Sensitivity of Runway Occupancy Time (ROT) to Various Rollout and Turnoff (ROTO) Factors

Volume I

S. H. Goldthorpe
McDonnell Douglas Corporation, Long Beach, California

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National Aeronautics and Space Administration
Langley Research Center
Hampton, Virginia 23681-0001
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1.0 SUMMARY

The sensitivity of runway occupancy time (ROT) to various operational factors associated with the operation of a research high-speed Rollout and Turnoff (ROTO) system has been investigated using a 3 degree of freedom (yaw, forward, lateral) non real-time aircraft simulation. Mean and standard deviation statistics were computed for the operational factors and were plotted for comparison of the various operational factors.

The operational factors are ranked, as follows, according to ROT sensitivity in descending order. This ranking gives equal weight to both MD-11 and MD-81 aircraft types and both ROT mean and standard deviation statistics.

- Ice/flood runway surface condition
- Exit entrance ground speed
- Number of exits
- High-speed exit locations and spacing
- Aircraft type, baseline at mid exit location 5950 ft
- Touchdown ground speed standard deviation
- Reverse thrust and braking method
- Accurate exit prediction capability
- Maximum Reverse Thrust availability
- Spiral-arc vs circle-arc exit geometry
- Dry/slush/wet/snow runway surface condition
- Maximum allowed deceleration
- Auto asymmetric braking on exit
- Do not stow reverse thrust before the exit
- Touchdown longitudinal location standard deviation
- Flap setting
- Anti-skid efficiency
- Crosswind conditions
- Stopping on the exit
- Touchdown lateral offset

ROT sensitivity to operational factors, documented in this report, is valid for the assumptions and models used for this study. It is believed that the results will apply to the general class of transport aircraft; however further effort is required to validate this assumption for the general case.
2.0 INTRODUCTION

The Terminal Area Productivity (TAP) research program was initiated by NASA to increase the airport capacity for transport aircraft operations. One element of the research program is called Low Visibility Landing and Surface Operations (LVLASO). A goal of the LVLASO research is to develop transport aircraft technologies which reduce ROT so that it does not become the limiting factor in the terminal area operations that determine the capacity of a runway. Under LVLASO, the objective of this study was to determine the sensitivity of Runway Occupancy Time (ROT) to various factors associated with the Rollout and Turnoff (ROTO) operation for transport aircraft.

The requirements of reference 1 and the ROTO guidance and control system design of reference 2 were used to find the sensitivity of ROT (mean and standard deviation) to the following operational factors, for two aircraft types (MD-81 & MD-11):

1. High-speed exit locations, spacing and number of exits.
2. Spiral-arc vs circle-arc exit shape.
3. The type of reverse thrust/braking method: constant-level deceleration (no exit prediction logic), roll deceleration (no braking) followed by maximum deceleration acceptable to passengers and variable-level deceleration. Auto (variable) and constant reverse thrust were employed for these methods.
4. ROTO System Capability: availability of auto, constant, idle and no reverse thrust on runway, availability of exit prediction logic with or without input errors, possible settings of reverse thrust at exit entrance, availability of auto-asymmetric braking, ability to stop on exit.
5. High-speed exit entrance ground speed.
7. Aircraft longitudinal touchdown dispersion standard deviation (stdev).
8. Aircraft touchdown landing ground speed stdev.
9. Crosswind conditions and lateral touchdown location.
10. Flap setting: normal vs full.
11. Anti-skid efficiency: 60%, 75% and 90%.
12. Maximum allowed deceleration: 6.5 (medium) and 9.0 (heavy) ft/sec².

This report is contained in two volumes. Volume 1 describes the ROTO system, modeling, operational factors studied, data gathering, data analysis, and statistical calculations. Volume 1 also contains summary plots and graphs used in the data analysis. Volume 2 contains the complete set of plotted ROT sensitivity data and 3D ROT dispersion and probability distribution graphs.

During the time of this study, as an aside from the studied operational factors of this report, actual MD-8x ROT data collected for high speed ROTO operations at Dallas Ft. Worth airport was obtained. Dallas-Ft. Worth airport, under flight crew discretion, conducts manual
high-speed ROTO operations under daylight VMC conditions with no runway/exit surface contamination. This applies to both narrow and wide body aircraft on 30 degree exits at exit entrance ground speeds up to 70 knots. Section 4 of the appendix compares actual MD-8x ROT data collected on Dallas-Ft. Worth runway 13R in November 1993 to simulated auto ROTO ROT data for a MD-81 dispersion on a dry runway surface condition. The simulation used the same single runway high-speed exit location as found on runway 13R.
3.0 MODELING

The model used in this study was documented in references 1 and 2. The computer model was implemented in both FORTRAN 77 code and MATLAB SIMULINK diagrams, which have been delivered to NASA Langley. The aircraft simulation is a 3 degree of freedom (yaw, forward, lateral) model. It calculates aerodynamic, thrust and tire forces on the airplane and solves the resulting equations of motion to determine aircraft accelerations, velocities and positions during a simulated rollout and turnoff. The simulation also includes hydraulic models of the nosewheel steering, rudder and autobrakes. The simulation begins at main gear touchdown. The model includes the following items:

