



National Transportation Safety Board

Crash During Test Flight
Gulfstream GVI (G650)
Roswell, NM
April 2, 2011

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Board Member

Boeing Test & Evaluation
Quarterly Safety Meeting
January 9, 2013

History of Flight

- April 2, 2011
- 0934 mountain daylight time
- Experimental Gulfstream G650
- Crashed during takeoff
- Roswell, New Mexico
- Two pilots and two flight test engineers fatally injured

History of Flight

- Planned one-engine-inoperative continued takeoff
- Flight crew tried to achieve takeoff safety speed (V_2)
- Stall occurred before stall warning system activated
- Right wing contacted runway

Airplane path



Right wing contact





Main landing gear

Concrete structure

ATC tower

Factors Leading to Accident

- Failed to fully investigate two previous uncommanded roll events
- Made persistent attempts to adjust pilot technique to achieve erroneously low V_2
- Used flawed assumption to determine takeoff speeds
- Overestimated in-ground-effect stall angle of attack
- Set stick shaker activation too high

Factors Leading to Accident

- Failed to establish adequate flight test operating procedures
- Did not adjust flight test schedule to account for program delays
- Failed to develop effective flight test safety management program

Broader Safety Issues

- Contradictory information about maximum lift coefficient in ground effect
- Effective flight test standard operating policies and procedures
- Flight-test specific safety management system guidance
- Coordination of high-risk test flights

Accident Flight 153

- Preflight briefing items included
 - Target pitch lowered from 10° to 9°
 - Pitch limit of 11°
- Test card did not specify how long pitch target applied or include pitch limit
- Test personnel had different understandings of target pitch and limit

Accident Flight 153

- Accident occurred on the 12th test run, which was flaps 10 one-engine-inoperative continued takeoff
- During previous 11 test runs, all target V_2 speeds were exceeded
- Takeoff rotation technique evolved to a continuously increasing pitch angle

Accident Flight 153

- No pause at 9° pitch target, and pitch rate slowed through 9°
- Slight roll to right began 2 seconds before liftoff
- Airplane stalled below predicted stall AOA and stick shaker activation setting
- Pilots had no warning before stall

Accident Flight 153

- PIC decreased pitch below stick shaker/PLI and applied corrective roll inputs
- Airplane right outboard wing remained stalled
- Stick shaker activated again, and PIC increased pitch and maintained full left control wheel and rudder
- Flight crew was unable to recover from stall or control right rolling moment

Gulfstream's Flight Test Risk Management Program

- Gulfstream had an FAA-accepted risk management process
- Overseen by flight test safety review board (SRB) co-chaired by director of flight test and vice president of flight operations
- SRB review and approval required before start of developmental flight testing
- Did not specify when SRB must be reconvened during developmental testing

Uncommanded Roll Events

- Two uncommanded roll events occurred before accident flight, in November 2010 and March 2011
- SRB not reconvened
- Testing should have stopped because uncommanded roll events were unexpected test result

Uncommanded Roll Events

- Flight 88, November 16, 2010: minimum unstick speed (V_{MU}) test
 - Flown by pilot-in-command (PIC) of accident flight
 - Flight crew recovered airplane
 - Testing not stopped
 - Attributed to over-rotation
 - Postaccident data review showed airplane stalled below predicted stall angle of attack

Uncommanded Roll Event (88)



Uncommanded Roll Events

- Flight 132, March 14, 2011: flaps 20, one-engine-inoperative test
 - Flown by second-in-command of accident flight
 - Flight crew recovered airplane
 - Testing not stopped
 - Attributed to “lateral-directional” event
 - Postaccident data review showed airplane stalled below predicted stall angle of attack

Uncommanded Roll Event (132)



Liftoff (09:33:50.6)



First Stick Shaker Activation (09:33:52.3)



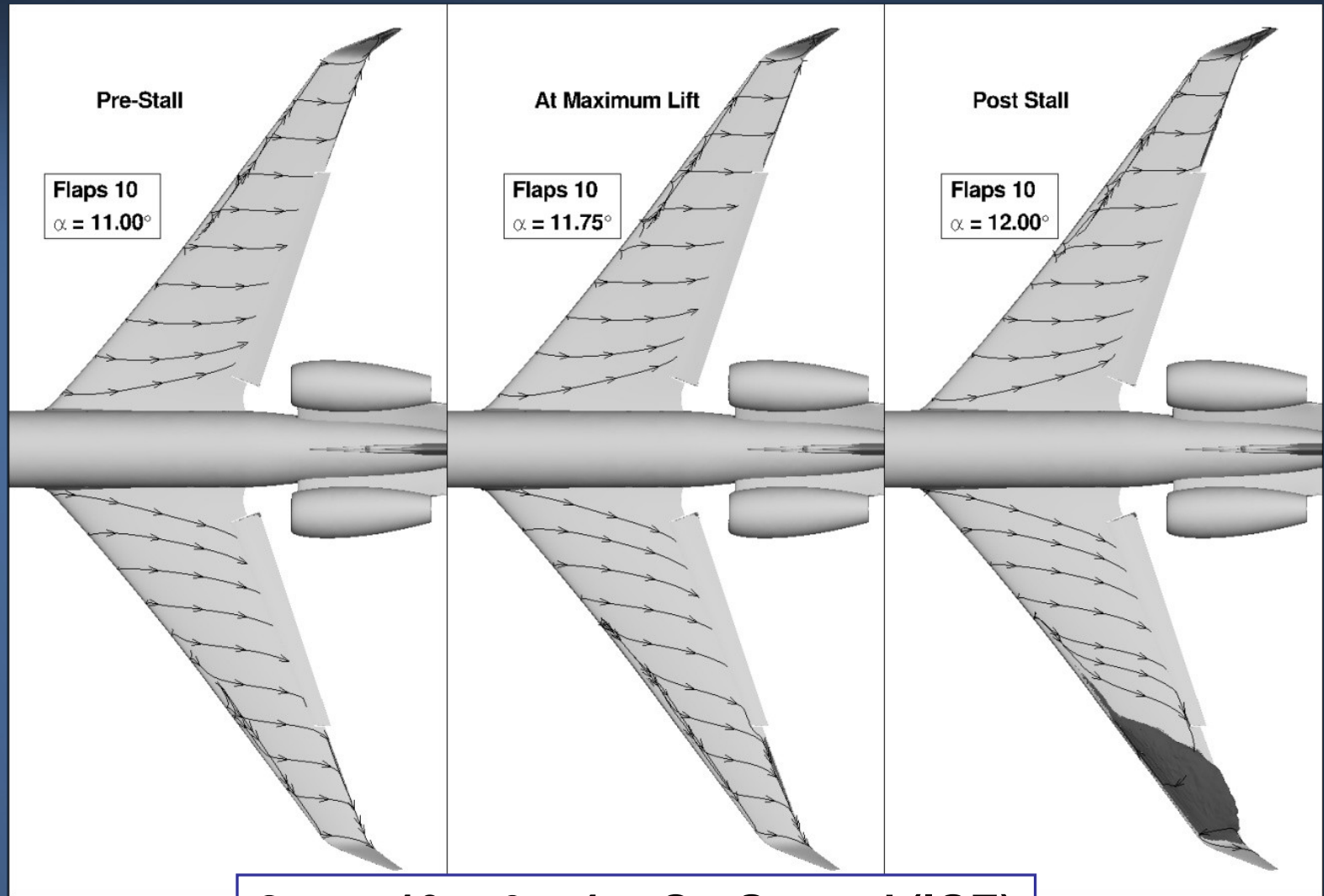
Second Stick Shaker Activation (09:33:53.6)



Airplane Departing Runway (09:33:54.7)

