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

Florian Ehrig, HAW Hamburg

1. Examiner: Professor Dr.-Ing. Dieter Scholz, MSME
2. Examiner: Professor Dr.-Ing. Hartmut Zingel

Industrial Supervising Tutor: Dipl.-Ing. Enrico Busse

In Cooperation with GFD mbH and Aero Group

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Structure of the Presentation

- **Introduction**
  - Takeoff and Balanced Field Length
  - 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
Introduction

- Balanced Field Length: Takeoff Distance + Accelerate-Stop Distance equal
- Decision Speed V1 is transition between Stop+Go Decision (min. $V_{\text{MCG}}$)
- 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

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

- Two different Solution Approaches possible

Used for Simulation

Iterative Time-Step Wise Integration

- All Forces considered speed dependently
- Time-Step Wise Actions considered
- Close to Physical Reality
- Higher Accuracy

Used in AFMS-9702-2 Reference

Average Speed Method

- 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

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<table>
<thead>
<tr>
<th></th>
<th>Calculation for Clean+Wet</th>
<th>Calculation for Stores+Wet</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ASD</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>TOD</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>AFMS</strong></td>
<td>AFMS Reference Data</td>
<td></td>
</tr>
<tr>
<td><strong>Uncalibrated</strong></td>
<td>Results</td>
<td>Results</td>
</tr>
<tr>
<td><strong>Calibrated</strong></td>
<td>Results</td>
<td>Results</td>
</tr>
</tbody>
</table>
```

Distance vs. Speed graph:
- ASD
- TOD
- Uncalibrated Results
- Calibrated Results
- AFMS Reference Data
Parameters and Forces

- **Thrust**
  \[ T_0 = 3400 \text{ lbs (Installed)} \]
  - 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
Water Spray Drag

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

\[ D_{imp} = k_{angle} \cdot 2 \cdot m_{imp,semi} \cdot (1 - e_{res}) \cdot v_{aircraft} \]

- Spray Drag Maximum (Worst Case)

\[ D_{imp} = 164 \, \text{N} \]

For Comparison: \[ T_0 = 13451 \, \text{N} \]
Balanced Field Length Calculation for a Learjet 35A/36A

Introduction

- 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

Forces Variation with Time after Engine Failure (Simulation Result)
Simulation Results, MSL

Climb Weight Limit

- 19600 lbs, MSL
- 18500 lbs, MSL
- 16000 lbs, MSL
- 13000 lbs, MSL

V_{MCG} Limit 109 KIAS
Integration into Four-Corner Sheet

- 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 $V_1$

Exception: TOW=13000 lbs

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

TOFL: +20%
V1: - 5%

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

TOFL: + ~23%
V1: - ~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

- 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

- Impact of 1 second reaction time considerably high

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Variation</th>
<th>Deviation Impact on BFL, Store</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T )</td>
<td>10%</td>
<td>-11,83%</td>
</tr>
<tr>
<td>( T )</td>
<td>-10%</td>
<td>15,38%</td>
</tr>
<tr>
<td>( C_{D,TO} )</td>
<td>10%</td>
<td>4,65%</td>
</tr>
<tr>
<td>( C_{D,TO} )</td>
<td>-10%</td>
<td>-2,90%</td>
</tr>
<tr>
<td>( \mu_{\text{roll, wet}} )</td>
<td>0.05 static</td>
<td>4,46%</td>
</tr>
<tr>
<td>( \mu_{\text{roll, wet}} )</td>
<td>10%</td>
<td>2,84%</td>
</tr>
<tr>
<td>( \mu_{\text{brake, wet}} )</td>
<td>10%</td>
<td>-2,14%</td>
</tr>
<tr>
<td>No 2 second margin at ( V_1 )</td>
<td>-</td>
<td>-4,02%</td>
</tr>
<tr>
<td>React. Time</td>
<td>+1 second</td>
<td>2,38%</td>
</tr>
</tbody>
</table>

- Aerodynamic Drag high Influence: Stores Installation creates \( \Delta C_D = 0,0136 \) (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
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)
Thank You for Your Attention
Balanced Field Length Calculation for a Learjet 35A/36A

Introduction
Calculation Approach
Parameters and Forces
Simulation Results
Conclusions

Image Sources: