to the maximum during the initial and mid-portions of the stop maneuver, because there appeared to be “plenty of runway available”. In some cases, less than full reverse thrust was used and the brakes were released for a period of time, letting the airplane roll on the portion of the runway that would have produced good braking action. When the airplane moved onto the final portion of the runway, the crew discovered that the presence of moisture on the top of rubber deposits in the touchdown and turnoff areas resulted in very poor braking capability, and the airplane could not be stopped on the runway. When an RTO is initiated on wet or slippery runways, it is especially important to use the full stopping capability until the airplane is completely stopped.

4.3.5.2 Atmospheric Conditions

In general, the lift the wings generate and thrust the engines produce are directly related to the airplane’s speed through the air and the density of that air. The flight crew should anticipate that the airplane’s takeoff performance will be affected by wind speed and direction as well as the atmospheric conditions which determine air density. Properly accounting for last minute changes in these factors is crucial to a successful Go/No Go decision.

The effect of the wind speed and direction on takeoff distance is very straightforward. At any given airspeed, a 10 knot headwind component lowers the ground speed by 10 knots. Since $V_1$, rotation, and liftoff speeds are at lower ground speeds, the required takeoff distance is reduced. The opposite occurs if the wind has a 10 knot tailwind component, producing a 10 knot increase in the ground speed. The required runway length is increased, especially the distance required to stop the airplane from $V_1$. There is also an additional conservatism in the wind accountability of the AFM calculations. As required by the regulations, the gain in takeoff performance due to headwind is reduced by 50% and the penalty due to tailwind is increased by 150%. Typical takeoff data supplied to the flight crew by their operations department will either provide takeoff weight adjustments to be applied to a zero wind limit weight or separate columns of limit weights for specific values of wind component. In either case, it is the responsibility of the flight crew to verify that last minute changes in the tower reported winds are included in their takeoff planning.

The effect of air density on takeoff performance is also straightforward in so far as the crew is normally provided the latest meteorological information prior to takeoff. However, it is the responsibility of the crew to verify the correct pressure altitude and temperature values used in determining the final takeoff limit weight and thrust setting.
4.3.5.3 Airplane Configuration

The planned configuration of the airplane at the time of takeoff must be taken into consideration by the flight crew during their takeoff planning. This should include the usual things like flap selection, and engine bleed configuration, as well as the unusual things like inoperative equipment covered by the Minimum Equipment List (MEL) or missing items as covered by the Configuration Deviation List (CDL). Recommendations on how to accomplish this with an eye toward maximizing the stopping margins will be covered in Section 4.3.6. This section will discuss the effect of the airplane's configuration on takeoff performance capability and/or the procedures the flight crew would use to complete or reject the takeoff.

4.3.5.3.1 Flaps

The airplane's takeoff field length performance is affected by flap setting in a fairly obvious way. For a given runway length and airplane weight, the takeoff speeds are reduced by selecting a greater flap setting. This is because the lift required for flight is produced at a lower \( V_2 \) speed with the greater flap deflection. Since the airplane will reach the associated lower \( V_1 \) speed earlier in the takeoff roll, there will be more runway remaining for a possible stop maneuver. On the "Go" side of the decision, increasing the takeoff flap deflection will increase the airplane drag, and the resulting lower climb performance may limit the allowable takeoff weight. However, the takeoff analysis used by the flight crew will advise them if climb or obstacle clearance is a limiting factor with a greater flap setting.

4.3.5.3.2 Engine Bleed Air

Whenever bleed air is extracted from an engine and the value of the thrust setting parameter is appropriately reduced, the amount of thrust the engine generates is reduced. Therefore, the use of engine bleed air for air conditioning/pressurization reduces the airplane's potential takeoff performance for a given set of runway length, temperature and altitude conditions.

When required, using engine and/or wing anti-ice further decreases the performance on some airplane models. This "lost" thrust may be recoverable via increased takeoff EPR or \( N_1 \) limits as indicated in the airplane operating manual. It depends on engine type, airplane model, and the specific atmospheric conditions.

4.3.5.3.3 Missing or Inoperative Equipment

Inoperative or missing equipment can sometimes affect the airplane's acceleration or deceleration capability. Items which are allowed to be missing per the certified Configuration Deviation List (CDL), such as access panels and aerodynamic seals, can cause airplane drag to increase. The resulting decrements to the takeoff limit weights are, when appropriate, published in the CDL. With these decrements applied, the airplane's takeoff performance will be within the required distances and climb rates.

Inoperative equipment or deactivated systems, as permitted under the Minimum Equipment List (MEL) can also affect the airplane's dispatched "Go" or "Stop" performance. For instance, on some airplane models, an inoperative in-flight wheel braking system may
require the landing gear to be left extended during a large portion of the climbout to allow the wheels to stop rotating. The "Go" performance calculations for dispatch must be made in accordance with certified "Landing Gear Down" Flight Manual data. The resulting new limit takeoff weight may be much less than the original limit in order to meet obstacle clearance requirements, and there would be some excess runway available for a rejected takeoff.

An MEL item that would not affect the "Go" performance margins but would definitely degrade the "Stop" margins is an inoperative anti-skid system. In this instance, not only is the limit weight reduced by the amount determined from the AFM data, but the flight crew may also be required to use a different rejected takeoff procedure in which the throttles are retarded first, the speedbrakes deployed second, and then the brakes are applied in a judicious manner to avoid locking the wheels and failing the tires. The associated decrement in the Field Length Limit Weight is usually substantial.

Other MEL items such as a deactivated brake may impact both the continued takeoff and RTO performance through degraded braking capability and loss of in-flight braking of the spinning tire.

The flight crew should bear in mind that the performance of the airplane with these types of CDL or MEL items in the airplane's maintenance log at dispatch will be within the certified limits. However, it would be prudent for the flight crew to accept final responsibility to assure that the items are accounted for in the dispatch process, and to insure that they, as a crew, are prepared to properly execute any revised procedures.

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4 U.K. CAA procedure adds "...apply maximum reverse thrust."
4.3.5.3.4 Wheels, Tires, and Brakes

The airplane’s wheels, tires, and brakes are another area that should be considered in light of the significant part they play in determining the results of a Go/No Go decision.

One design feature which involves all three components is the wheel fuse plug. All jet transport wheels used for braking incorporate thermal fuse plugs. The function of the fuse plug is to prevent tire or wheel bursts by melting if the heat transferred to the wheels by the brake becomes excessive. Melting temperatures of fuse plugs are selected so that with excessive brake-heat, the inflation gas (usually nitrogen) is released before the structural integrity of the tire or wheel is seriously impaired. Both certification limitations and operational recommendations to avoid melting fuse plugs are provided to operators by the manufacturer, as is discussed in Section 4.3.5.3.6 under the heading, Residual Brake Energy.

While fuse plugs provide protection from excessive brake heat, it is also important to recognize that fuse plugs cannot protect against all types of heat induced tire failures. The location of the fuse plug in the wheel is selected to ensure proper response to brake heat. This location in combination with the inherent low thermal conductivity of tire rubber means that the fuse plugs cannot prevent tire failures from the rapid internal heat buildup associated with taxiing on an underinflated tire. This type of heat buildup can cause a breakdown of the rubber compound, ply separation, and/or rupture of the plies. This damage might not cause immediate tire failure and because it is internal, it may not be obvious by visual inspection. However, the weakened tire is more prone to failure on a subsequent flight. Long taxi distances especially at high speeds and heavy takeoff weights can aggravate this problem and result in a blown tire. While underinflation is a maintenance issue, flight crews can at least minimize the possibility of tire failures due to overheating by using low taxi speeds and minimizing taxi braking whenever possible.

Correct tire inflation and fuse plug protection are significant, but will never prevent all tire failures. Foreign objects in parking areas, taxiways and runways can cause severe cuts in tires. The abrasion associated with sustained locked or skidding wheels, which can be caused by various antiskid or brake problems can grind through the tire cords until the tire is severely weakened or a blow-out occurs. Occasionally, wheel cracks develop which deflate a tire and generate an overloaded condition in the adjacent tire on the same axle. Some of these problems are inevitable. However, it cannot be overemphasized that proper maintenance and thorough walk around inspections are key factors in preventing tire failures during the takeoff roll.
Tire failures may be difficult to identify from the flight deck, and the related Go/No Go decision is therefore, not a simple task. A tire burst may be loud enough to be confused with an engine compressor stall, may just be a loud noise, or may not be heard. A tire failure may not be felt at all, may cause the airplane to pull to one side, or can cause the entire airplane to shake and shudder to the extent that instruments may become difficult to read. Vibration arising out of failure of a nose wheel tire potentially presents another complication. During takeoff rotation, vibration may actually increase at nosewheel lift-off due to the loss of the dampening effect of having the tire in contact with the runway. A pilot must be cautious not to inappropriately conclude, under such circumstances, that another problem exists.

Although continuing a takeoff with a failed tire will generally have no significant adverse results, there may be additional complications as a result of a tire failure. Failed tires do not in themselves, usually create directional control problems. Degradation of control can occur however, as a result of heavy pieces of tire material being thrown at very high velocities and causing damage to the exposed structure of the airplane and/or the loss of hydraulic systems. On airplanes with aft mounted engines, the possibility of pieces of the failed tire being thrown into an engine must also be considered.

An airplane's climb gradient and obstacle clearance performance with all engines operating and the landing gear down exceeds the minimum certified engine-out levels that are used to determine the takeoff performance limits. Therefore, leaving the gear down after a suspected tire failure will not jeopardize the aircraft if all engines are operating. However, if the perceived tire failure is accompanied by an indication of thrust loss, or if an engine problem should develop later in the takeoff sequence, the airplane's climb gradient and/or obstacle clearance capability may be significantly reduced if the landing gear is not retracted. The decision to retract the gear with a suspected tire problem should be in accordance with the airline's/manufacturer's recommendations.

If a tire failure is suspected at fairly low speeds, it should be treated the same as any other rejectable failure and the takeoff should be rejected promptly. When rejecting the takeoff with a blown tire, the crew should anticipate that additional tires may fail during the stop attempt and that directional control may be difficult. They should also be prepared for the possible loss of hydraulic systems which may cause speedbrake or thrust reverser problems. Since the stopping capability of the airplane may be significantly compromised, the crew should not relax from a maximum effort RTO until the airplane is stopped on the pavement.
Rejecting a takeoff from high speeds with a failed tire is a much riskier proposition than continuing, especially if the weight is near the Field Limit Weight. The chances of an overrun are increased simply due to the loss of braking force from one wheel. If additional tires should fail during the stop attempt, the available braking force is even further reduced. In this case, it is generally better to continue the takeoff, as can be seen in Figure 18. The subsequent landing may take advantage of a lower weight and speed if it is possible to dump fuel. Also, the crew will be better prepared for possible vibration and/or control problems. Most important, however, is the fact that the entire runway will be available for the stop maneuver instead of perhaps, as little as 40% of it. As shown in Figure 18, as much as 60% of the runway may remain after stopping the airplane from a landing if fuel dumping is an option. Even in a case where only the minimum fuel is burned off in returning to the field, approximately 40% of the runway would remain available for contingencies.

As can be seen from this discussion, it is not a straightforward issue to define when a takeoff should be continued or rejected after a suspected tire failure. It is fairly obvious however, that an RTO initiated at high speed with a suspected tire failure is not a preferred situation. McDonnell Douglas Corporation, in a recent All Operator Letter\(^5\), has addressed this dilemma by recommending a policy of not rejecting a takeoff for a suspected tire failure at speeds above \(V_{1} - 20\) knots. The operators of other aircraft should contact the manufacturer for specific recommendations regarding tire failures.

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4.3.5.3.5 Worn Brakes

The investigation of one recent RTO incident which was initiated "very near V1", revealed that the overrun was the result of 8 of the 10 wheel brakes failing during the RTO. The failed brakes were later identified to have been at advanced states of wear which, while within accepted limits, did not have the capacity for a high energy RTO.

This was the first and only known accident in the history of commercial jet transport operation that can be traced to failure of the brakes during an attempted RTO. The National Transportation Safety Board (NTSB) investigated the accident and made several recommendations to the FAA. The recommendations included the need to require airplane and brake manufacturers to verify by test and analysis that their brakes, when worn to the recommended limits, meet the certification requirements. Prior to 1991, maximum brake energy limits had been derived from tests performed with new brakes installed.

The FAA recently mandated a program to test and demonstrate the energy capacity of worn brakes. The test program used the brake manufacturer’s dynamometer facilities and is now completed for all FAA certified transport airplanes. Worn brake energy certification is an extensive program which has redefined brake wear limits. For most steel brake part numbers, the allowable wear of the brake has been reduced so that the remaining heat sink material could absorb the required energy.

Worn brake stopping force capability is also undergoing review by the regulatory agencies. Recent tests have shown that at high energy levels some worn brakes exhibit a decrease in stopping force capability as compared to new brakes. This loss in force capability translates into an increase in the stopping distance required. However, the loss is generally less than the force that can be made up by considering the effect of the thrust reversers. Furthermore, in many cases, the full capability of the new brakes as demonstrated during certification testing was not utilized in the development of the AFM. As a result, worn brake capability, even though less than new brake capability, often meets or exceeds the performance that had been reflected in the AFM.

Virtually all brakes in use today have wear indicator pins to show the degree of wear and when the brake must be removed from the airplane. In most cases, as the brake wears the pin moves closer to a reference point, such that when the end of the pin is flush with the reference (with full pressure applied), the brake is "worn out". As of late 1991, tests have been completed which show that brakes at the allowable wear limit can meet AFM brake energy levels. As a result, "wear pin length" is not significant to the flight crew unless the pin indicates that the brake is worn out and should be removed from service. There are no changes to flight crew or dispatch procedures based on brake wear pin length.

4.3.5.3.6 Residual Brake Energy

After a brake application, the energy which the brake has absorbed is released as heat and until this heat is dissipated, the amount of additional energy which the brake can absorb without failure is reduced. Therefore, takeoff planning must consider the effects of residual brake energy (or brake temperature) if the previous landing involved significant braking and/or the airplane turnaround is relatively short. There are two primary sources of information on this subject. The brake temperature limitations and/or cooling charts in the airplane operating manual provide recommended information on temperature limitations and/or cooling times and the procedures necessary to dissipate various amounts of brake energy. In addition, the Maximum Quick Turnaround Weight (MQTW) chart in the certified AFM is a regulatory requirement that must be followed. This chart shows the gross weight at landing where the energy absorbed by the brakes during the landing could be high enough to cause the wheel fuses plugs to melt and establishes a minimum waiting/cooling time for these cases. The MQTW chart assumes that the previous landing was conducted with maximum braking for the entire stop and did not use reverse thrust, so for many landings where only light braking was used there is substantial conservatism built into the wait requirement.
Most brakes have been designed so that the limiting fuse plug energy is quite high and therefore in most cases, the requirement of the AFM to wait a specified time is not reached. The large majority of dispatches are in this category and no special brake cooling considerations are involved. There are however, cases where landing energies can be significant, especially at high temperature, high altitude fields such as Denver, Johannesburg and Mexico City. For this type of dispatch, the most important case is where the wheel fuse plugs are very hot but do not melt. If on the other hand, one or more fuse plugs do melt as a result of brake energy at landing, the associated wheel and tire assemblies must be replaced and the maintenance will usually take much longer than any MQTW wait requirement. The required brake cooling will be accomplished while maintenance is performed.

If the MQTW chart shows that the mandatory waiting period is required, the airplane can legally be dispatched as soon as the cooling time period has elapsed. If heavy braking was used during the preceding landing, the wheels and tires may still be at relatively high temperatures, i.e., just below the fuse plug release point. Even if the mandatory waiting period was not required, nearly the same temperatures can be involved if the landing parameters were close to the limiting values. The brake energy requirements of the subsequent takeoff should be carefully considered since wheels and tires cool very slowly, especially in high ambient temperature and low wind conditions. An RTO performed with the initial wheel temperature at near fuse plug melt temperatures, may result in fuse plug releases before the airplane can be brought to a complete stop. In extreme cases, this type of situation can lead to thrown tire tread damage and/or increased stopping distances. While service history shows that the combination of heavy braking on landing, with a minimum length (MQTW) turnaround, and a significant speed RTO is rare, flight crews should be aware of the potential brake cooling problems and consult the manufacturer's guidance material.

The guidance information for critical brake energy conditions is contained in the Brake Cooling Chart and/or the brake temperature limitations of the Operations Manual. This chart provides the recommended cooling times and/or brake temperature limits for defined landing conditions which are translated into brake energy values. The chart takes into consideration a number of practical factors such as the level of braking used, thrust reverser activity, and the amount of taxi roll distance. Many cooling charts also correlate Brake Temperature Monitoring System readouts to the recommended cooling times, therefore this system can be a convenient means to predict cooling requirements. Strict adherence to the brake cooling and the MQTW charts will avoid any operational problems with excessive brake heat in a subsequent RTO.

4.3.5.3.7 Speedbrake Effect on Wheel Braking Performance

While jet transport pilots generally understand the aerodynamic drag benefit of speedbrakes and the capability of wheel brakes to stop an airplane, the effect of speedbrakes on wheel brake effectiveness during an RTO is not always appreciated. The reason speedbrakes are so critical is their pronounced effect on wing lift. Depending on flap setting, the net wing lift can be reduced, eliminated or reversed to a down load by raising the speedbrakes, thereby increasing the vertical load on the wheels which can greatly increase braking capability.

Speedbrakes are important since for most braking situations, especially any operation on slippery runways, the torque output of the brake, and therefore the amount of wheel brake retarding force that can be developed is highly dependent on the vertical wheel load. As a result, speedbrakes must be deployed early in the stop to maximize the braking capability. During RTO certification flight tests, the stopping performance is obtained with prompt deployment of the speedbrakes. Failure to raise the speedbrakes during an RTO or raising them late will significantly increase the stopping distance beyond the value shown in the AFM.

Figures 19 and 20 summarize the effect of speedbrakes during an RTO. For a typical mid-sized two-engine transport, at a takeoff
weight of 225,000 lbs, the total load on the main wheels at brake release would be approximately 193,000 lbs. As the airplane accelerates along the runway, wing lift will decrease the load on the gear, and by the time the airplane approaches $V_1$ speed, (137 knots for this example), the main gear load will have decreased by nearly 63,000 lbs. The data in Figure 20 graphically depicts how the forces acting on the airplane vary with airspeed from a few knots before the RTO is initiated until the airplane is stopped. When the pilot begins the RTO by applying the brakes and closing the thrust levers, the braking force rises quickly to a value in excess of 70,000 lbs. The nearly vertical line make by the braking force curve in Figure 20 also shows that the airplane began to decelerate almost immediately, with virtually no further increase in speed.

The next action in a typical RTO procedure is to deploy the speedbrakes. By the time this action is completed, and the wheel brakes have become fully effective, the airplane will have slowed several knots. In this example of an RTO initiated at 137 knots, the airspeed would be about 124 knots at this point. The weight on the main gear at 124 knots would be approximately 141,600 lbs with the speedbrakes down, and would increase by 53,200 lbs when the speedbrakes are raised. The high speed braking capability is substantially improved by this 38% increase in wheel load from 141,600 to 194,800 pounds, which can be seen by noting the increase in braking force to 98,000 pounds. In addition, the speedbrakes have an effect on aerodynamic drag, increasing it by 73%, from 8,500 to 14,700

The combined result, as indicated by the table in Figure 19, is that during the critical, high speed portion of the RTO, the total stopping force acting on the airplane is increased by 34% when the speedbrakes are deployed.

Since both the force the brakes can produce and the aerodynamic effect of the speedbrakes vary with speed, the total effect for the RTO stop is more properly indicated by averaging the effect of the speedbrakes over the entire stopping distance. For this example, the overall effect of raising the speedbrakes is an increase of 14% in the average total stopping force acting throughout the RTO.

One common misconception among pilots is that the quick use of thrust reversers will offset any delay or even the complete lack of speedbrake deployment during an RTO. This is simply not true. On a dry runway, delaying the deployment of the speedbrakes by only 5 seconds during the RTO will add over 300 ft. to the stop distance of a typical mid-sized two-engine jet transport, including the effects of engine-out reverse thrust. As a worst case illustration, if reverse thrust was not used and the speedbrakes were not deployed at all, the AFM stopping distance would be increased by more than 700 ft. Although the exact figures of this example will vary with different flap settings and from one airplane model to another, the general effect will be the same, namely that speedbrakes have a very pronounced effect on stopping performance. Appendix 4-H contains additional data on the effect of these and other procedural errors on the stopping distance requirements of specific airplane models.

<table>
<thead>
<tr>
<th>Drag</th>
<th>8,500 lbs</th>
<th>14,700 lbs</th>
<th>+73%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lift</td>
<td>52,000 lbs</td>
<td>-1,200</td>
<td>-10%</td>
</tr>
<tr>
<td>Net load on wheels</td>
<td>141,600</td>
<td>194,800</td>
<td>+38%</td>
</tr>
<tr>
<td>Max. braking force</td>
<td>75,900</td>
<td>98,000</td>
<td>+29%</td>
</tr>
<tr>
<td>Max. stopping force (brakes &amp; drag)</td>
<td>94,400</td>
<td>112,700</td>
<td>+34%</td>
</tr>
</tbody>
</table>
4.3.5.3.8 Carbon and Steel Brake Differences

Recent emphasis on the apparent tendency for carbon brakes to wear out in proportion to the total number of brake applications, as opposed to steel brakes which wear out in proportion to energy absorbed by the brakes, has generated interest in other operational differences between the two types of brakes. While the emphasis on wear difference is necessary, since the economics of brake maintenance is so significant, for most other operational aspects the two brakes can be considered equivalent.

As far as RTO capability is concerned, the type of brake involved does not matter since each brake installation is certified to its particular takeoff energy capability. This means that either carbon or steel brakes, even fully worn, will be able to perform the maximum certified RTO condition applicable to that installation in a satisfactory manner.

One difference between steel and carbon brakes that is often claimed is an increased tolerance to thermal overload. To understand this in proper perspective, recognize that although the friction elements in a carbon brake (rotating and stationary disks) are made of carbon material which has good strength and friction characteristics at high temperatures, the brake structure, brake hydraulics, the wheel, and the tire are essentially the same as used for an equivalent steel brake. Within the limitations represented by this non-carbon equipment then, an overheated carbon brake will continue to function reasonably well in situations where an equivalent steel brake with its metallic disks might not. An overload condition could be caused by excessive taxi braking.
riding the brakes, or inappropriate turnaround procedures after landing. In this type of situation, carbon brakes will generally demonstrate better friction characteristics and therefore develop more torque and stopping force than equivalent steel brakes.

The difficulty with this carbon brake thermal advantage is that it is nearly impossible to judge the extra amount of braking that could be done before affecting the ability of the non-carbon components to perform in an RTO situation. This is because the thermal effects on the limiting hardware are so highly time and ambient condition dependent. For instance, whether an airplane has carbon brakes or steel brakes will not matter if enough time has elapsed after a heavy brake application such that the wheel fuse plugs release before the airplane can complete the next takeoff or a subsequent RTO attempt. Pilots should concentrate on proper braking procedures rather than attempt to capitalize on any extra carbon brake advantage. Attention to the brake cooling chart recommendations will avoid these thermal problems and ensure that the airplane stopping performance can be achieved regardless of whether steel or carbon brakes are installed.

The increased thermal overload capability of carbon brakes is closely related to the idea that carbon brakes do not "fade". In other words, they always produce the same torque throughout the stop even as the brake temperature increases. Although many carbon brakes do develop nearly constant torque, some fade considerably in certain conditions. On the other hand, some steel brakes do not fade very much at all, depending to a large extent on the degree of conservatism built into the brake. In either case, brake fade is taken into account in the AFM performance, for the specific brake installed on each particular airplane. Therefore, brake fade does not need to be an operational concern to the flight crew.

A second factor with steel brakes is the potential loss of structural strength of the rotors and stators at the extreme operating temperatures associated with limiting energy values. This could cause a structural failure of one or more brake stators near the end of the stop. In this case the brake will continue to function but with reduced torque capability. The remaining components, which are common to carbon and steel brakes, are less likely to be affected. As a generalization, a steel brake is more exposed to the possibility of structural failure when the temperatures are excessive.

An RTO from at or near the brake energy limits can also mean that after stopping on the runway, the brakes may not be capable of stopping the airplane again, even from low taxi speeds. This is especially true for steel brakes due to the increased chance of structural failure. Therefore, it is important that the crew consider the probable condition of the airplane wheels, brakes, and tires after completing a high speed RTO before attempting to move the airplane from the runway.

One other difference between carbon and steel brakes that might be evident in certain RTO's is brake welding. Steel brakes, which usually have rotors of steel and stators of a copper-iron mix (with a number of special ingredients) can weld together, preventing further wheel rotation. This can even happen before the airplane comes to a full stop, particularly in the last several knots where the antiskid system is not effective. If this does happen, it increases the possibility of a tire blowout as the locked wheel skids to a stop. The energy range where this type of welding can occur is often well below the maximum AFM dispatch energy level but usually above the wheel fuse plug melting level. For most very high energy RTO's, the surfaces of the brake disks remain above the melting point through the entire stop and sometimes for several minutes after. Carbon brakes do not have any tendency to weld together.

Some of the other brake differences are unique to particular designs or to particular design philosophies. For instance, carbon brakes can operate at higher temperatures than steel brakes - provided extra attention is given to protecting the associated equipment. This is typical of most carbon brake designs. However, for some airplane models, commonality and/or interchangeability requirements are more important and have resulted in carbon brakes with the same specified temperature and energy limits as steel brakes.
4.3.5.3.9 High Brake Energy RTO's

Brake rotor and stator temperatures associated with RTO's which involve brake energies at or near certified maximum values, reach approximately 2000°F for steel brakes, and 2500°F for most carbon brakes. These high temperatures may, in some situations, ignite certain items in the wheel, tire, and brake assembly. While considerable design effort is made to preclude fires whenever possible, the regulations recognize the rarity of such high energy situations and allow brake fires after a maximum energy condition, provided that any fires that may occur are confined to the wheels, tires and brakes, and which would not result in progressive engulfment of the remaining airplane during the time of passenger and crew evacuation. It is important then, for flight crews to understand the nature of possible fires and the airplane takeoff parameters that could involve these very high brake energies.

