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Balanced Field Length Calculation for a Learjet 35A/36A with Under-Wing Stores on a Wet Runway

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In Cooperation with GFD mbH and Aero Group

HAW Hamburg, 31.08.2012

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Structure of the Presentation

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  - Learjet 35A/36A with Under-Wing Stores, Existing Takeoff Operation Envelope
- **Calculation Approach**
  - Equation of Motion and Possible Calculation Approaches
  - Calibration Concept and Simulation Architecture
- **Parameters and Forces**
  - Main Flight Mechanical Parameters
  - Impingement Spray Drag Force
- **Simulation Results**
  - Simulation Output and Calibration
  - Integration into Existing Data Set and Relations
  - Result Plausibility and Variation Effects
- **Conclusions**
  - Main Conclusions from Results
  - Additional Benefits of Numerical Simulation
  - Résumé

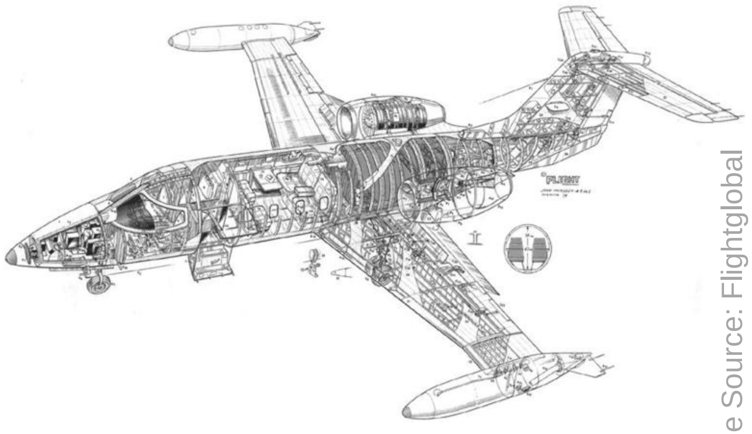
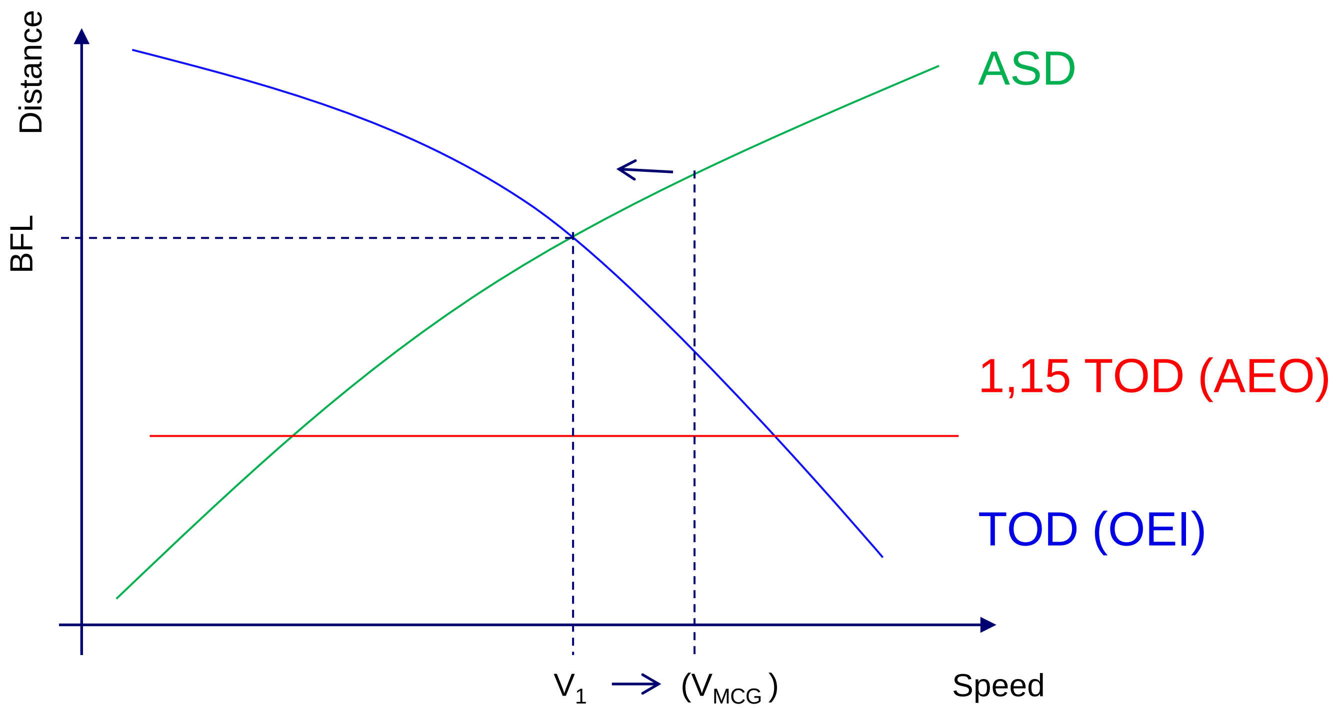