- ROTO Exit Geometry (spiral-arc, see reference 3)
- Nosewheel, Rudder and Autobrake Actuation & Steering Hysteresis
- Tire-runway Coefficient of Friction
- Forces - Aerodynamic, Thrust, Braking Drag, Main & Nose Gear (Vertical & Side)
- Aircraft Equations of Motion - Acceleration, Velocity, Position
- Navigation
- Winds
- ROTO Control Laws
- Exit Prediction Logic
A variety of aircraft types may be simulated by providing the simulation with unique aircraft characteristics. These characteristics are described below for an MD-81 and MD-11. MD-11 data was used if specific data was not obtained for an aircraft characteristic (rudder actuator dynamics, autobrake).

**AIRCRAFT SIMULATION DATA**

**Aircraft Data at Main Gear Touchdown**

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Description</th>
<th>MD-81</th>
<th>MD-11</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>weight</td>
<td>82,000</td>
<td>340,000</td>
<td>lbs</td>
</tr>
<tr>
<td></td>
<td>min</td>
<td>128,000</td>
<td>480,000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>max</td>
<td>128,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CG</td>
<td>center of gravity (% MAC)</td>
<td>-8%</td>
<td>12%</td>
<td>%</td>
</tr>
<tr>
<td></td>
<td>fwd most</td>
<td>33.4%</td>
<td>34%</td>
<td>%</td>
</tr>
<tr>
<td></td>
<td>aft most</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VEAS</td>
<td>airspeed</td>
<td>110</td>
<td>130</td>
<td>knots</td>
</tr>
<tr>
<td></td>
<td>min</td>
<td>143</td>
<td>166</td>
<td></td>
</tr>
<tr>
<td></td>
<td>max</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>XDISP</td>
<td>longitudinal dispersion (feet)</td>
<td>1362</td>
<td>1375</td>
<td>feet</td>
</tr>
<tr>
<td></td>
<td>mean</td>
<td>198</td>
<td>225</td>
<td></td>
</tr>
<tr>
<td></td>
<td>stdev</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GRNDSPD</td>
<td>ground speed</td>
<td>116.44</td>
<td>141</td>
<td>knots</td>
</tr>
<tr>
<td></td>
<td>mean</td>
<td>10.36</td>
<td>11.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>stdev</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ELEV</td>
<td>elevator (deg, assumed constant)</td>
<td>8</td>
<td>8</td>
<td>degrees</td>
</tr>
<tr>
<td>FLAPS</td>
<td>flaps</td>
<td>28</td>
<td>35</td>
<td>degrees</td>
</tr>
<tr>
<td></td>
<td>normal</td>
<td>40</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td></td>
<td>full</td>
<td></td>
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</table>

**Aircraft Geometry Data**

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Description</th>
<th>MD-81</th>
<th>MD-11</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>SW</td>
<td>wing area</td>
<td>1209.3</td>
<td>3647.5</td>
<td>feet²</td>
</tr>
<tr>
<td>BW</td>
<td>wing span</td>
<td>107.8</td>
<td>165.37</td>
<td>feet</td>
</tr>
<tr>
<td>LMAC</td>
<td>length of mean aerodynamic chord</td>
<td>13.209</td>
<td>24.648</td>
<td>feet</td>
</tr>
<tr>
<td>A</td>
<td>distance -- nose gear to CG</td>
<td>65.52</td>
<td>72.932</td>
<td>feet</td>
</tr>
<tr>
<td></td>
<td>(fwd cg)</td>
<td>70.04</td>
<td>78.236</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(aft cg)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>distance -- main gear to CG</td>
<td>6.6b</td>
<td>7.732</td>
<td>feet</td>
</tr>
<tr>
<td></td>
<td>(fwd cg)</td>
<td>2.384</td>
<td>2.457</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(aft cg)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BC</td>
<td>distance -- center gear to CG</td>
<td>0</td>
<td>10.234</td>
<td>feet</td>
</tr>
<tr>
<td></td>
<td>(fwd cg)</td>
<td>0</td>
<td>5.00</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(aft cg)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>distance -- lift moment arm</td>
<td>-3.4</td>
<td>-3.056</td>
<td>feet</td>
</tr>
<tr>
<td></td>
<td>to CG (fwd cg)</td>
<td>1.110</td>
<td>-2.218</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(aft cg)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HCG</td>
<td>CG height</td>
<td>8.8</td>
<td>15.476</td>
<td>feet</td>
</tr>
<tr>
<td></td>
<td>(fwd cg)</td>
<td>7.32</td>
<td>15.476</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(aft cg)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LTAIL</td>
<td>distance -- tail center of</td>
<td>62.39</td>
<td>83.719</td>
<td>feet</td>
</tr>
<tr>
<td></td>
<td>pressure to CG</td>
<td>-17.016</td>
<td>-56.18</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(fwd cg)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(aft cg)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IWAV</td>
<td>aircraft yaw moment of inertia</td>
<td>4.1E6</td>
<td>2.56E7</td>
<td>slug-ft²</td>
</tr>
</tbody>
</table>
Aerodynamic Coefficients
(assumes normal flaps, slats extended, spoilers deployed, elevator = 8 degrees)