There are two primary combustibles in the assembly, namely the tire, and brake grease. Brake hydraulic fluid will also burn if there is a hydraulic leak directed at a very hot brake disk. Tire fires can occur if the rubber compound temperature exceeds approximately 650°F. Tire fires usually burn fairly slowly for the first several minutes when started by brake heat. Grease fires are even less active, typically involving a small, unsteady, flickering flame, sometimes with considerable smoke. The probability of a crew experiencing a brake fire at the conclusion of an RTO is very low, considering brake design factors, the dispatch parameters, and service history. The following discussion will assist flight crews in understanding the factors associated with a very high energy stop.

First, not all airlines identify the factor that is limiting for a particular takeoff, such as Field Length, Tire Speed, or Brake Energy. Therefore, the crew may not know if they are at or near a brake energy limit weight. Since the maximum brake energy condition is reflected in the AFM performance by the Maximum Brake Energy Speed, \( V_{\text{MBE}} \), and since the regulations prevent \( V_1 \) from exceeding \( V_{\text{MBE}} \), the crew does not necessarily need to know they are brake energy limited to perform a successful RTO. The RTO procedures remain the same.

Second, consider that few of the world's departures are conducted at a Field Length Limit Weight, and only a small proportion of these would be at the Brake Energy Limit Weight where \( V_1 \) equals \( V_{\text{MBE}} \). More significantly, only a small portion of the RTO's that might occur during these brake energy limited takeoffs would involve a stop from or near \( V_1 \). Service history shows that there have been very few brake fires as a result of high brake energy RTO's. Brake/tire fires occur in service occasionally, but are almost always due to some equipment failure condition during a landing. Fires have also occurred during some airplane brake certification flight test RTO's while attempting to establish maximum brake energy levels. A few have been dramatic and highly publicized, but usually result in changes which are incorporated in the wheel/brake design to reduce any unacceptable risk. The final, certified capability is either less than originally tested or the equipment is improved to meet the required capability.

In terms of practical guidelines for flight crews, takeoffs at or near \( V_{\text{MBE}} \), are normally encountered at high altitude airports or at very hot temperatures. An RTO from close to \( V_1 \) speed under these conditions will require the brakes to absorb a significant amount of energy during the stop. Flight crews can use the Brake Cooling Chart of the airplane operating manual to determine brake energy values if the situation warrants such a review. In cases where an extremely high brake energy might be encountered, the possibility of a brake fire should therefore be considered by the flight crew during the pre-takeoff briefing. If a high speed RTO is subsequently performed the tower should immediately be advised that the airplane is still on the runway, that a high brake energy stop was made, and that emer-
4.3.5.4 Reverse Thrust Effects

Most of the takeoffs planned in the world do not include reverse thrust credit. This is because the rejected takeoff certification testing under FAA rules does not include the use of reverse thrust. An additional stopping margin is produced by using maximum reverse thrust. We stress the word "maximum" in relation to the use of reverse thrust because of another commonly held misconception. Some pilots are of the opinion that idle reverse is "equally or even more" effective than full or maximum reverse thrust for today's high bypass ratio engines. This is simply not true. The more EPR or N₁ that is applied in reverse, the more stopping force the reverse thrust generates. The data shown in Figure 21 is typical for all high bypass engines. Similar data on other specific airplane models can be found in Appendix 4-D.⁶

On wet or slippery runways, the wheel brakes are not capable of generating as high a retarding force as they are on a dry surface. Therefore, the retarding force of the reversers generates a larger percentage of the total airplane deceleration.

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4.3.5.5 Runway Parameters

Runway characteristics which affect takeoff performance include length, slope, clearway and/or stopway. The effect of runway length is straightforward; however, slope, clearway, and stopway deserve some discussion.

A single value of runway slope is typically chosen by the operator to perform takeoff analysis calculations. This single value is usually taken from information published by the navigation chart services or the airport authorities. On closer inspection however, many runways are seen to have distinct differences in slope along the length of the runway. The single published value may have been determined by a variety of methods, ranging from a simple mathematical average of the threshold elevations, to some weighted average methods proposed by ICAO in an advisory publication.\footnote{ICAO Circular 91-AN/75, The Effect of Variable Runway Slopes on Takeoff Runway Lengths for Transport Aeroplanes, dated 1968.}

As a simple example, consider a runway which has only one slope discontinuity. The first two-thirds of the runway has an uphill slope of +2% and the last third has a downhill slope of -2%. The equivalent single slope for this runway, as determined from the ICAO Circular methods, could vary from +1.3% to -0.3%. When the takeoff analysis is made for this runway, the limit weights will be the same as would be determined for an actual single slope runway. However, as the airplane commences a takeoff on the 2% upslope runway, it will accelerate more slowly than it would on any of the equivalent single slope runways, which will result in its achieving \( V_1 \) speed further along the runway than was planned. If no event occurs which would precipitate an RTO, the final acceleration to \( V_R \) and liftoff will be higher than planned and the overall performance will probably come out close to what was scheduled.

On the other hand, if an event worthy of an RTO should occur just prior to the airplane reaching \( V_1 \), most, if not all of the stop maneuver will have to be carried out on a 2% downhill slope surface instead of the equivalent single slope value, and the RTO will have been initiated with less runway remaining than was assumed in determining the limit weight for that takeoff. There is little the crew can do in this type of situation, other than in the vein of situational awareness, emphasize in their briefing that an RTO near \( V_1 \) for anything other than a catastrophic event is not advisable.

A clearway is an area at least 500 feet wide centered about the extended centerline of the runway with a slope equal to or less than 1.25%. This area is called the clearway plane. No obstructions, except threshold lights, can protrude above this clearway plane. Use of clearway to increase takeoff weight “unbalances the runway” and results in a lower \( V_1 \) speed. The acceleration to \( V_2 \) and 35 feet is completed over the clearway. The maximum clearway used to calculate performance is restricted by the regulations to one-half the demonstrated distance from liftoff to 35 feet.

A stopway is an area at least as wide as the runway and centered about the extended centerline. It must be capable of supporting the weight of the airplane without causing damage. Use of stopway also “unbalances the runway” resulting in a higher takeoff weight and increased \( V_1 \) speed. An RTO initiated at this \( V_1 \) will come to a stop on the stopway. For the sake of completeness, it should be pointed out that not all stopways will qualify as clearways, nor will a clearway necessarily qualify as a stopway. The specified criteria for each must be met independently before it can be used for takeoff performance calculations.

The use of clearway and/or stopway does not necessarily offer any additional margin for RTO stopping. In both cases, the takeoff performance is “unbalanced” by adjusting \( V_1 \) speed to plan that the stop will be completed by the end of the paved surface.
4.3.5.6 Lineup Distance Accountability

Up to this point in time, most operators have not adjusted the available takeoff runway for the distance needed to align the airplane with the runway for takeoff. There has been no regulatory requirement to do so, except in Australia and Germany. However, revisions to both the FAR's and the JAR's are in work which, if passed into law, will require that a lineup distance be considered in determining limit takeoff weights. Accounting for runway lineup distances will reduce the available runway length and hence the allowable limit takeoff weight from any given runway. Operators can minimize the impact of runway alignment accountability by rebalancing the limit takeoff weight/$V_1$ calculation using separate accelerate-go and accelerate-stop distances adjustments as shown in Figure 22.

The takeoff distance (TOD) adjustment is made based on the initial distance from the main gear to the beginning of the runway since the screen height is measured from the main gear, as indicated by distance "A" in Figure 22. The accelerate-stop distance (ASD) adjustment is based on the initial distance from the nose gear to the beginning of the runway, as indicated by distance "B" in Figure 22.

![Figure 22: Lineup distance adjustments](image)

- ASD available
- TOD available
- Runway length

A: Adjustment to takeoff distance
B: Adjustment to accelerate-stop distance
When determining a runway lineup allowance, the characteristics for maneuvering each airplane model onto each runway should be used in calculating the required corrections. For example, runways with displaced takeoff thresholds or ample turning aprons should not need further adjustment. As shown in Figure 23, runways that require a 90 degree turn-on, or taxiing on the runway with a 180 degree turn at the end may require a lineup adjustment. Appendix 4-I contains the appropriate minimum lineup distance adjustments to both the accelerate-go (TOD) and accelerate-stop (ASD) cases that result from a 90 degree turn onto the runway and a 180 degree turn maneuver on the runway, for all Boeing airplanes. Operators should develop or obtain similar information on other airplanes in their fleet from the manufacturer.