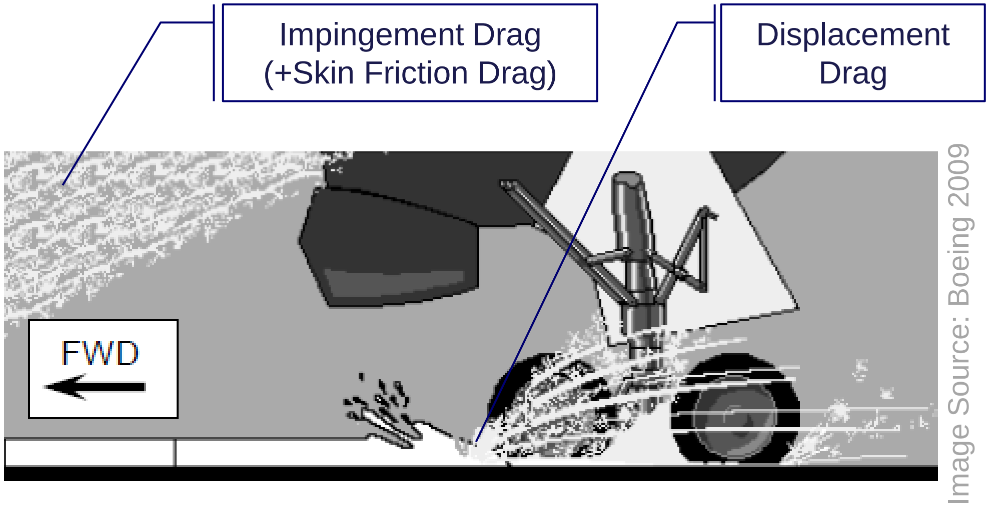
Image Source: Flightglobal

Introduction

- **Balanced Field Length: Takeoff Distance + Accelerate-Stop Distance equal**
- **Decision Speed V1 is transition between Stop+Go Decision (min. V_{MCG})**
- **Takeoff Field Length: Larger of Balanced Field Length and AEO Takeoff Dist.**



- **Learjet 35A/36A operated by GFD with Under-Wing Stores**
- **Currently no takeoff operations permitted for Stores+Wet Runway Conditions**
- **Wet Runway: Braking Coefficient Reduction**
  Precipitation Drag Increment
  Screen Height Reduction

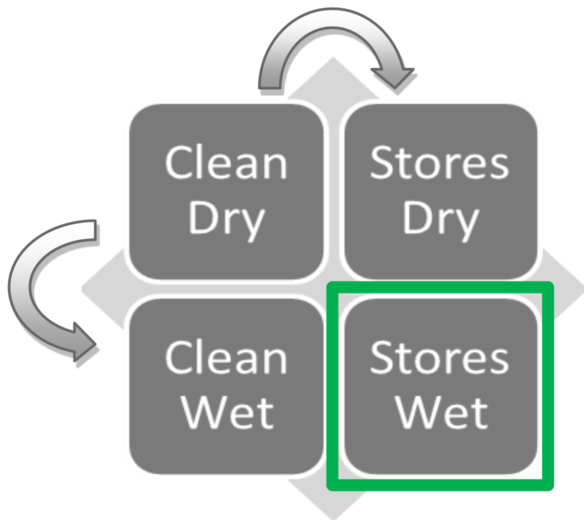


- **4-Corner-Sheet Concept – Existing and New Configuration Performance Data**
- **Based on AFMS 9702-2 (Extended Tip Tanks), Wet Data Addendum**
- **Standard Corrections for Transition between Conditions and Configurations**

TOFL: Factor 1,15 or 1,25
V1: + 5 kts

TOFL: Factor 1,2
V1: ca. - 7 kts

Exception:
TOW<15000 lbs



How does the Stores+Wet Configuration Integrate ?

Calculation Approach

- **Equation of Motion for Acceleration on Ground**

$$S_G = m \cdot \int_0^{v_{LOF}} \frac{v_G}{T - D - F_f - m \cdot g \cdot \sin\gamma} dv_G$$

- **Two different Solution Approaches possible**

Used for Simulation	Used in AFMS-9702-2 Reference
Iterative Time-Step Wise Integration	**Average Speed Method**
• All Forces considered speed dependently • Time-Step Wise Actions considered • Close to Physical Reality • Higher Accuracy	• All Forces averaged at 0,707 V_{LOF} • Average OEI Drag Coefficients • Easier, simplified Calculation • Result Precision limited