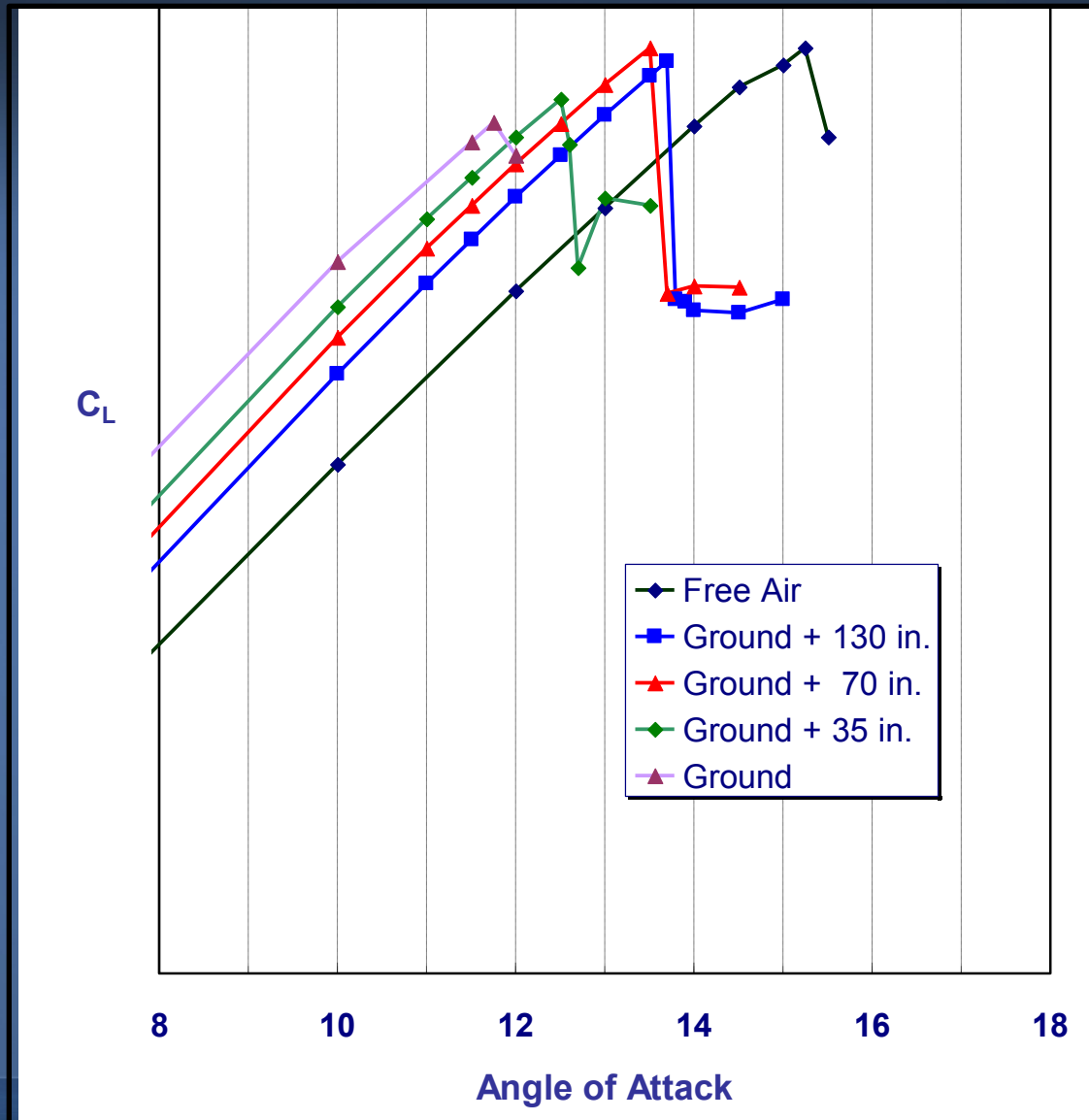


Gulfstream CFD Study Results

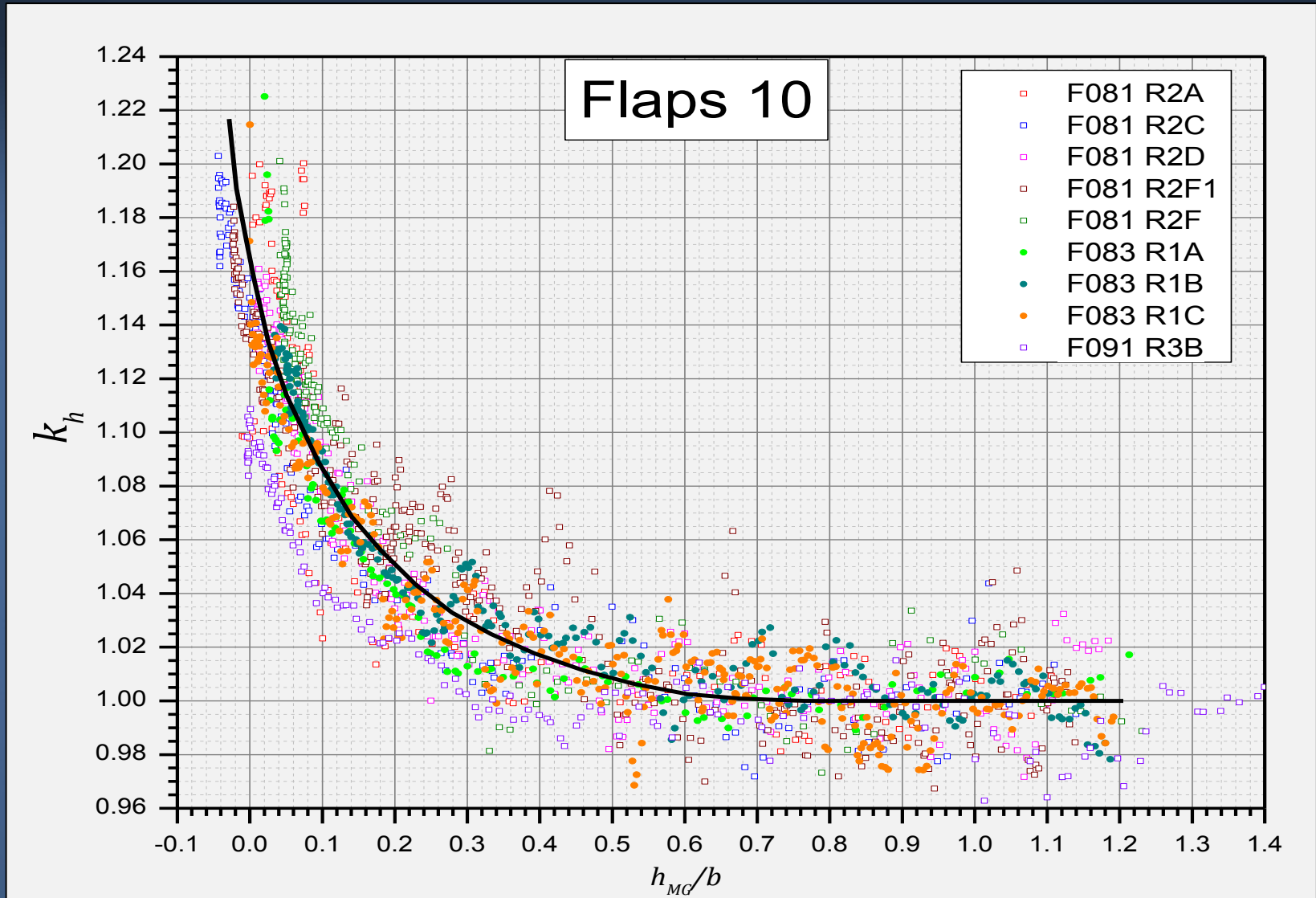


$\delta_{\text{Flap}} = 10^\circ : \beta = 4^\circ : \text{On Ground (IGE)}$

Gulfstream CFD Study Results