**90 Degree Turn to Centerline**

**180 Degree Turn on a 60m Runway**

*Figure 23 Typical line-up maneuver*
4.3.5.7 Takeoffs Using Reduced Thrust

There are two methods of performing a reduced thrust takeoff. The first is to use a fixed derate of the engine to a lower thrust rating. For example, a JT9D-7F engine operated at a JT9D-7 rating, or a CFM56-3C-1 engine operated at 20,000 lbs of thrust (-B1 rating) instead of the full 23,500 lb rating. When a fixed derate is used, the engine EGT and RPM limits are reduced and the crew are not to exceed the reduced limits in normal operation. As a result of the lower limit thrust with a fixed derate, the minimum control speeds \( V_{mcg} \) and \( V_{mca} \) are also reduced. Since the choice of derate thrust levels is usually restricted to one or two preselected values, it is rare that the takeoff performance at the derated thrust would be reduced to exactly match field length limit levels. However, if the actual airplane weight should equal the Field Length Limit Weight for the derated thrust, the performance margins are identical to that described in Section 4.3.4.1.

The second way of reducing takeoff thrust is to use the Assumed Temperature Method. The fundamental difference between fixed derates and the Assumed Temperature Method is that the operating limits of the engine are not reduced when using the Assumed Temperature Method. The flight crew may increase the thrust to the full engine rating at any time during the takeoff if it is deemed appropriate. For instance, British CAA Flight Manuals include a recommendation to increase thrust on the operating engines to the full rating in the event that an engine fails during the takeoff. As a result, the \( V_{mcg} \) and \( V_{mca} \) speeds are not reduced below the full rating values when using the Assumed Temperature Method.

Fixed derates and the Assumed Temperature Method also differ in terms of the performance margins that are inherent to their use. As was previously mentioned, at limit weights, a takeoff performed using a fixed derate takeoff thrust will conform to the minimum performance levels of the regulations, just as a limit weight takeoff would when using full rated takeoff thrust. The associated \( V_1 \) speed provides the standard certification "margins" of a 35 foot screen height or a stop at the end of the runway in the event of an engine failure.

When using the Assumed Temperature Method, additional "margins" are created in both the "Go" and "Stop" cases. As the name implies, the technique used to calculate the performance with the Assumed Temperature Method is to assume that the temperature is higher than it actually is, and to calculate takeoff thrust and speeds at the higher temperature.

The primary reason that the use of the Assumed Temperature Method results in performance margins is that the true airspeed of the airplane is lower than would be the case if the actual temperature were equal to the assumed temperature. A typical performance comparison is provided in Figure 24 showing margins in both climb gradient and stopping distance required. A similar comparison for other airplane models is included in APPENDIX 4-H for reference.

It should also be pointed out that the Assumed Temperature Method of reduced thrust can be used in combination with Fixed Derate thrust reduction. The only difference is that the "full Rated Thrust" becomes the Derate value, not the maximum possible engine rating.
An example of the margins inherent in the use of the Assumed Temperature Method is shown in Figure 24 for a typical large four-engine jet transport. The Field Length Limit Weight for the 10,100 ft. runway is 762,200 lbs when the OAT is 16 Deg C, but the actual airplane weight is only 717,500 lbs. This excess weight capability permits the use of an assumed temperature of 40 Deg C.

In this example, if an engine were to fail one second before \( V_1 \), the airplane would reach a height of 35 feet and \( V_2 \) speed 750 feet before the end of the runway. If the takeoff were rejected at \( V_1 \), there would be 750 feet more runway available to stop the airplane than would be required. Adding the additional distance margin due to the use of reverse thrust, which for this example airplane is about 270 feet, means that there would be approximately 1020 feet of additional runway available for the RTO.

### Conditions:

- Typical Large Four-Engine Jet Transport
- Sea Level
- OAT = 16 deg C (60 deg F)
- 10,100 ft runway
- Field Length Limit Weight = 762,200 lbs
- Actual Airplane Weight = 717,500 lbs which permits an assumed temperature of 40 deg C (104 deg F)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Actual temp is 16 deg C and assumed temp is 40 deg C</th>
<th>Actual temp is 40 deg C</th>
<th>Resulting Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPR</td>
<td>1.376</td>
<td>1.376</td>
<td>—</td>
</tr>
<tr>
<td>( V_1 ) (KIAS/TAS)</td>
<td>146/146</td>
<td>146/152</td>
<td>-6 KTAS</td>
</tr>
<tr>
<td>( V_R ) (KIAS/TAS)</td>
<td>156/156</td>
<td>156/163</td>
<td>-7 KTAS</td>
</tr>
<tr>
<td>( V_2 ) (KIAS/TAS)</td>
<td>164/164</td>
<td>164/171</td>
<td>-7 KTAS</td>
</tr>
<tr>
<td>Thrust at ( V_1 ), lbs per engine</td>
<td>31,210</td>
<td>30,960</td>
<td>250 lbs</td>
</tr>
<tr>
<td>FAR Field Length—ft</td>
<td>9,310</td>
<td>10,100</td>
<td>790 ft</td>
</tr>
<tr>
<td>Accelerate-stop distance (engine-out)—ft</td>
<td>9,050</td>
<td>9,800</td>
<td>750 ft</td>
</tr>
<tr>
<td>Accelerate-go distance (engine-out)—ft</td>
<td>9,050</td>
<td>9,800</td>
<td>750 ft</td>
</tr>
<tr>
<td>Accelerate-go distance (all engine)—ft</td>
<td>8,100</td>
<td>8,800</td>
<td>700 ft</td>
</tr>
<tr>
<td>Second Segment Gradient</td>
<td>3.54%</td>
<td>3.42%</td>
<td>+0.12%</td>
</tr>
<tr>
<td>Second segment rate of Climb—ft per minute</td>
<td>582</td>
<td>586</td>
<td>-4 fpm</td>
</tr>
</tbody>
</table>
4.3.5.8 The Takeoff Data the Pilot Sees

Let's look at the takeoff data from the standpoint of the data used to plan the takeoff. The typical takeoff data table (sometimes referred to as runway analysis or gross weight tables) shows the limit takeoff weight for a specific runway over a range of ambient temperatures. There may also be corrections for wind, pressure altitude, bleed configurations, and runway surface conditions. Each table usually shows the limit weights for only one flap setting. Some airlines show the takeoff speeds and the takeoff thrust EPR or N₁ setting along with the limit weights. The tables can display limit weights for Field Length, Climb, Obstacle Clearance, Tire Speed and Brake Energy, and tell which factor is limiting for each wind and temperature. This tabular display of the takeoff data has become the standard tool for using the assumed temperature method to reduce the takeoff power setting and thereby improve engine life.

This takeoff data is some of the most important data used on any flight. It is essential that flight crews know their actual takeoff weight and that they use the proper takeoff speeds. It is equally important that the flight crew be aware of their proximity to the limit weights for that takeoff’s ambient conditions. These limit weights and speeds are more than just numbers. They represent the maximum certified takeoff performance of the airplane. If the actual takeoff weight is less than the limit weight, the crew should use the normally obtained V₁ speed as a “limit speed” unless their operations department has provided them with a specific method of unbalancing the V₁ speed to utilize the excess runway available. The operator should assure that a suitable, non-ambiguous method of presenting the V₁ speed is chosen, whether it is a balanced or unbalanced speed.

4.3.6 Increasing the RTO Safety Margins

There are a number of choices and techniques the crew can make and practice that will increase the RTO margins for takeoff. Some involve airline policy and require the publication of additional data (such as multiple flap setting takeoff weight and speed data) and some are just good personal technique.

4.3.6.1 Runway Surface Condition

The crew cannot control the weather like they can the airplane’s configuration or thrust. Therefore, to maximize both the “GO” and “STOP” margins, they must rely judiciously applying their company’s wet or contaminated runway policies as well as their own understanding of how the performance of their airplane may be affected by a particular runway surface condition.

If the actual airplane weight is less than the limit weight, the crew should treat the normally obtained V₁ speed as a “limit speed” unless their operations department has provided them with a specific method of unbalancing the V₁ speed to utilize the excess runway available. The operator should assure that a suitable, non-ambiguous method of presenting the V₁ speed is chosen, whether it is a balanced or unbalanced speed.
### 4.3.6.2 Flap Selection

<table>
<thead>
<tr>
<th>8,700 FT RUNWAY SEA LEVEL 37 °C</th>
<th>FLAP SETTING</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Runway limit weight, lb (kg)</td>
<td>358,300</td>
<td>374,200</td>
<td>389,000</td>
<td>393,600</td>
</tr>
<tr>
<td></td>
<td>(162,494)</td>
<td>(169,705)</td>
<td>(176,417)</td>
<td>(178,503)</td>
</tr>
<tr>
<td>Climb/Obstacle limit weight, lb (kg)</td>
<td>414,100</td>
<td>407,300</td>
<td>393,600</td>
<td>383,000</td>
</tr>
<tr>
<td></td>
<td>(187,800)</td>
<td>(184,717)</td>
<td>(178,503)</td>
<td>(173,696)</td>
</tr>
</tbody>
</table>

Often the RTO safety margin can be increased by selection of an alternative takeoff flap setting. Consider for example, the effect of takeoff flap selection on the performance limit weights of a typical large two-engine airplane, as shown in Figure 25.