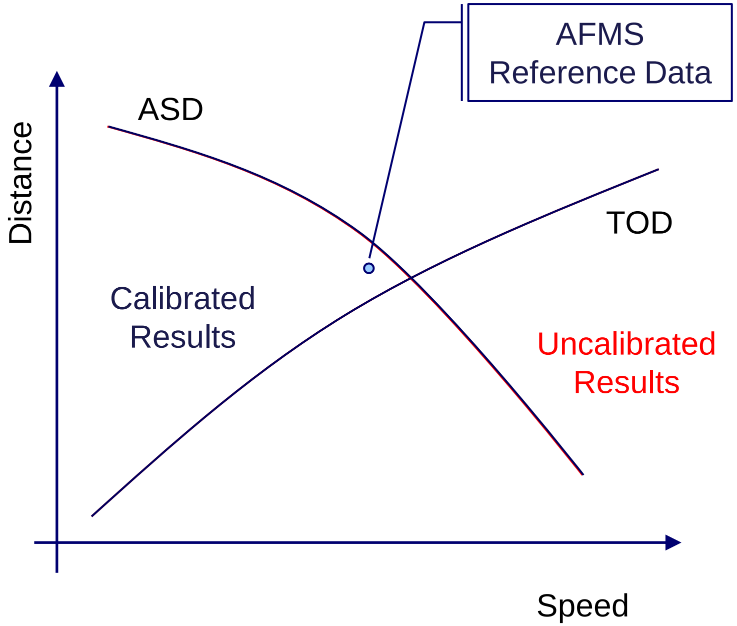
Simulation Architecture to compare Simulation Results to AFMS Reference

Calculation for Clean+Wet

- Determination of Calibration Factors

Calculation for Stores+Wet

- Determination of Simulation Results
- Determination of Calibrated Results



Parameters and Forces

- **Thrust**
  T_0 = 3400 lbs (Installed)
  - Variation with M, PA
  - Variation with OAT
  - Installation Loss 3%
  - Flat Rating Characteristics
  - Calibration with limited Engine Test Data

- **Lift Coefficient**
  $C_{L,G} = 0{,}241$
  - Lift Curve Slope Wing
  - Zero Lift Angle Change with Wing Twist
  - Flap Lift Increment
  - Zero Lift Angle Change with Flaps
  - Fuselage Lift Carryover
  - Lift depletion after Spoiler Extension

- **Runway Friction Coefficient**
  - Speed Dependent Rolling Friction Coefficient
  - Braking Coefficient CS-25.109, Anti-Skid ON
  - Max. Brake Energy Chart (Dry)
  - Gear Load Factor (Braking Case)

- **Drag Coefficient**
  $C_{D,TO,AEO} = 0{,}0606$
  $C_{D,TO,OEI} = 0{,}0797$
  - Equivalent Skin Friction Drag Coefficient, Learjet Wetted Areas determined at Aero, HAW
  - Induced Drag with Oswald Efficiency Factor Estimation based on Literature Values
  - Flap Drag Coefficient Increment
  - Gear Drag Coefficient Increment
  - Store Drag Coefficient Increment
  - Spoiler Drag Coefficient Increment
  - Windmilling Drag
  - Asymmetrical Flight Condition Drag

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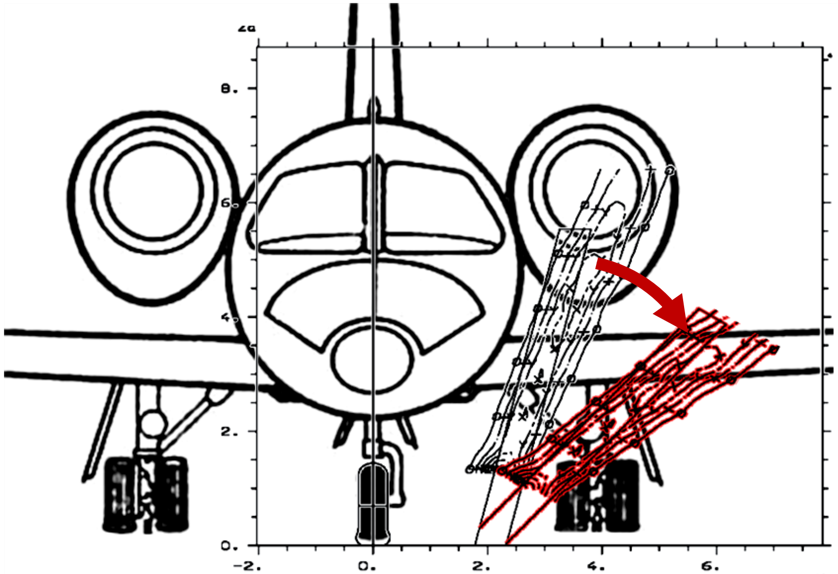
Water Spray Drag

- **Subject to intensive investigation**
- **Equation developed on the base of Water Mass Flow (NLR/NASA-inspired)**

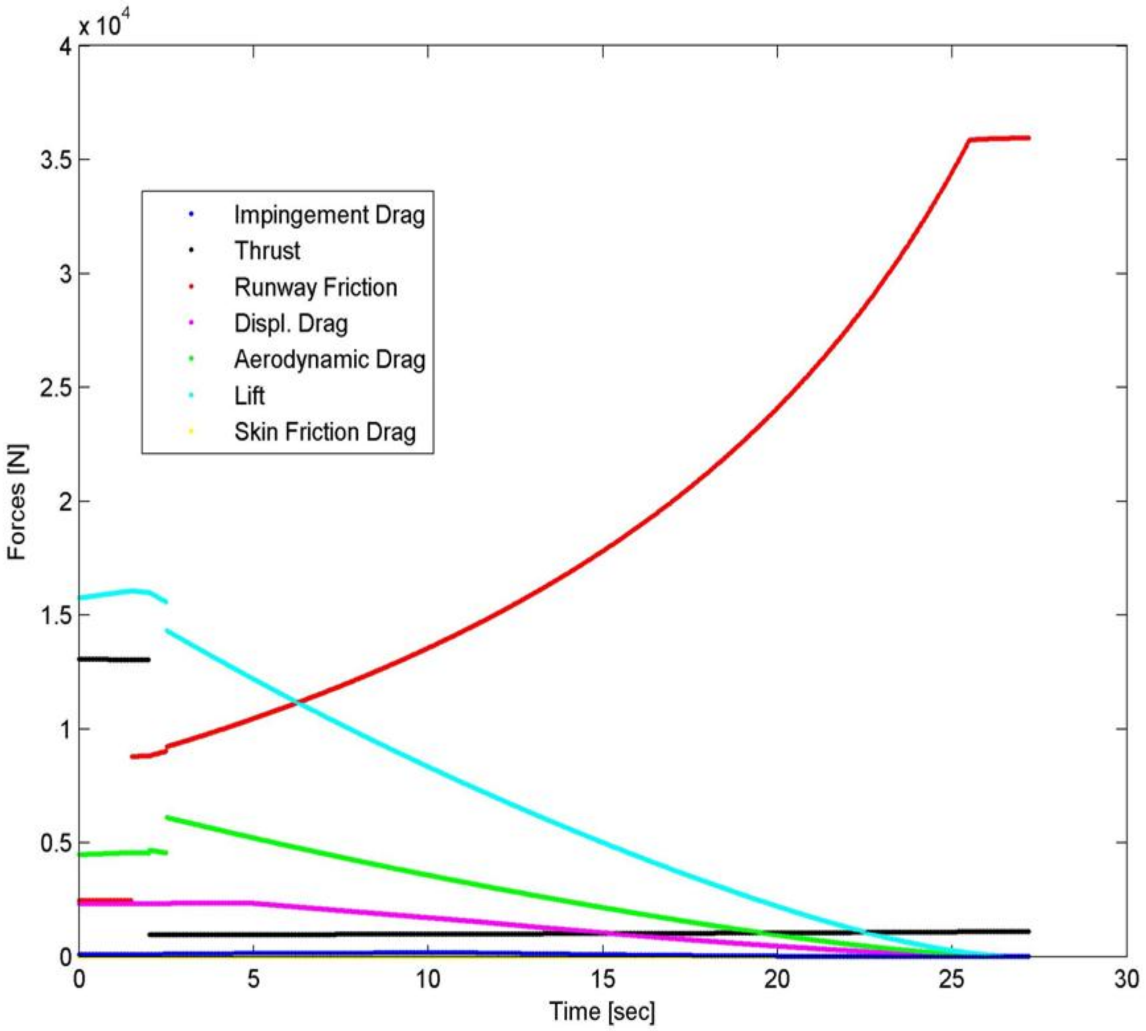
$$D_{imp} = k_{angle} \cdot 2\,\dot{m}_{imp,semi} \cdot (1 - e_{res}) \cdot v_{aircraft}$$