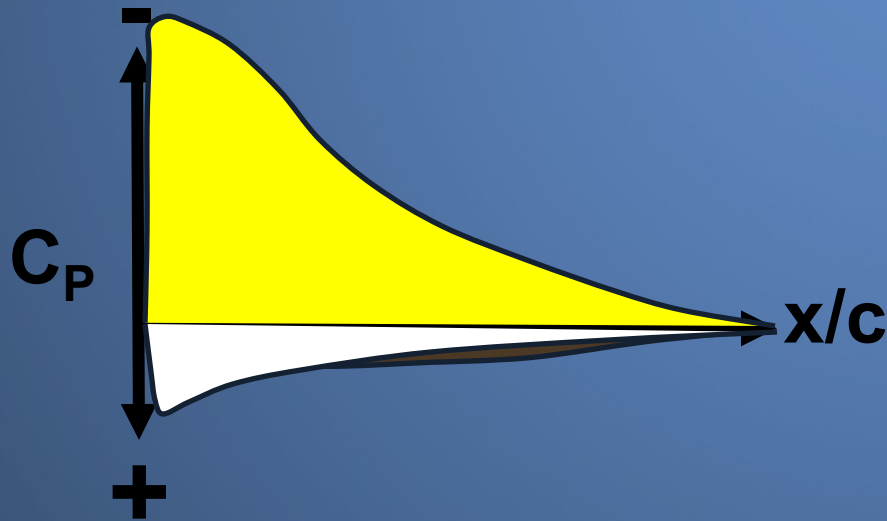
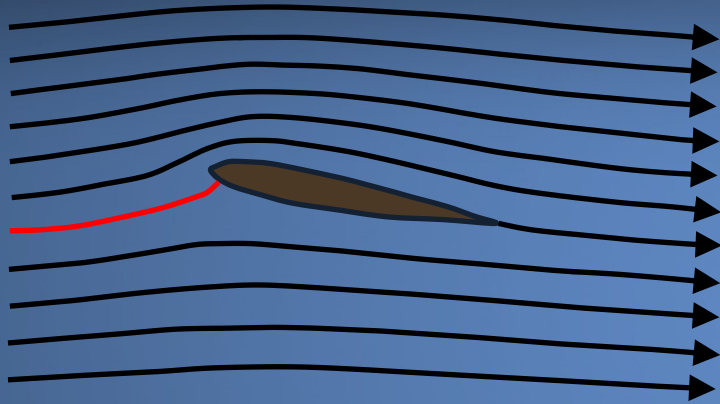


Decay of Ground Effect With Height

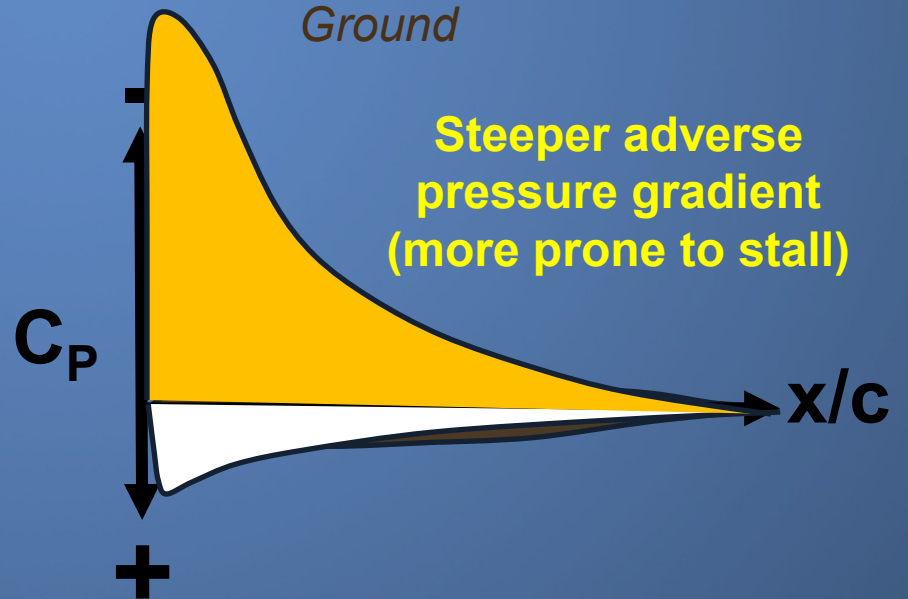
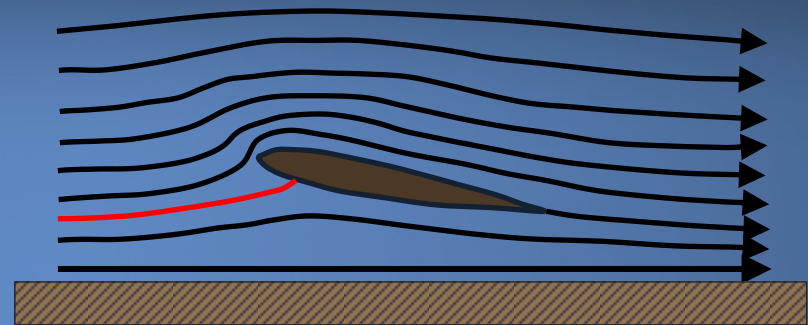