If a flight requires the absolute maximum takeoff weight, the above weight limits would dictate choosing Flaps 15 since 389,000 pounds is the highest weight allowed. Flaps 20 is Climb/Obstacle limited to a lower weight and Flaps 1 and 5 are Runway limited to lower weights. If the actual takeoff weight desired is equal to the maximum limit weight, there is no flap selection option. The takeoff will need to use Flaps 15.

More typical, however, the airplane’s actual takeoff weight is well below the maximum. There are then two viable ways to improve RTO stopping distance margin: either by flap selection or by reduced $V_1$ techniques. Section 4.3.6.8 contains a discussion on reduced $V_1$.

If the flight’s actual takeoff weight was 374,200 pounds, investigating the above table indicates Flaps 5, Flaps 15, or Flaps 20 are all acceptable. Flaps 5 is runway limited so it offers no additional RTO margin. However, Flaps 15 and Flaps 20 both offer an opportunity for additional stopping distance margin. These additional stopping margins have been calculated for this example and are shown in Figure 26.

Thus, if there are no other constraints such as obstacles or critical noise abatement procedures that would prevent the selection of a greater flap setting, the crew could give themselves 1000 feet of extra stopping distance in case an RTO was required on this takeoff.

Remember that there are some disadvantages to selecting a higher flap setting. These disadvantages include diminished climb performance and slightly more fuel consumed due to the higher drag configuration and the additional flap retraction cleanup time that will be required.

<table>
<thead>
<tr>
<th>FLAP SETTING</th>
<th>5</th>
<th>15</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>STOPPING MARGIN</td>
<td>ZERO</td>
<td>850 FT</td>
<td>1000 FT</td>
</tr>
</tbody>
</table>

Figure 26
Effect of Flap selection on RTO stopping margins
Thus, if there are no other constraints such as obstacles or critical noise abatement procedures that would prevent the selection of a greater flap setting, the crew could give themselves 1000 feet of extra stopping distance in case an RTO was required on this takeoff.

Remember that there are some disadvantages to selecting a higher flap setting. These disadvantages include diminished climb performance and slightly more fuel consumed due to the higher drag configuration and the additional flap retraction cleanup time that will be required.

4.3.6.3 Runway Lineup

Positioning the aircraft on the runway in preparation for takeoff is an important element in maximizing the amount of pavement available for a possible RTO maneuver. Correct runway lineup technique should always be practiced regardless of whether or not there is excess runway available. As discussed in Section 4.3.5.6, optimum runway lineup procedures can be developed by reference to the turning diagrams presented in Appendix 4-I or by contacting the manufacturer. The flight crew should be familiar with their airline’s policy on line-up distance and be proficient in executing the proscribed maneuvers. Operators should also encourage airport authorities to provide turn guidance striping on runways requiring 180 deg turns.

Even if a lineup allowance has been made, it is up to the crew operating the flight to align the airplane on the runway using the shortest possible distance. If they can do it in a shorter distance than taken into account by their company, then there is that much extra margin for the takeoff.

4.3.6.4 Setting Takeoff Thrust

At takeoff thrust settings, gas turbine (jet) engines operate at very high RPM. It typically takes several seconds for the engines to spool up from a low idle or taxi thrust to takeoff power after the thrust levers are advanced. During this time, the aircraft is not accelerating at full potential because the engines are not yet developing full power.

The demonstrated takeoff distance is achieved when the takeoff thrust is set prior to releasing the brakes, but this technique is often not practical in line operations due to expedited takeoff clearances, engine FOD hazards, and passenger comfort. As a result, most takeoffs are performed as “rolling takeoffs”, with the thrust being set as the airplane begins the takeoff roll. However, this technique must be accomplished promptly to avoid compromising the takeoff performance. A delayed application of takeoff thrust will increase the time and distance to reach $V_1$ speed, consequently, less runway will be left to stop the airplane should an RTO be necessary. The thrust should be set promptly, according to the airframe manufacturer’s recommendations. The non-flying pilot or Flight Engineer then typically makes any final adjustments and monitors the engines for any abnormalities.

On airplanes equipped with autothrottles, an additional item to be aware of is that some autothrottle systems incorporate “Thrust Hold” features which will stop advancing the thrust levers after the airplane reaches a predetermined threshold airspeed value. A delay in engaging the autothrottle can result in the thrust stabilizing below the takeoff target setting and the initial acceleration being less than required.

The engine instruments should be monitored closely for any abnormal indications. Past RTO accidents have occurred after an engine problem was identified early in the takeoff roll, but no action was initiated until the airplane had reached or exceeded $V_1$.

Company operations manuals or training manuals contain correct procedures for setting takeoff thrust. Observing these procedures assures efficient engine acceleration and, as a consequence, proper aircraft acceleration throughout the entire takeoff roll.
4.3.6.5 Manual Brake Application Techniques

Modulation of brake pressure, or “pumping the brakes” was the way most of us were taught to apply automobile brakes when braking conditions were less than favorable. This prevented sustained skids and therefore afforded both better braking and directional control. Both benefits occur because a skidding tire produces less frictional force than a tire which continues to rotate. Flight deck observation and simulator testing, however, both indicate that this technique has at times been carried over into the cockpit of jet transports. With the antiskid control systems in jet transport airplanes this technique is not only totally unnecessary, it results in degraded stopping capability and therefore excessive stopping distance especially for adverse runway conditions. Proper braking technique in an RTO is to apply full brake pedal force (“stand on it”) and maintain full brake pedal force until the airplane comes to a complete stop.

The pilot’s foot position relative to the rudder pedal can also have an effect on the achievement of full brake pressure. It was noted during the Takeoff Safety Training Aid Human Performance Study\(^8\) that foot position during the takeoff roll tends to be an individual preference. Some pilots prefer to have their feet “up on the pedals” to be ready to apply full brakes if required. Pilots who prefer this technique also noted that their toes are “curled back” to avoid unwanted brake applications when applying rudder. The other technique is to rest the heels on the floor during the takeoff roll, and then raise them to be on the pedal to apply full braking. No problems were noted with either technique.

One technique which did not work well was also noted, however. It was not possible to apply maximum brake pedal deflection, and hence full brake pressure, if the heel of the foot is left on the floor, unless the pilot has very big feet. In an RTO stop maneuver, the feet should be up on the rudder pedals and steady, heavy pressure applied until the airplane is completely stopped. Pilots should develop a habit of adjusting their seat and the rudder pedals prior to leaving the gate. The ability to apply maximum brake pedal force as well as full rudder should be checked by both pilots. On some airplane models, the brake pedal force required to set the parking brake is essentially the same as that required to achieve maximum manual braking. On other airplanes, it may be significantly less. It is up to each crew member to be sure that their understanding of the airplane they are currently operating is correct. The data in Appendix 4-G gives the actual brake pedal forces required to achieve maximum brake pressure, to set the parking brake, and to disarm the RTO autobrake.

The importance of maintaining maximum braking and full reverse thrust during an RTO until the airplane “rocks to a stop” cannot be over stressed. During a reject from \(V_1\), the goal is safety, not passenger comfort. The amount of distance required to decelerate from a given speed at the high weights associated with takeoff is significantly greater than from the same speed at a typical landing weight. If the pilot tries to judge the amount of runway remaining against the current speed of the airplane, the visual perception that the airplane will stop on the runway (“we’ve got it made”) will prompt a decrease in the stopping effort. It is precisely at this point in the RTO that the difference between a successful Go/No Go decision and an accident can occur. The brakes may be nearing their energy absorption limits and the airplane may be entering a portion of the runway contaminated with rubber deposits, which can be very slick if wet. In several of the RTO accidents and incidents of the past, there was excess runway available to complete the stop, but the premature relaxation of the stopping effort contributed to an overrun.

An additional consideration in completing a successful RTO is that the crew should assess the condition of the airplane after it comes to a stop. If there is evidence of a fire or other significant hazard to the passengers, an evacuation on the runway is definitely preferable to “clearing the active.” Every second counts in an actual emergency evacuation. In at least one RTO accident, many of the fatalities were caused by delaying the evacuation until the aircraft was clear of the runway.