- **Spray Drag Maximum (Worst Case)**

$$D_{imp} = 164\ \mathrm{N}$$

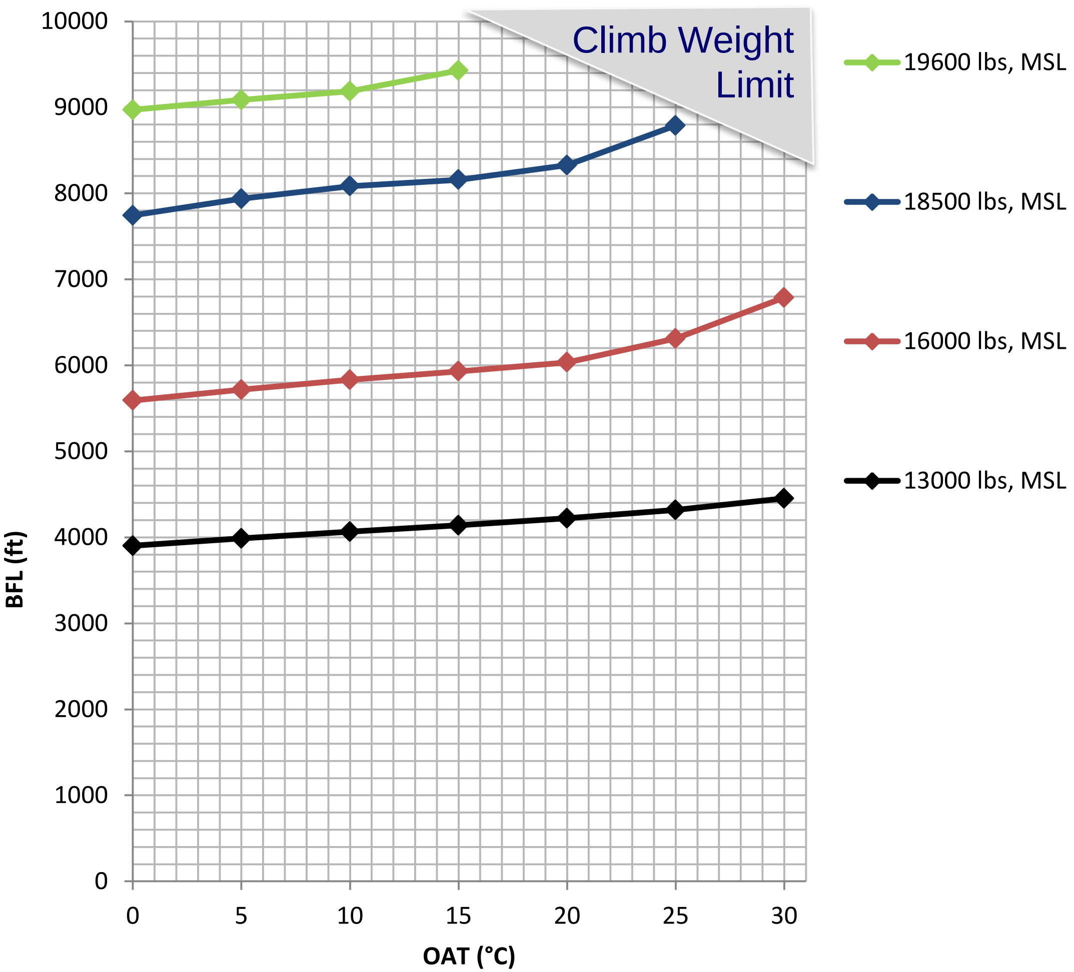
For Comparison: $T_0 = 13451\ \mathrm{N}$

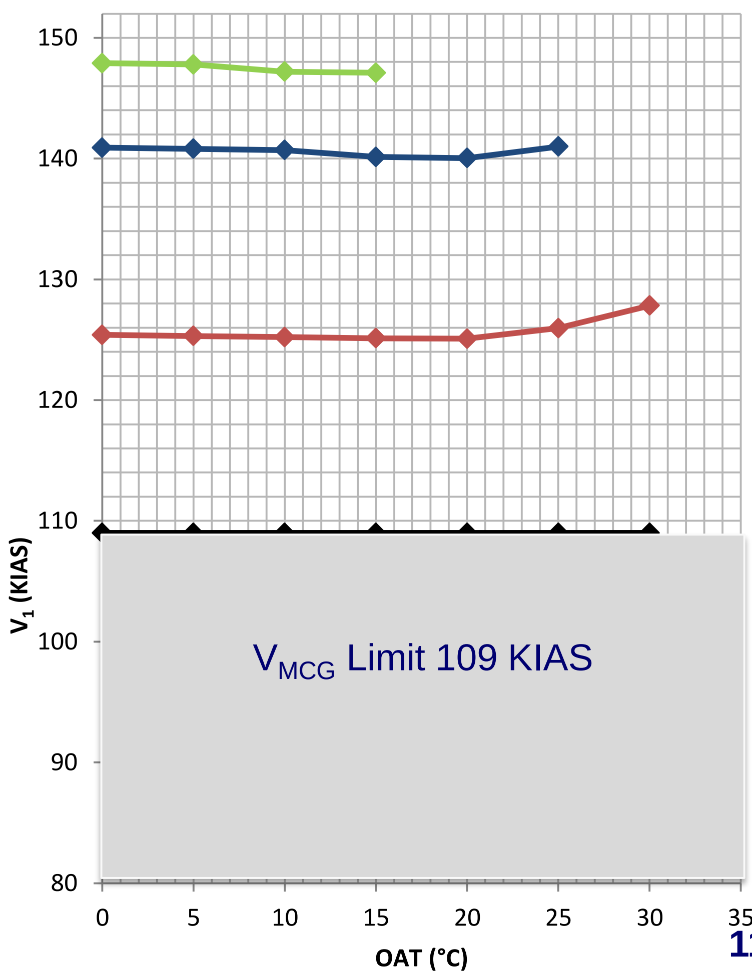


Forces Variation with Time after Engine Failure (Simulation Result)