Mechanism of Reduced C_{Lmax} in Ground Effect

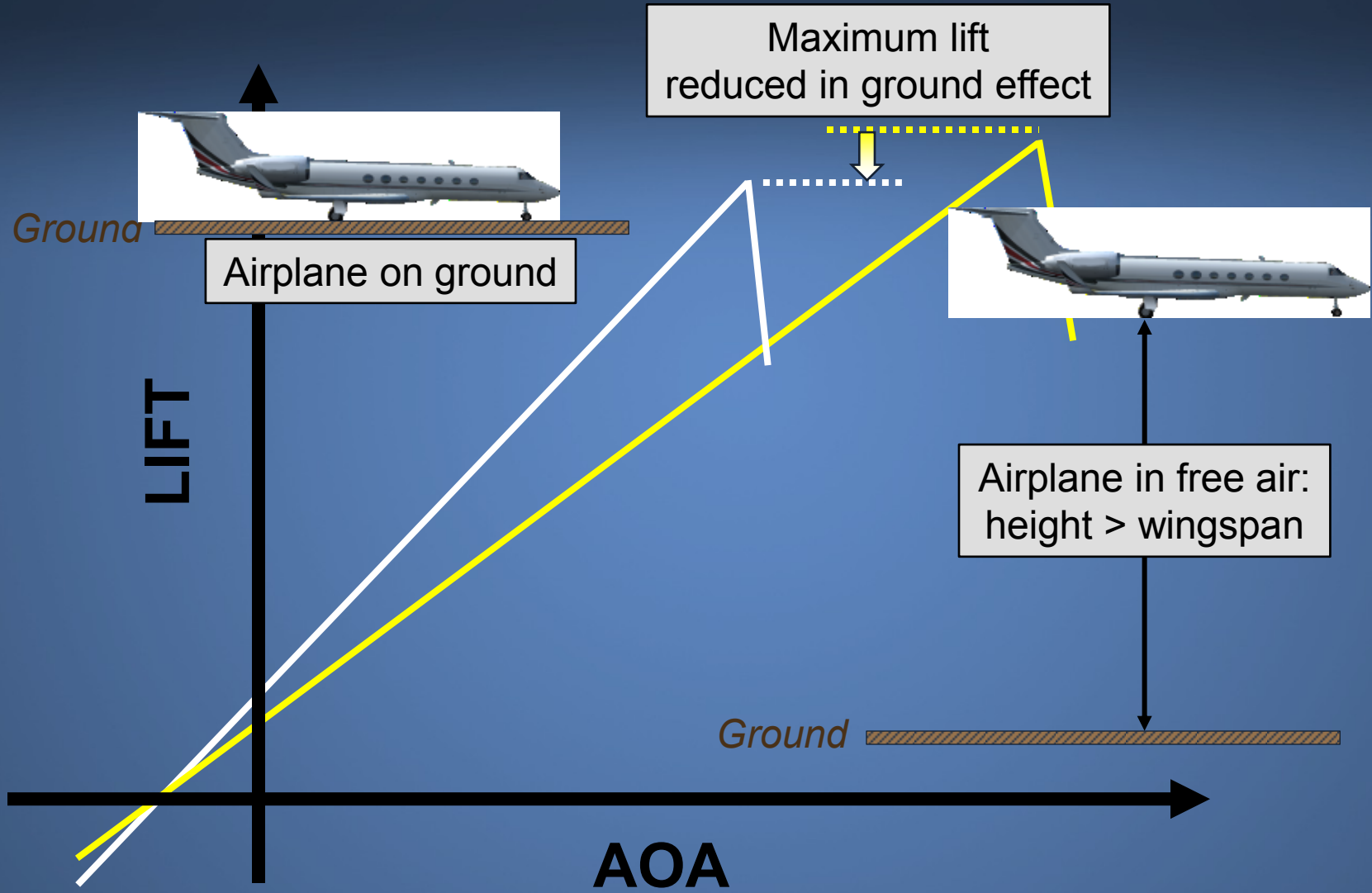
Airfoil in free air



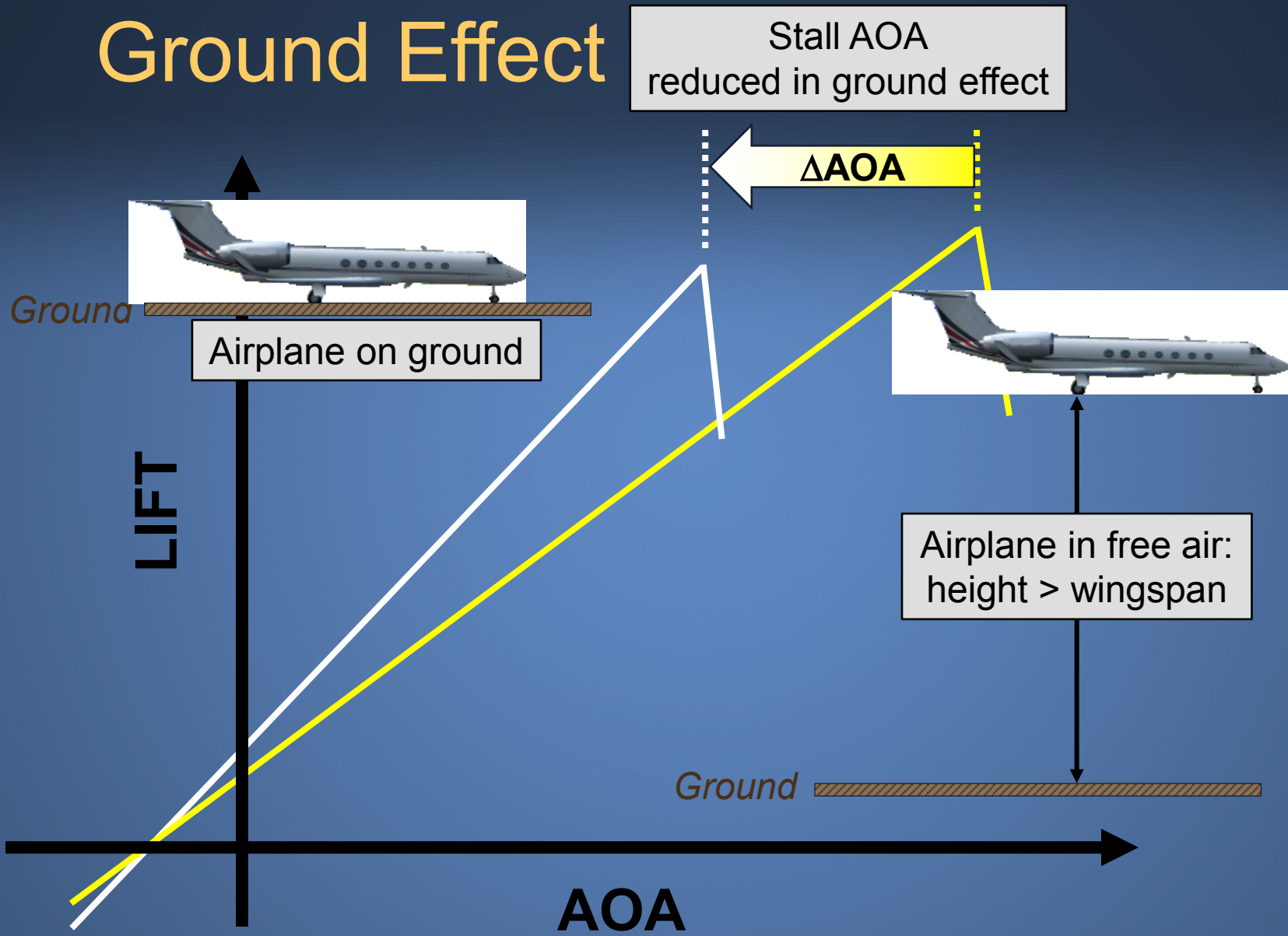
Airfoil in ground effect



Ground Effect

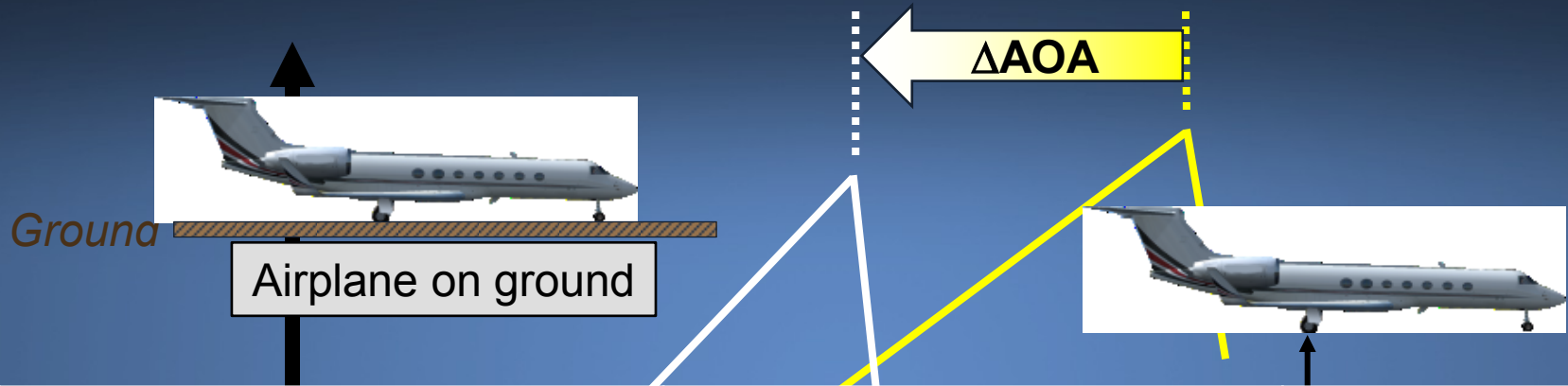


Ground Effect



Ground Effect

Stall AOA
reduced in ground effect



Estimated ΔAOA (from V_{MU} tests)	Actual ΔAOA (from postaccident CFD)	Difference
1.6°	3.25°	1.65°

RESULT: No warning before stall in ground effect

Missed opportunity: Actual ΔAOA indicated by two previous roll events

AOA

Takeoff Speeds

- Takeoff roll starts with airplane at rest



START

Runway

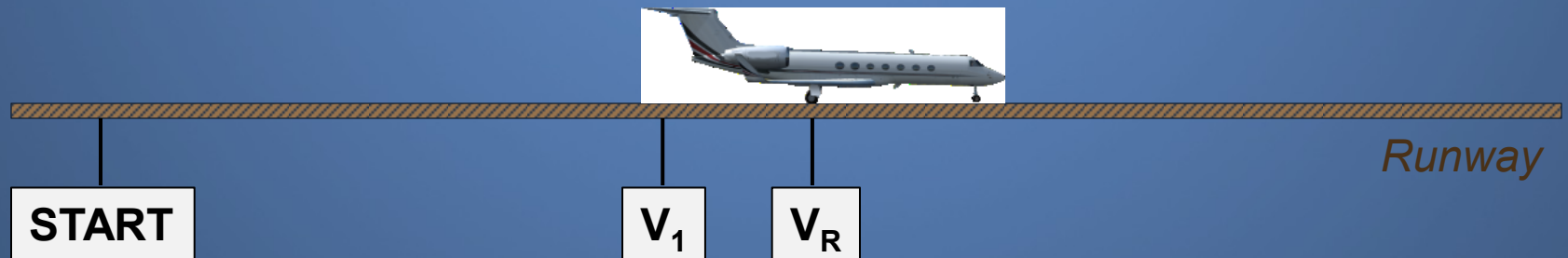
Takeoff Speeds

- The takeoff roll starts with the airplane at rest
- Decision speed (V_1): With a failed engine, distance to climb to 35 feet same as distance to stop