\(^8\) Takeoff Safety Training Aid Human Performance Study, Appendix 4-E
4.3.6.6 Antiskid Inoperative Brake
Application

Antiskid inoperative dispatches represent a special case for brake application techniques. In this situation the pilot executing the RTO should apply steady moderate pedal pressure consistent, in his judgment, with runway conditions, airplane dispatch weight and the available runway length. Full brake pressure should not be applied with the antiskid system inoperative due to the risk of tire failure. To minimize the possibility of skidding a tire, which can lead to a blowout, the speedbrakes should be deployed before brakes are applied. This provides the highest possible wheel loads to keep the wheels rotating with the forward motion of the airplane.

4.3.6.7 RTO Autobrakes

Autobrake system functions and crew actions to initiate these functions vary from one airplane model to another. For example, some systems include automatic spoiler extension, others do not. Therefore, training in use of the system must be tailored to the particular system installed. The following discussion illustrates the general intent of autobrake systems.

Brake application is an immediate pilot action when initiating an RTO, and this application should be of maximum effort. An automatic brake application system called “RTO AUTO-BRAKES” is being installed on more and more airplanes today to insure that this critical step is performed as rapidly as possible when an RTO is initiated. This system is designed to automatically apply maximum brake pressure if during the takeoff roll, all of the thrust levers are retarded to idle, and the aircraft speed is above a specified value (usually 85-90 knots). RTO Autobrakes, therefore, achieve the same airplane stopping performance as a proper, manual application of full foot pedal braking. No time delays are built in to the RTO autobrakes such as are used in some landing autobrake settings.

The use of “RTO AUTOBRAKES” eliminates any delay in brake application and assures that maximum effort braking is applied promptly. Possible application delays arising from distractions due to directional control requirements in crosswinds, or application of less than maximum brake force, are completely eliminated. The results of the Takeoff Safety Training Aid Human Performance Study also suggest that, on the average, those RTO’s performed with RTO autobrakes ARMED resulted in more runway distance remaining after the stop than did the RTO’s performed using manual braking only. This result is more significant because few pilots left the autobrakes engaged for more than a few seconds before overriding them and applying full manual braking. The difference in stopping performance is attributed to the first few seconds of high deceleration with the autobrakes at full pressure.

When the RTO autobrakes are ARMED for takeoff, the pilot not flying must monitor the system and advise the pilot flying if a DISARM condition occurs. The pilot flying should also monitor the deceleration of the airplane for acceptability and be prepared to apply manual braking if required or, the pilot performing the reject procedure should apply maximum manual braking during the RTO. In this latter case, arming the RTO autobrake function only serves as a backup if for some reason manual braking is not applied.

The brake pedal forces required to disarm the autobrakes may vary significantly between the landing autobrake settings and the RTO autobrake setting of any given airplane, between one airplane model and another of the same manufacturer, as well as between the various manufacturers airplanes. It is not surprising that this point is not fully understood throughout the pilot community. It is important that pilot’s be made aware of how the details of any particular airplane’s autobrake system might affect RTO performance. For this reason, Appendix 4-C has been included to give the brake pedal forces required to disarm the autobrakes.

9 Takeoff Safety Training Aid Human Performance Study, Appendix 4-E
4.3.6.8 Reduced \( V_1 \) Techniques

When the actual airplane weight is less than the Field Length Limit Weight, there is more runway available than is required by the regulations to perform the takeoff. As was discussed in Section 4.3.4.2, \( V_1 \) can be chosen from a range of permissible speeds between the minimum \( V_1 \) and the maximum \( V_1 \). The minimum \( V_1 \) speed still satisfies the continued takeoff criteria, the maximum \( V_1 \) speed meets the rejected takeoff requirements, and any value of \( V_1 \) chosen between these two limit speeds would actually provide performance in excess of that specified by the continued or rejected takeoff criteria. An example would be if the \( V_1 \) speed is determined in the usual manner from simplified presentations in the airplane operating manual, Quick Reference Handbook (QRH), or most onboard computer systems. This speed is typically a maximum \( V_1 \) which means the actual accelerate-stop and accelerate-go distances will be equal to each other but less than the actual runway available. This is pictured in Figure 27.

If \( V_1 \) were reduced to a speed below the QRH value, an additional surplus of accelerate-stop distance is available. However, the lower the \( V_1 \) speed, the greater the spread between \( V_1 \) and \( V_2 \) and the greater the distance required to accelerate (with one-engine out) to the takeoff safety speed, \( V_2 \). This added engine-out acceleration requirement increases the accelerate-go distance. In fact, it may be possible to reduce \( V_1 \) to the minimum \( V_1 \), so that the accelerate-go distance exactly matches the runway available, as shown in the lower portion of Figure 27. The resulting lower \( V_1 \) must be checked to insure that it conforms to the \( V_{mcg} \) limit criteria for that aircraft.

If the \( V_1 \) speed were chosen to be less than the balanced \( V_1 \) but greater than the minimum \( V_1 \), additional distance margins would exist for both the continued and rejected takeoff conditions. Any \( V_1 \) speed that meets this criteria is referred to as a "reduced \( V_1 \) speed" in the remainder of this discussion, and any method used by an operator to determine reduced \( V_1 \) speeds is referred to as a "reduced \( V_1 \) policy".

Initiating a reduced \( V_1 \) policy will require additional procedural and performance information to be disseminated by the operator.
The basic information required to determine a reduced $V_1$ speed is currently published in each Airplane Flight Manual. Airline performance engineers can readily establish some simple and conservative delta $V_1$/excess weight trades for in-service use. For example, one operator has determined that for its area of operation, it is conservative to reduce $V_1$ by one knot for each 1000 lbs that actual takeoff weight is below the allowable runway weight on one aircraft model in their fleet. A $V_1$ reduction of one knot per 2000 lbs is used for a different model aircraft. Note, these example trade values are only appropriate for their particular airframe-engine combinations and area of operation. It is cautioned that a reduced $V_1$ technique such as this should not be used by the flight crew unless an appropriate delta $V_1$/weight trade has been established by the operator.

As was seen in Section 4.3.5.7, when the actual weight of the airplane is less than the Field Length Limit Weight, the use of the Assumed Temperature Method to reduce takeoff thrust results in margins in both the Go and Stop distances required.

A reduced $V_1$ policy can also be effectively used in combination with the Assumed Temperature Method of reduced thrust, thereby maximizing both engine life and RTO stopping margins. An example of this procedure is shown in Figure 28 for a typical large four-engine jet transport.

---

**Figure 28**

Combining reduced thrust and reduced $V_1$ to increase stopping margins

---

**Table 4.48**

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<thead>
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<th>ELEVATION 0 FT</th>
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<tr>
<td>FLAPS 20</td>
<td>JTD-7 ENGINES/WET</td>
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<tr>
<td>A/C ON</td>
<td>NORMAL V1</td>
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<tr>
<td>DRY RUNWAY</td>
<td>ZERO WIND</td>
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<th>CLIMB WEIGHT LIMIT</th>
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<th>RUNWAY 26R</th>
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<td>WEIGHT LIMIT</td>
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<td>7032F</td>
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<tr>
<td>7302F</td>
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<tr>
<td>7365F</td>
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**Table 4.48**

| MAXIMUM BRAKE RELEASE WT. MUST NOT EXCEED STRUCTURAL LIMIT OF 800, 000 LBS |
| MINIMUM FLAP RETRACTION HEIGHT IS 400 FT |

LIMITE CODE IS P=FIELD, T = TIRE, B= BRAKE ENERGY, V=VMCG, **=OBSTACLE |
RUNWAY 26L IS 10100 FT LONG WITH 0 FT CLEARWAY 0 FT STOPWAY 0A SLOPE |
RUNWAY 26R IS 11000 FT LONG WITH 0 FT CLEARWAY 0 FT STOPWAY 0A SLOPE |
OBSTACLES CONSIDERED ARE (FROM LIFTOFF END OF RUNWAY, HT/DIST IN FT/FT): |
RUNWAY HT DIST |
| 26L | NONE |
| 26R | NONE |
Recalling the reduced thrust example of section 4.3.5.7, if the actual airplane weight was 717,500 lbs and the actual OAT was 16 Deg C, an assumed temperature takeoff using thrust calculated for 40 Deg C could be made from a 10,100 ft runway. For this example, both the accelerate-stop and accelerate-go actual distances were 750 ft less than would be calculated from the AFM.

But what if a 1000 ft. longer runway was available for this takeoff? In this example, the original runway will be referred to as Runway 26L and the longer runway is Runway 26R. As shown in Figure 28, The Field Length Limit -Weight for Runway 26R at 40 Deg C. is 26,100 lbs higher than for Runway 26L. This excess weight capability could be used to further reduce the takeoff thrust setting, however, in this example, the use of a higher assumed temperature is not possible because the Climb Limit (714,400 lbs) is less than the actual weight (717,500 lbs) for temperatures above 40 Deg C. Since the airplane's climb gradient is not affected by the value of V1 used, it is now possible to utilize at least a portion of the 1000 ft of excess runway to accelerate to V2 and climb to 35 ft by reducing the V1 speed. Using a previously established and conservative delta V1/excess weight trade of 1 knot per 2000 lbs, V1 could be reduced by 13 knots. With this lower value of V1, the accelerate-stop distance required is decreased by 2,130 ft. At the same time, the required accelerate-go distance is increased by 380 ft.