- **Excess Thrust Balance**
  - **Dominating: Thrust, Drag, Friction and Displacement Drag**
  - **Negligible: Skin Friction and Impingement Drag**
- **Time Step Wise Effects**
  - **Time Dependant Retardation Device Activation**
  - **Increase in Braking Friction after Spoiler Activation**
- **Conclusion**
  - **Store Installation critical through Aerodynamic Drag Increment**
  - **Precipitation Effects at 3 mm water depth: only Displ. Drag**

Simulation Results, MSL





Integration into Four-Corner Sheet

TOFL: +15% / +25%
V1: + 4%

TOFL: +20%
V1: - 5%

TOFL: + ~23%
V1: - ~1%

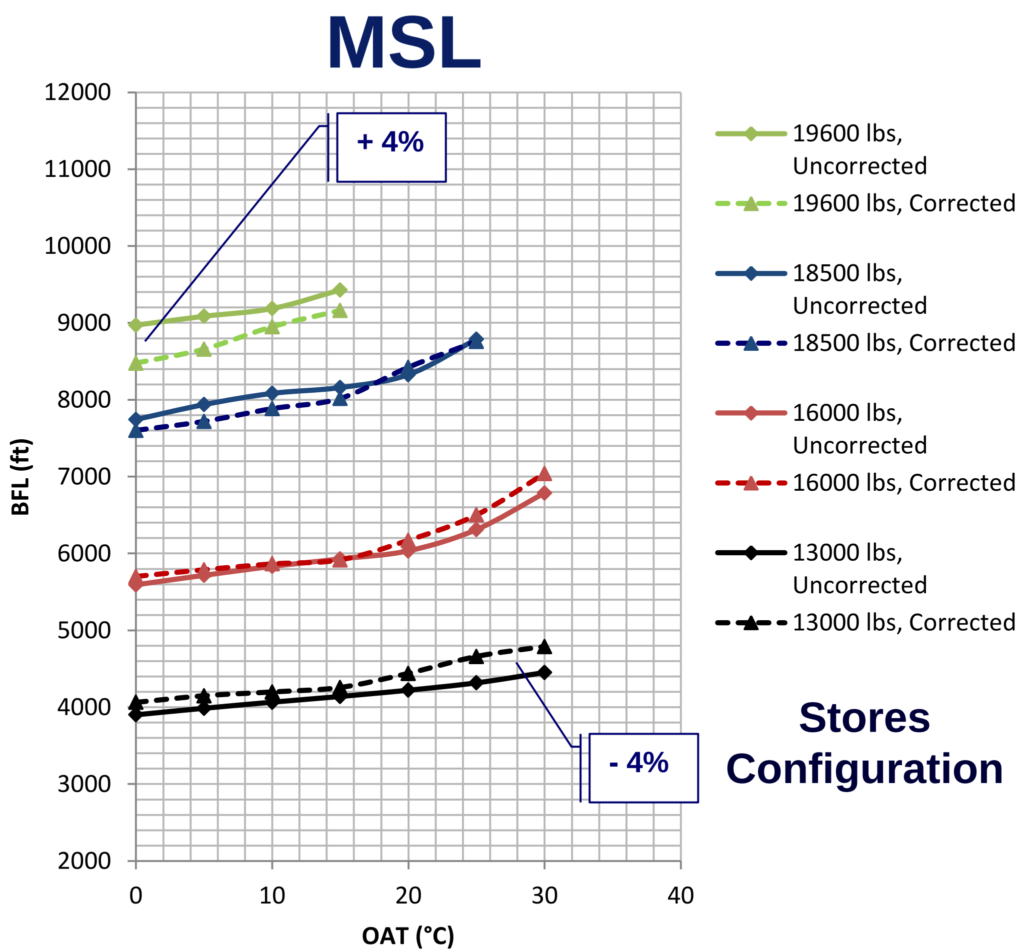
TOFL: + ~22%
V1: + ~8%

Exception: TOW=13000 lbs

- **Consistent Adjustment Factors**
  - **Average percental Values provided for Simulation**
  - **BFL Increase from all directions, same Magnitudes**
  - **V1 Behavior not compareable**
- **Exception for V_{MCG} - influenced Results**
- **Wet reduces Braking Performance**
- **Wet reduces Acceleration Performance**
- **Stores also increase Braking Performance**