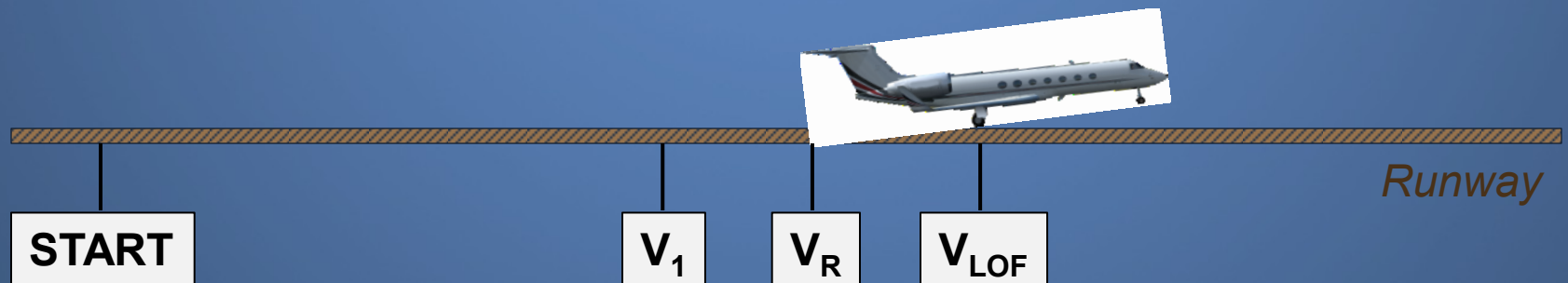
Takeoff Speeds

- Rotation speed (V_R): pilot pulls column to raise the nose for takeoff



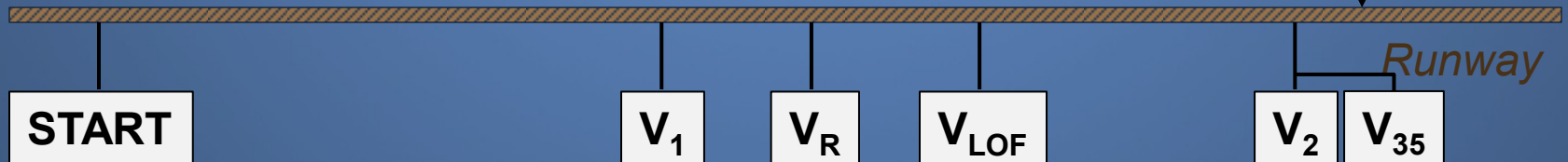
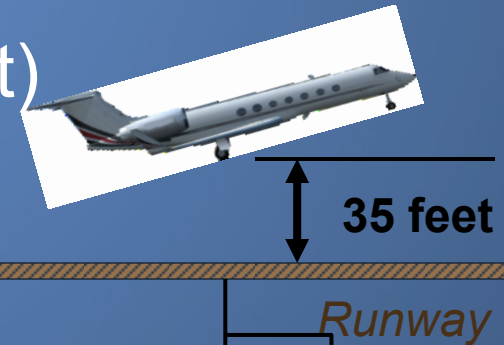
Takeoff Speeds

- Liftoff speed (V_{LOF}): main gear leaves runway



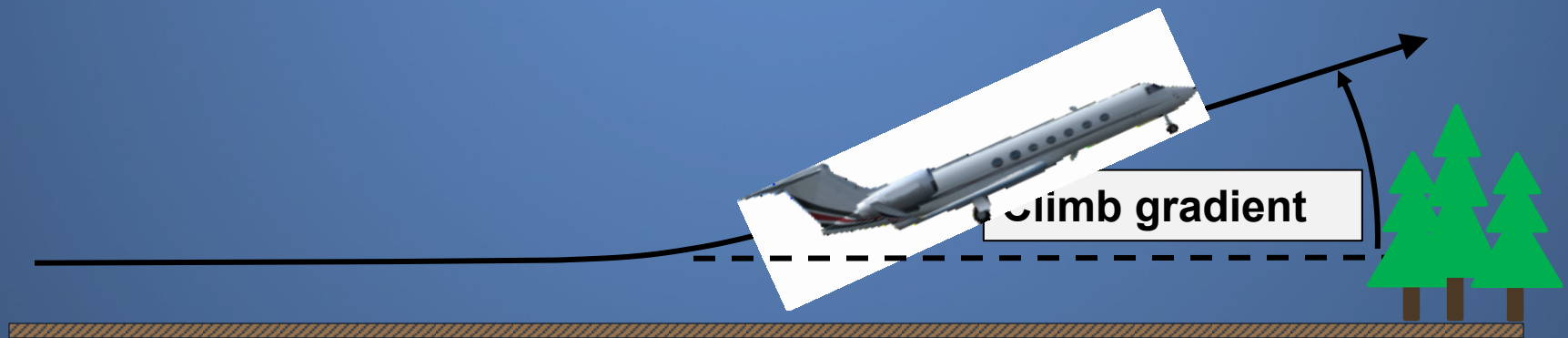
Takeoff Speeds

- Takeoff safety speed (V_2): target climb speed with a failed engine, to be achieved by 35 feet above ground level (agl)
- V_{35} : actual speed at 35 feet agl
- Test objective: $V_{35} = V_2$
- Test results: $V_{35} > V_2$ (overshoot)

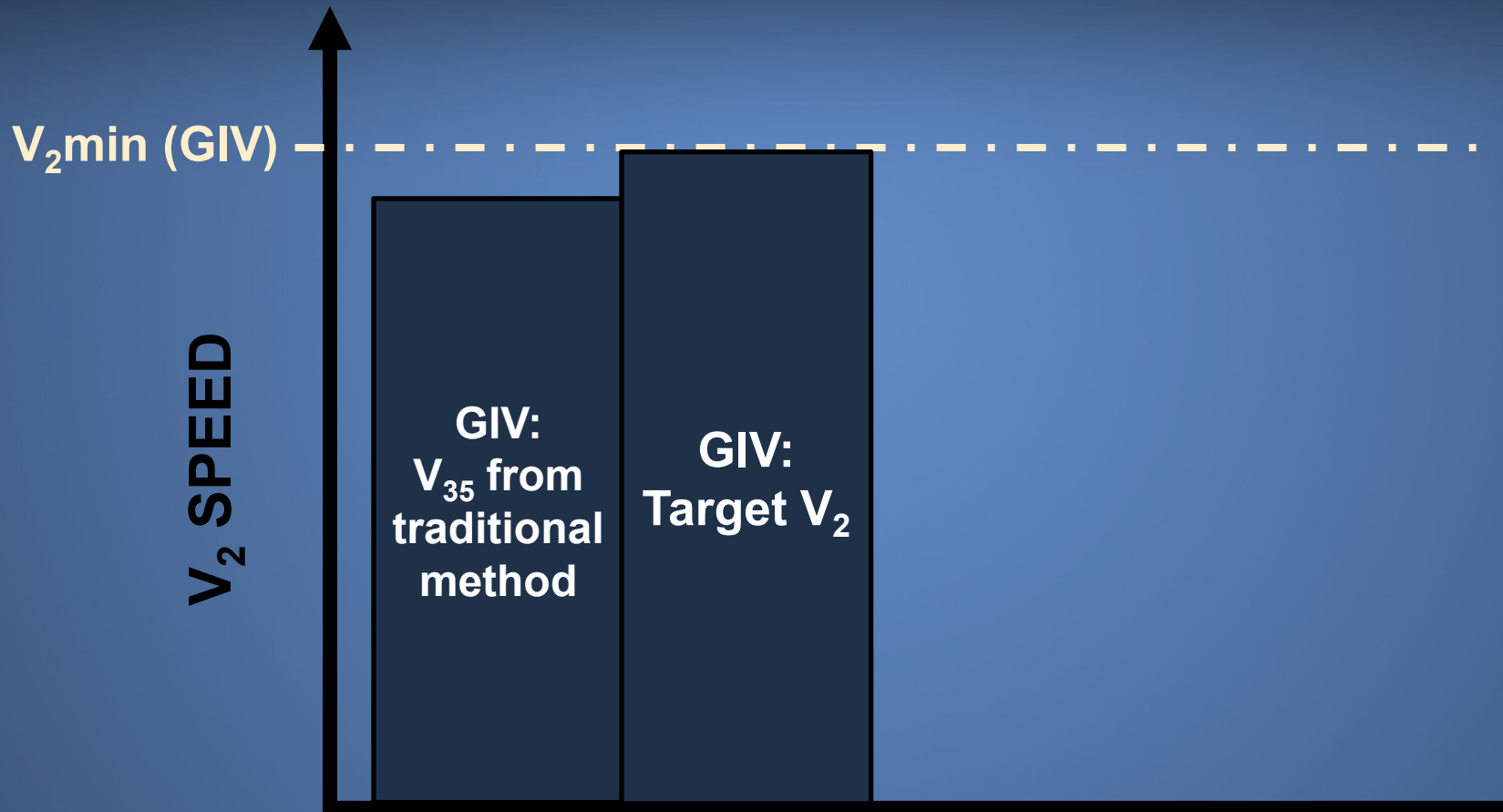


Takeoff Safety Speed (V_2)