Taking into account the possible additional distance margins resulting from the use of the longer runway (1000 ft), engine-out reverse thrust (270 ft), Assumed Temperature Method reduced thrust (750 ft), and reduced V1, the total additional runway margins for this example takeoff situation are shown in Figure 29. The data in Appendix 4-H provides additional model specific examples of the use of Assumed Temperature Method reduced thrust and a reduced V1 policy.

<table>
<thead>
<tr>
<th>Source</th>
<th>Takeoff Distance (TOD)</th>
<th>Accelerate-Stop Distance (ASD)</th>
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</thead>
<tbody>
<tr>
<td>Runway 26R</td>
<td>1000 ft.</td>
<td>1000 ft.</td>
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<tr>
<td>Reverse thrust</td>
<td>- -</td>
<td>270 ft.</td>
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<tr>
<td>Reduced thrust</td>
<td>750 ft.</td>
<td>750 ft.</td>
</tr>
<tr>
<td>Reduced V1</td>
<td>- 380 ft.</td>
<td>2130 ft.</td>
</tr>
<tr>
<td>TOTAL MARGIN</td>
<td>1370 ft.</td>
<td>4150 ft.</td>
</tr>
</tbody>
</table>

Figure 29
Operational Margins associated with reverse thrust, reduced thrust, and Reduced V1
4.3.6.9 The $V_1$ Call

One important factor in avoiding RTO overrun accidents is for the crew to recognize reaching $V_1$ when the airplane does, in fact, reach $V_1$ — not after. The airplane’s stopping performance cannot match that specified in the Airplane Flight Manual if the assumptions used to derive that performance are violated — knowingly or inadvertently. Operationally, careful attention to procedures and teamwork are required to match the human performance recognized by the AFM.

Basic operating procedures call for the pilot flying the airplane to include airspeed in his instrument scan during the takeoff ground roll. Hence he is always aware of the approximate speed. The pilot not flying monitors airspeed in more detail and calls-out “Vee-One” as a confirmation of reaching this critical point in the acceleration.

The pilot flying cannot react properly to $V_1$ unless the $V_1$ call is made in a timely, crisp, and audible manner. One method of accomplishing this by a major U.S. carrier is their adoption of a policy of “completing the $V_1$ callout by the time the airplane reaches $V_1$.” This is an excellent example of the way airlines are implementing procedures to improve RTO safety. It is a good procedure and it should preclude a situation where the “No Go” decision is inadvertently made after $V_1$. However, the success of such a policy in reducing RTO’s after $V_1$, without unduly compromising the continued takeoff safety margins, hinges on the line pilot’s understanding of the specific airplane model’s performance limitations and capabilities.

Another proposal for calling $V_1$ is to use a call such as “Approaching $V_1$” with the $V_1$ portion occurring as the airspeed reaches $V_1$. Either of these proposals accomplish the task of advising the flying pilot that the airplane is close to the speed where an RTO for all but the most serious failures is not recommended.

A frequently cited factor in RTO accidents that occurred when the First Officer was flying, is the lack of any airspeed calls by the Captain during the takeoff. This type of poor crew coordination may be overcome in future airplane designs by the use of automated “$V_1$” and “Engine Failure” calls which will eliminate much of the variability experienced in today’s operations. Even with an automated call system however, an “Approaching” call by the non-flying pilot would still seem to be an appropriate method of ensuring airspeed situational awareness for both pilots.

4.3.6.10 Crew Preparedness

Important crew factors directly related to eliminating RTO overrun accidents and incidents are:

- Brief those physical conditions which might affect an RTO that are unique to each specific takeoff.

- Both pilots must be sure to position their seats and rudder pedals so that maximum brake pressure can be applied.

- Both pilots should maintain situational awareness of the proximity to $V_1$.

- Use standard callouts during the takeoff.

- Transition quickly to the stopping configuration.

- Don’t change your mind. If you have begun an RTO, stop. If you have reached $V_1$, go, unless the pilot has reason to conclude that the airplane is unsafe or unable to fly.

- Use maximum effort brake application.

- Assure deployment of speedbrakes.

- Use maximum reverse thrust allowable.

The accident records frequently show that slow or incomplete crew action was the cause of, or contributed to, an RTO overrun event. The crew must be prepared to make the Go/No Go decision on every takeoff. If a “No Go” decision is made, the crew must quickly use all of the stopping capability available. Too often, the records show uncertainty in the decision process and a lack of completeness in the procedures. Be ready to decide and be ready to act.
4.4 Crew Resource Management

Crew Resource Management (CRM) is a term that can mean many things. In this context it is simply intended to encompass the factors associated with having the crew members work effectively together to make optimal Go/No Go decisions and effectively accomplish related procedures. It is recognized that the content of a CRM discussion on Go/No Go decisions must reflect the needs and culture of each individual operator. Therefore, the material contained in this section is provided only as an example of the type of CRM information which could be provided to the line pilot.

4.4.1 CRM and the RTO

Effective CRM can improve crew performance and in particular, decision making during takeoff. Often, Go/No Go decisions must be made “instantaneously” and as a result, the significance of CRM is not readily apparent. However, the fact that a critical decision must be made and implemented using rapidly changing, often incomplete information in a dynamic environment in which the time available decreases as the criticality of the decision increases, is reason for effective CRM. Some aspects of CRM are especially important with respect to the Go/No Go decision.

4.4.2 The Takeoff Briefing

Crew members must know what is expected of them and from others. For optimum crew effectiveness, they should share a common perception - - a mental image - - of what is happening and what is planned. This common perception involves a number of CRM areas: communications, situational awareness, workload distribution, cross-checking and monitoring.

A variety of means are used to achieve this common perception. This begins with airline standard operating policies (SOP’s) that clearly define captain and first officer as well as pilot flying and pilot not flying responsibilities and duties. Training reinforces the crew’s knowledge and skill, while standardization insures acceptable, consistent performance, across all fleets and cultures within an airline.

A takeoff briefing is another means of improving the crew’s awareness, knowledge, and team effectiveness; especially when special circumstances or conditions exist. The briefing is not necessarily a one-way process. In fact, asking for clarification or confirmation is an excellent way to ensure mutual understanding when required. A simple, “standard procedures” takeoff briefing might be improved by adding, “I’m not perfect, so back me up on the speedbrakes and my use of the RTO autobrakes” or, “If we’re not sure of an engine failure 5 knots before V1, we’ll continue the takeoff and I’ll state ‘CONTINUE TAKEOFF”’. These briefings can improve team effectiveness and understanding of the Go/No Go decision planning and communications to be used. Such additions might be especially appropriate on the first segment of a flight with a relatively new first officer or a crew’s first flight of the month.

A review of actions for a blown tire, high speed configuration warning, or transfer of control are examples of what might be appropriate for before takeoff (or before engine start) review. Such a briefing should address items that could affect this takeoff, such as runway contamination, hazardous terrain or special departure procedures. The briefing should not be a meaningless repetition of known facts, but rather a tool for improving team performance, that addresses the specific factors appropriate to that takeoff.
4.4.3 Callouts

Meaningful communication, however brief, regarding a non-normal situation during takeoff and RTO can often mean the difference between success and disaster. For this reason, communications must be precise, effective, and efficient. Standard callouts contribute to improved situational awareness. These callouts, coupled with all crewmembers being aware of airspeed, maximize the opportunity for a common understanding of what actions are proper in the event of a non-normal situation. The crewmember noting a problem should communicate clearly and precisely without inferring things that may not be true. For example, the loss of fuel flow indication alone does not necessarily mean an engine failure. Use of standard terms and phraseology to describe the situation is essential. The pilot tasked to make the RTO decision should clearly announce this decision, whether it be to continue or reject.

4.4.4 The Use of All Crew Members

It's important to understand that all crewmembers on the flight deck play an important role in the Go/No Go decision and RTO maneuver. Company policies shape these roles, however, how the team is organized for each takeoff can make a difference in team performance. Knowing your own capabilities and that of the other crewmembers is part of situational awareness and should be used in planning for a given takeoff. Although it's "the first officer's leg", it might not be an effective plan to task an inexperienced first officer with a marginal weather takeoff when weight is also limited by field length. Consider the possibility of an RTO when assigning takeoff duties.

4.4.5 Summary

Each airline approaches CRM in a slightly different manner, but the goal of effective teamwork remains the same. This material is an example of the type of CRM information that could be used to promote a common perception of RTO problems and actions.
## Takeoff Safety Background Data

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