  ➔ Antagonist effect on V_1

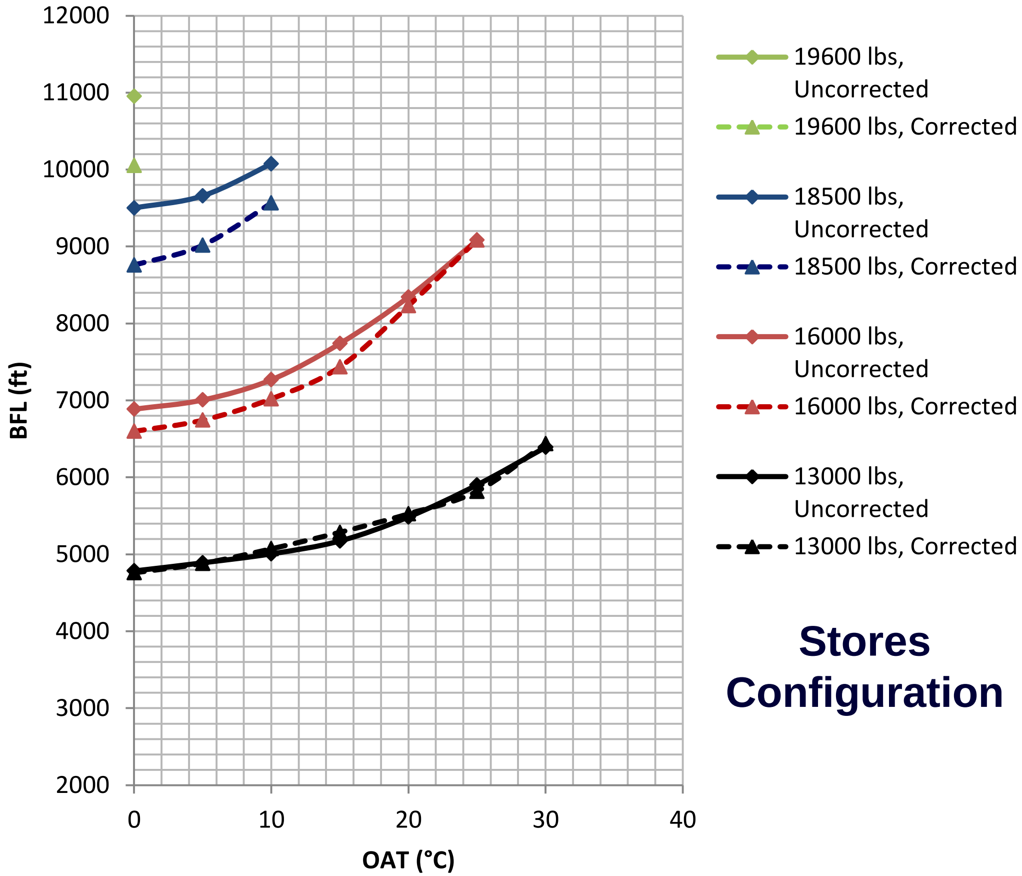
Result Deviation to Reference/Calibration



- **Deviation from Reference Data**
  - **Small Deviation from AFMS**
  - **Precision of Simulation comp. to AFMS: average +/- 4% for BFL**
  - **Simulation conservative for**
    higher TOW
    lower OAT
    higher PA
  - **Calibrated V_1 speeds + 1 KIAS**

Result Deviation to Reference/Calibration

4000 ft PA



Stores Configuration

- **Deviation from Reference Data**
  - **Small Deviation from AFMS**
  - **Precision of Simulation comp. to AFMS: average +/- 4% for BFL**
  - **Simulation conservative for**
    higher TOW
    lower OAT
    higher PA
  - **Calibrated V_1 speeds + 1 KIAS**

Parameter Variation Effects

- **Testing Variation of Important Parameters to check Plausibility of Results**

- **Important Parameters:**
  - **Thrust**
  - **Drag**
  - **Rolling and Braking Friction**
  - **V_1 Margin CS-25.109**
  - **Pilot Reaction Time**