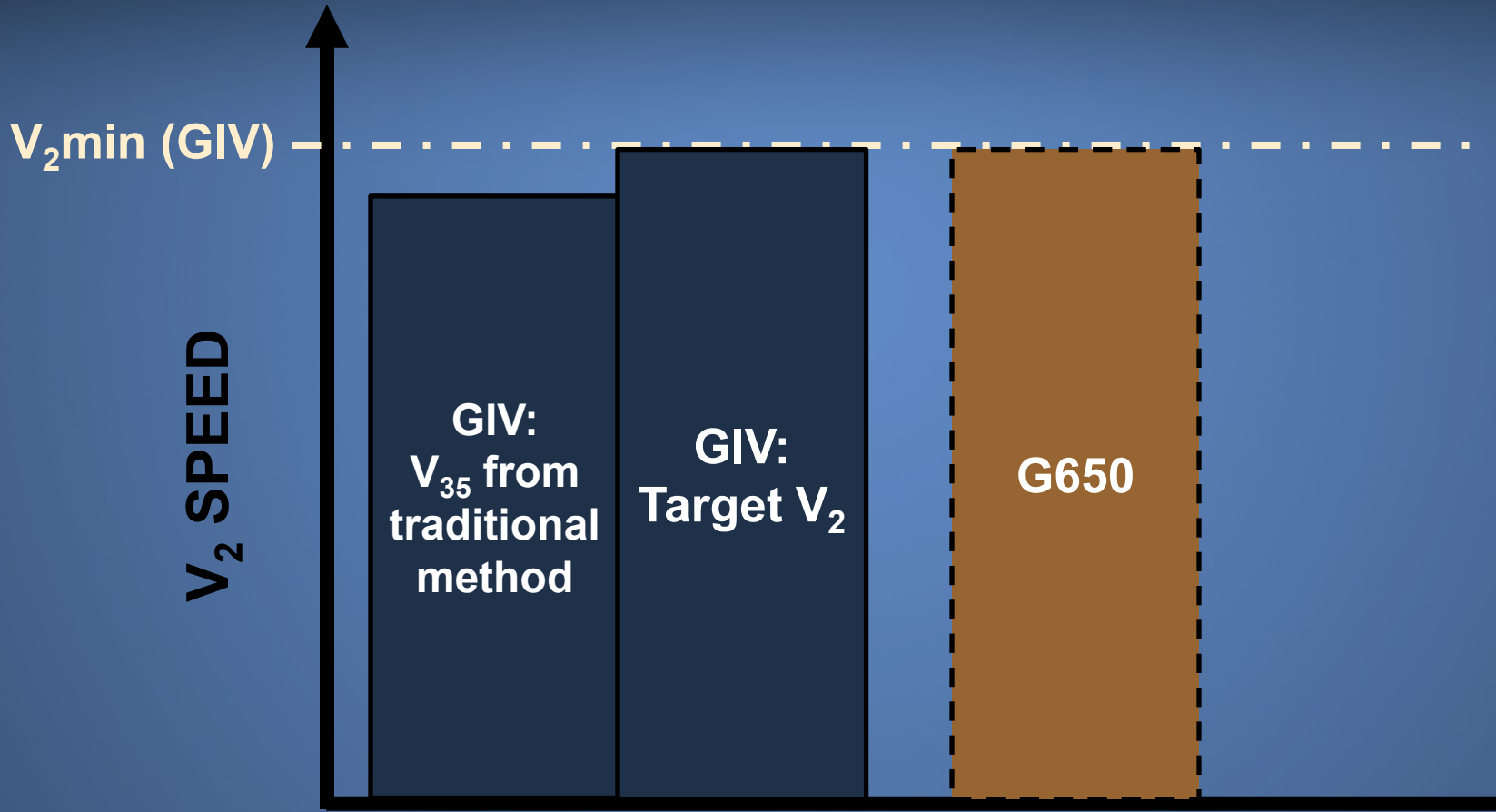
- V_2 requirements intended to ensure
 - Safe AOA margin from stall
 - Safe control of asymmetric thrust with one engine inoperative
 - Safe minimum climb gradient with one engine inoperative



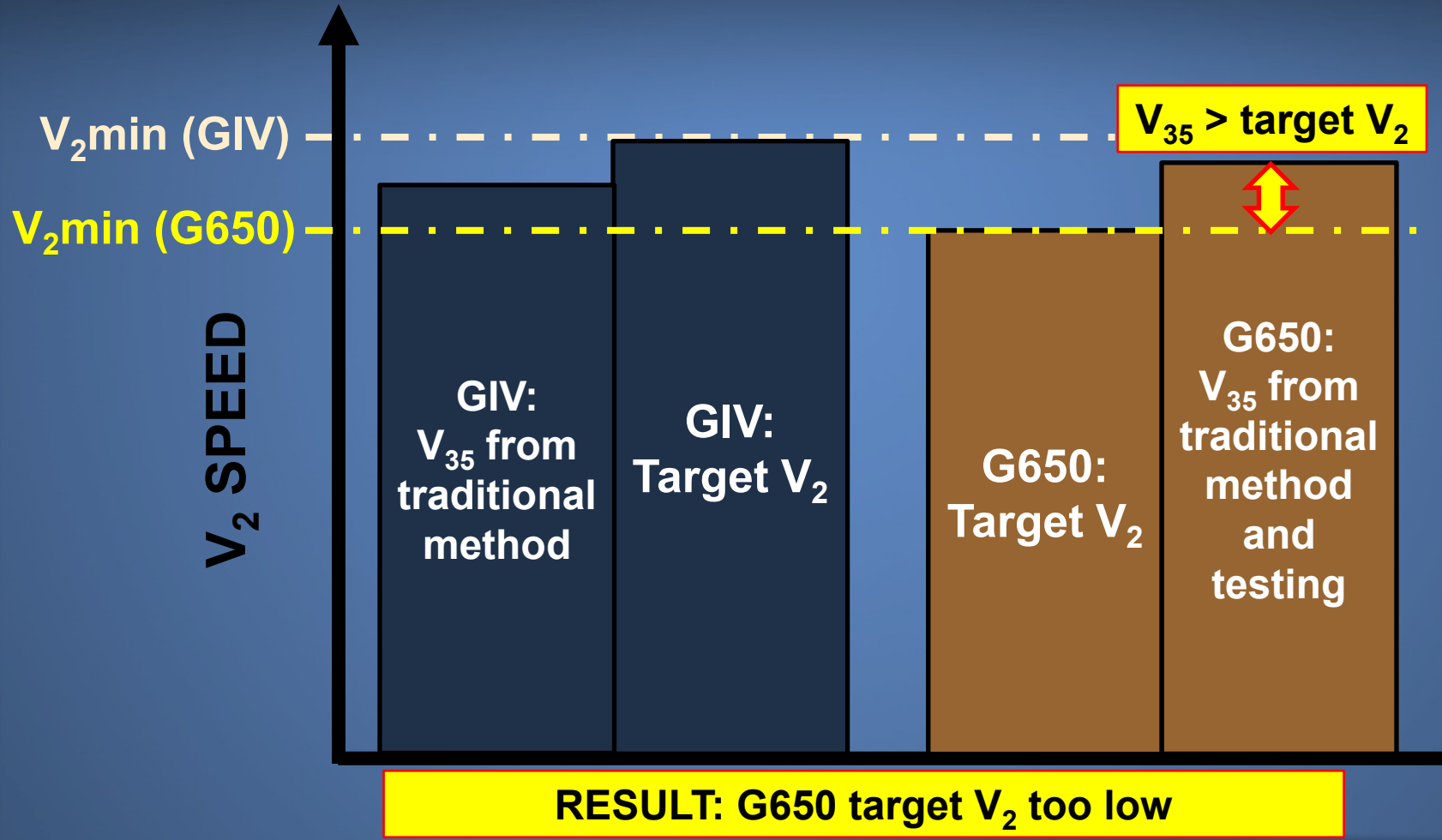
V₂ Development



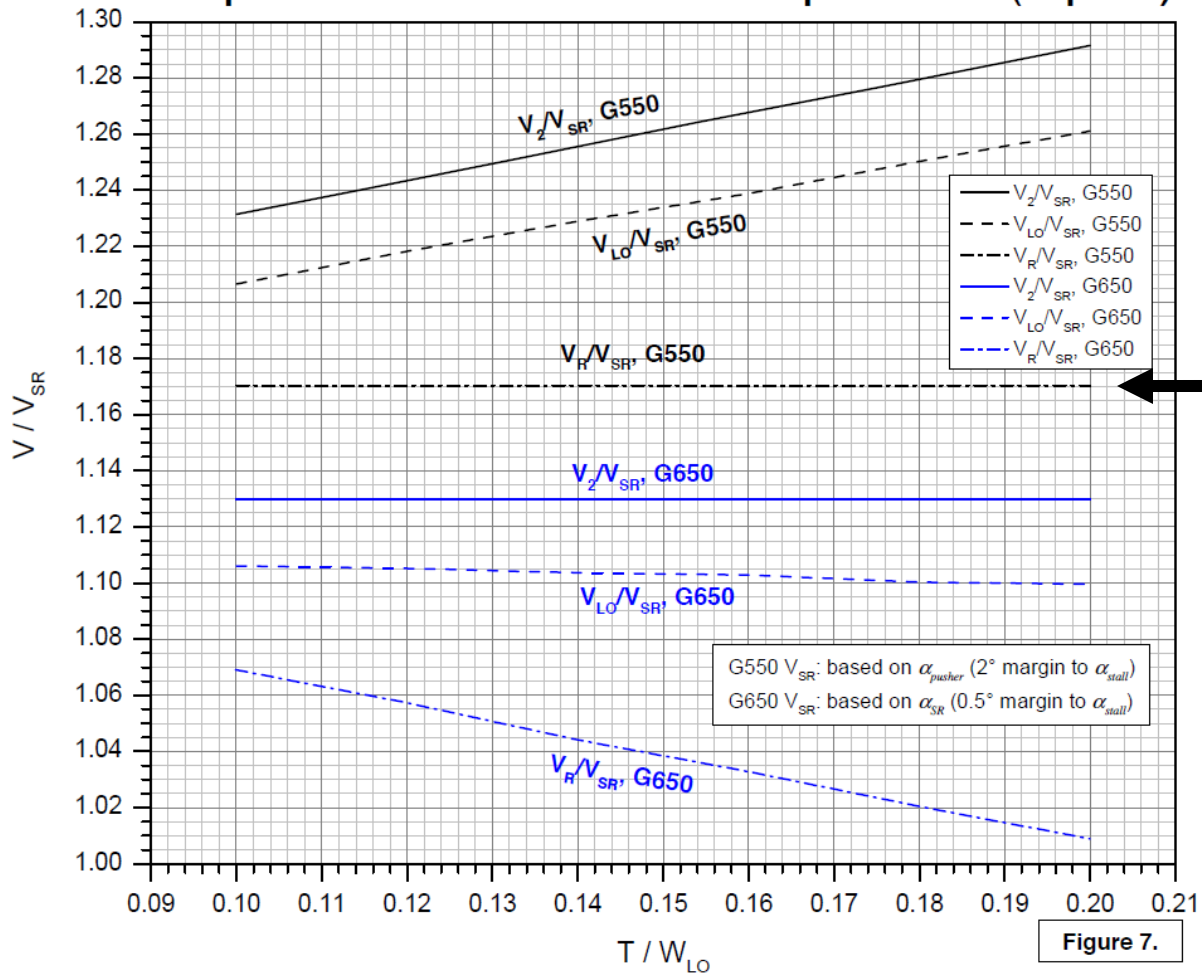
V₂ Development



V₂ Development



Comparison of G550 & G650 takeoff speed ratios (flaps 10)

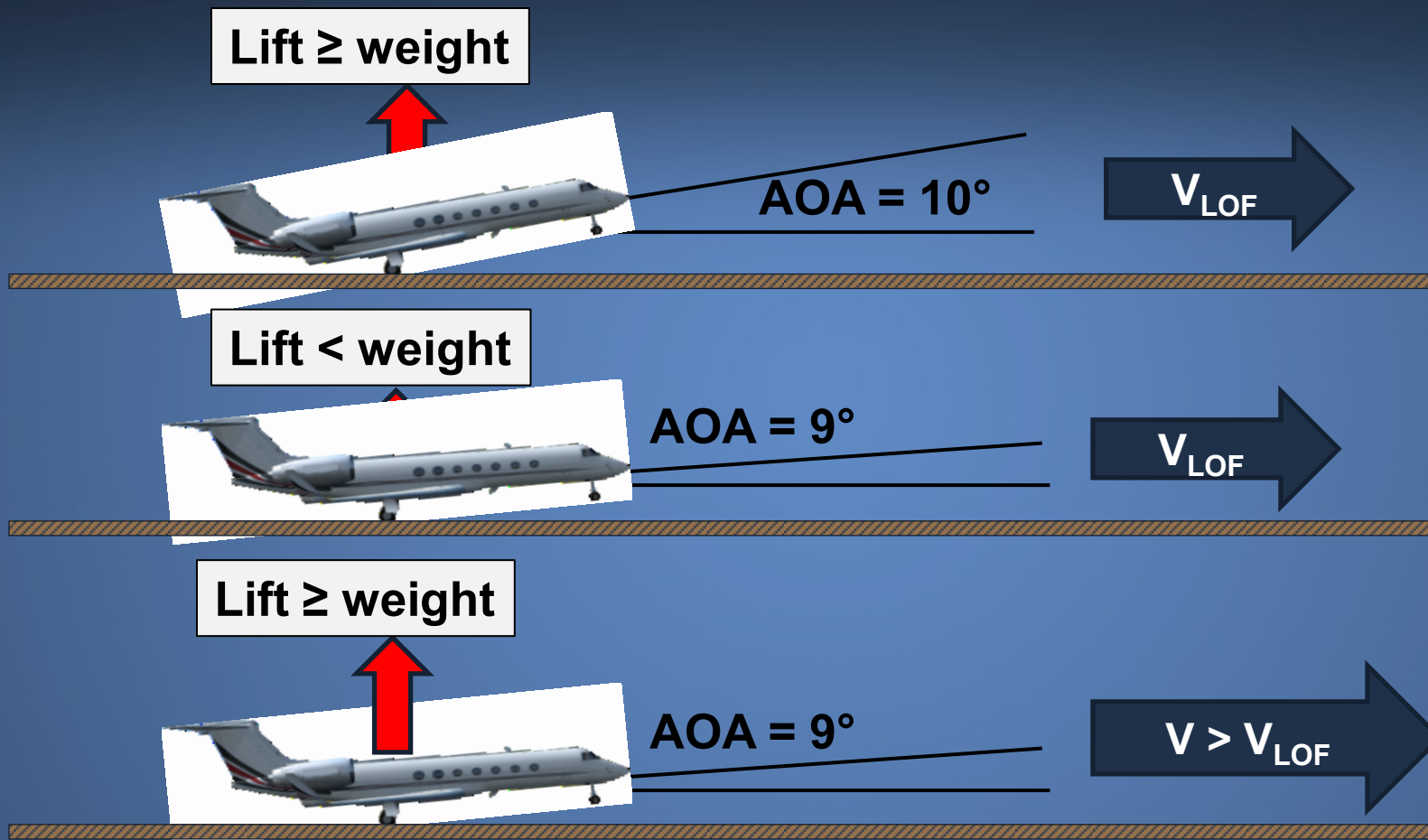


G550 ↑
G650 ↓

Tail Power Limited

G550 Decrements Applied to Lower G650 V2 Targets

Change in Flaps 10 Target Pitch Angle



Reduction in pitch without increase in speed exacerbated V_2 overshoots

V_2 and Takeoff Distance

- Takeoff distance increases with higher V_2
- Achieving target V_2 necessary to satisfy takeoff distance guarantee
- No analysis of physics of G650 rotation to validate speeds or determine root cause of overshoots

Takeoff Rotation Techniques

- Gulfstream attempted to solve V_2 overshoot problem through takeoff rotation technique
- Pitch attitude for climb at V_2 greater than target pitch for takeoff rotation
- V_{35} reduced by reducing time to achieve climb pitch attitude
 - Achieve target pitch sooner (high rotation rate)
 - Increase pitch above target sooner

Takeoff Rotation Techniques: Achieve Target Pitch Sooner

- Abrupt column pull with high force
- V_2 overshoots reduced but not eliminated
- Primary flight test engineer concerned that technique too difficult to be accepted by FAA
- On accident flight, PIC stated technique “doesn’t work”