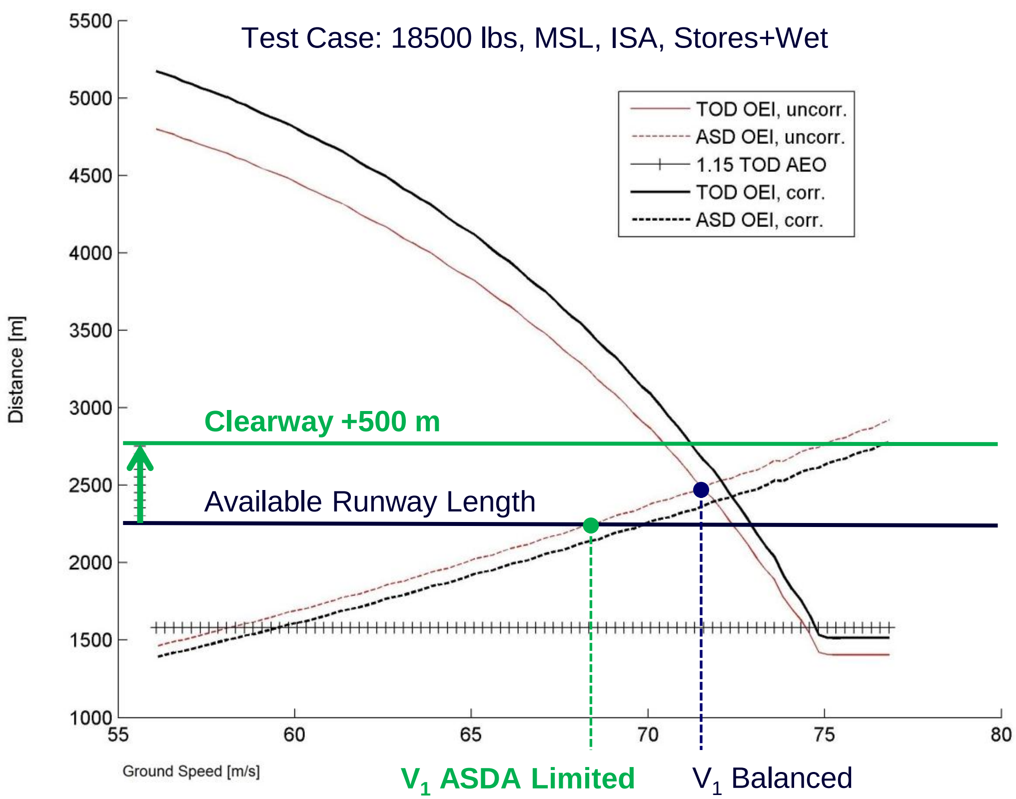
Test Case: 18500 lbs, MSL, ISA

Parameter	Variation	Deviation Impact on BFL,Store
T	10%	-11,83%
T	-10%	15,38%
$C_{D,TO}$	10%	4,65%
$C_{D,TO}$	-10%	-2,90%
$\mu_{roll,wet}$	0,05 static	4,46%
$\mu_{roll,wet}$	10%	2,84%
$\mu_{brake,wet}$	10%	-2,14%
No 2 second margin at V_1	-	-4,02%
React. Time	**+1 second**	**2,38 %**

- **Impact of 1 second reaction time considerably high**

- **Aerodynamic Drag high Influence:**
  Stores Installation creates ΔC_D = 0,0136 (33%) regarding clean aircraft C_D = 0,0410

Additional Benefit: BFL - Plots



- **Possibility to operate Off-Balance**
- **Additional Operational Benefit**
  - **Stopway/Clearway may be considered**
  - **TOW may be increased**
  - **TODA/ASDA increase permits takeoff on previously TOW Limited Runways**
- **Observations from Example**
  - **TODA increased**
  - **Takeoff with Clearway not TOW limited**
  - **ASDA Limited V_1 decreases**

Conclusions

- **Validation of Simulation Results**
  - **Integration into existing Data coherent**
  - **Deviations to Reference data relatively small**
  - **Physical Effects considered in detail and validated**

- **Choice of Numerical Simulation Approach**
  - **Simulation: High Physical Accuracy**
  - **Calibration adjusts accuracy to AFMS level (simplified approach, possibly less accurate)**
  - **Calibration Concept: Beneficial to adjust TOD/ASD Function Parameters**

  - **Calibration in most cases lower BFL, higher V1 => Simulation Results generally more conservative**

- **Level of Detail of Model Data could have been simplified for**
  - **Lift Coefficient**
  - **Spray Impingement Drag**
  - **Water Skin Friction Drag**

Additional Benefits of Numerical Simulation

- **High Precision Approach close to physical Reality**
- **Validation of GFD-Adjustment Factor of 1,35 for TOW < 15000 lbs, Clean+Wet**
- **Testing of further aircraft configurations, reaction times, environmental conditions**
- **BFL-Plots with possibility to operate Off-Balance**

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Résumé of Important Conclusions

- **Drag effect of Stores almost entirely Aerodynamic also on Wet Runway**

- **Wet Runway + Stores Influence always negative on BFL**
- **V_1 cannot be lowered globally for wet runway conditions**

- **Numerical Takeoff Simulation yields considerable Benefits but:**
  - **Detailed Parameter Estimation necessary**
  - **Precision only possible through constant comparison with AFMS (Calibration)**

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Thank You for Your Attention

Image Sources:

Boeing 2009 BOEING COMMERCIAL AIRPLANES: *Performance Engineer Operations Course*. Seattle : Boeing, Sept 2009

Flightglobal FLIGHTGLOBAL: *Learjet 35A/36A Cutaway.* www.flightglobal.com/airspace/media/businessaircraftcutaways/gates-learjet-35-36-cutaway-5694.aspx (09.08.2012)