Takeoff Rotation Techniques: Increase Pitch Above Target Sooner

- Less abrupt column pull with moderate force
- Reduced pauses at target pitch angle
- Increase in pitch to climb attitude became “almost...continuous”
- V_2 overshoots reduced but not eliminated
- Accident takeoff: AOA exceeded stall AOA in ground effect

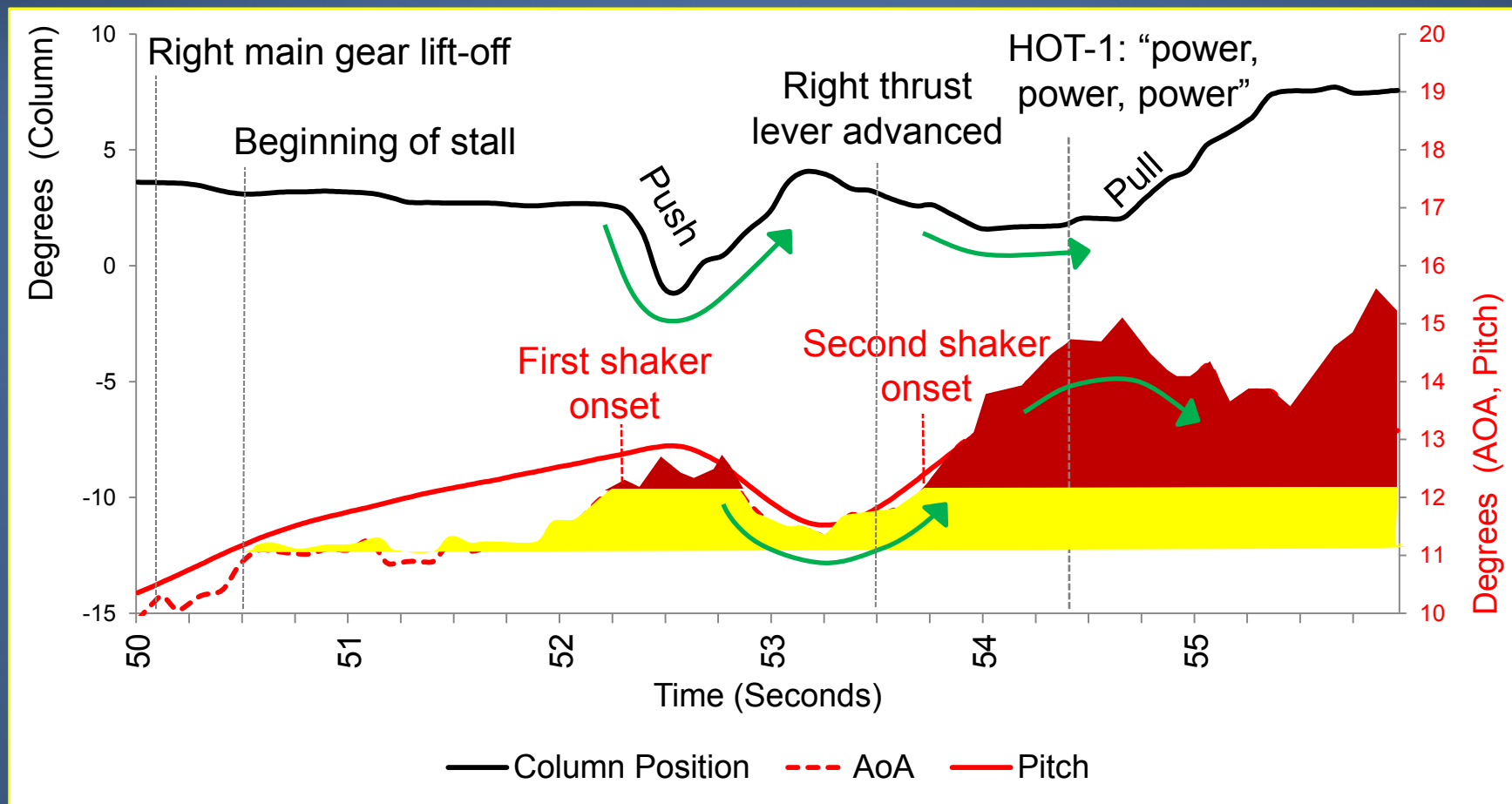
Takeoff Rotation Techniques: Summary

- Erroneously low target V_2 speeds resulted in overshoots
- Reduction of pitch target without increase in target speeds exacerbated V_2 overshoots
- V_2 overshoots threatened takeoff distance guarantee
- Pitch angle and AOA increased sooner in successive takeoffs to reduce V_2 overshoots

Takeoff Rotation Techniques: Summary

- Accident takeoff: AOA exceeded stall AOA in ground effect
- Asymmetrical stall resulted in uncontrollable rolling moment
- Estimate of stall AOA in ground effect too high
 - No stick shaker before stall
 - Actual stall AOA could have been determined from previous events

PIC Response to the Stall and Roll



Flight Crew Response to Stall and Roll

- PIC's column push after first stick shaker activation was appropriate
- Pitch was reduced below PLI, and stick shaker activation ceased
- Airplane remained in a stall that overpowered lateral controls
- PIC was likely confused by airplane's response

Flight Crew Response to Stall and Roll

- PIC's column pull after second stick shaker activation was inappropriate
- Airplane was departing runway
- Conflicting cues, stress, and time pressure likely influenced PIC's response
- Recovery after second stick shaker activation was highly unlikely

G650 Program Management

- Technical planning and oversight
- Program scheduling
- Safety risk management

G650 Program Management: Technical Planning and Oversight

- Company manual separated duties of test planning and conduct from analysis and reporting
- Duty separation intended to facilitate timely and accurate task completion
- Duties were combined during G650 field performance testing
- FTE1 did not finalize analysis of key data in time to facilitate refinement of takeoff speeds

G650 Program Management: Technical Planning and Oversight

- Inadequate control gates
- Inadequate validation processes
 - Independent reviews of speed calculations
 - Physics-based dynamic analysis/simulation

G650 Program Management: Technical Planning and Oversight

- Inadequate development and implementation of on-site team member roles
- During accident flight, FTE2's responsibilities were unclear
- No engineer was assigned responsibility to monitor safety-related parameters compared with briefed limits

G650 Program Management: Program Schedule

- Ambitious schedule
- Frequent delays
- Unachievable deadlines
- Schedule pressure can lead to decision biases, shortcuts, and errors

G650 Program Management: Program Schedule

- Organizational processes can counterbalance schedule pressure
- Gulfstream lacked adequate technical oversight and safety management
- Schedule pressure likely played role in several key errors

G650 Program Management: Program Schedule

Schedule pressure likely influenced

- Decision to experiment with pilot technique rather than thoroughly analyze V_2 overshoots
- Decision to change target pitch without analyzing effect on takeoff speeds
- Decision to create pitch limit without adequately defining limit or including it on test cards
- Acceptance of oversimplified and inaccurate explanations for previous incidents

G650 Program Management: Safety Management

- Gulfstream had an FAA-accepted flight test risk assessment program
- No formal identification of stall-related events as potential hazard during continued takeoff testing
- Gulfstream's program lacking in area of safety assurance
- Previous stall-related events not adequately investigated

G650 Program Management: Safety Management

- FAA flight test safety guidance presented in terms specific to FAA's organizational structure
- FAA and International Civil Aviation Organization guidance not tailored to unique aspects of flight test (nonroutine, high-risk operations)

Probable Cause

An aerodynamic stall and subsequent uncommanded roll during a one-engine-inoperative takeoff flight test, which were the result of:

- (1) Gulfstream's failure to properly develop and validate takeoff speeds for the flight tests and recognize and correct the takeoff safety speed (V_2) error during previous G650 flight tests,
- (2) the G650 flight test team's persistent and increasingly aggressive attempts to achieve V_2 speeds that were erroneously low, and
- (3) Gulfstream's inadequate investigation of previous G650 uncommanded roll events, which indicated that the company's estimated stall angle of attack while the airplane was in ground effect was too high

Probable Cause - Contributing Factors

- Gulfstream's failure to effectively manage the G650 flight test program by pursuing an aggressive program schedule without ensuring that the roles and responsibilities of team members had been appropriately defined and implemented
- Engineering processes had received sufficient technical planning and oversight
- Potential hazards had been fully identified
- Appropriate risk controls had been implemented and were functioning as intended

Recommendations

Ten recommendations issued as a result of the accident investigation

- Gulfstream received two
- FTSC received three
- FAA received five



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