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Description</th>
<th>MD-81</th>
<th>MD-11</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDRAG</td>
<td>aircraft drag coefficient (fwd cg)</td>
<td>0.227</td>
<td>0.1746</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>(aft cg)</td>
<td>0.219</td>
<td>0.1651</td>
<td>-</td>
</tr>
<tr>
<td>CLIFT</td>
<td>aircraft lift coefficient (fwd cg)</td>
<td>0.385</td>
<td>0.123</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>(aft cg)</td>
<td>0.550</td>
<td>0.226</td>
<td>-</td>
</tr>
<tr>
<td>CMOM</td>
<td>aircraft pitch moment coefficient (fwd cg)</td>
<td>0.83</td>
<td>0.515</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>(aft cg)</td>
<td>0.105</td>
<td>0.216</td>
<td>-</td>
</tr>
<tr>
<td>CMR</td>
<td>rudder yaw moment coefficient</td>
<td>-.0012</td>
<td>-.00262</td>
<td>1/degree</td>
</tr>
<tr>
<td>CNB</td>
<td>aircraft side slip moment coefficient</td>
<td>0.00332</td>
<td>0.0037</td>
<td>-</td>
</tr>
<tr>
<td>CYB</td>
<td>aircraft side slip force coefficient</td>
<td>-.018</td>
<td>-.024</td>
<td>-</td>
</tr>
<tr>
<td>DCLDE</td>
<td>change in CLIFT due to elevator</td>
<td>0.0083</td>
<td>0.008</td>
<td>-</td>
</tr>
<tr>
<td>DMODE</td>
<td>change in CMOM due to elevator</td>
<td>-.0385</td>
<td>-.025</td>
<td>-</td>
</tr>
</tbody>
</table>

Wing and Center Gear Tire Properties

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Description</th>
<th>MD-81</th>
<th>MD-11</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC</td>
<td>center gear cornering power per tire</td>
<td>0</td>
<td>4426</td>
<td>lbs/deg</td>
</tr>
<tr>
<td>NM</td>
<td>wing gear cornering power per tire</td>
<td>2625</td>
<td>4806</td>
<td>lbs/deg</td>
</tr>
<tr>
<td>SPM</td>
<td>wing and center gear tire static pressure</td>
<td>170</td>
<td>188</td>
<td>psi</td>
</tr>
<tr>
<td>NWLG</td>
<td>number of wing gear wheels</td>
<td>2</td>
<td>4</td>
<td>-</td>
</tr>
<tr>
<td>NWCLG</td>
<td>number of center gear wheels</td>
<td>0</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>TREAD</td>
<td>distance between wing landing gears</td>
<td>16.47</td>
<td>34.677</td>
<td>feet</td>
</tr>
</tbody>
</table>

Constants Used to Calculate Nose Gear Cornering Power and Strut Moment

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Description</th>
<th>MD-81</th>
<th>MD-11</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>DELB</td>
<td>nose gear tire deflection at load RB</td>
<td>0.4</td>
<td>1.1</td>
<td>inch</td>
</tr>
<tr>
<td>DELS</td>
<td>nose gear tire rated deflection</td>
<td>1.25</td>
<td>3.4</td>
<td>inch</td>
</tr>
<tr>
<td>HS</td>
<td>nose gear tire section height</td>
<td>5</td>
<td>9.8</td>
<td>inch</td>
</tr>
<tr>
<td>OD</td>
<td>nose gear tire outside diameter</td>
<td>25.75</td>
<td>39.6</td>
<td>inch</td>
</tr>
<tr>
<td>RB</td>
<td>nose gear tire vertical load at deflection DELB</td>
<td>2000</td>
<td>8000</td>
<td>lbs</td>
</tr>
<tr>
<td>RP</td>
<td>nose gear tire rated pressure (loaded)</td>
<td>185</td>
<td>203</td>
<td>psi</td>
</tr>
<tr>
<td>RS</td>
<td>nose gear tire rated load</td>
<td>6900</td>
<td>39500</td>
<td>lbs</td>
</tr>
<tr>
<td>S</td>
<td>nosewheel spacing</td>
<td>14</td>
<td>25</td>
<td>feet</td>
</tr>
<tr>
<td>SP</td>
<td>nose gear tire static pressure (loaded)</td>
<td>175</td>
<td>167</td>
<td>psi</td>
</tr>
<tr>
<td>THETA</td>
<td>nosewheel forward cant angle</td>
<td>8</td>
<td>9.5</td>
<td>degrees</td>
</tr>
<tr>
<td>WS</td>
<td>nose gear tire section width</td>
<td>6.4</td>
<td>15.5</td>
<td>inch</td>
</tr>
</tbody>
</table>
### Nosewheel Actuation
(NASA Report 195026 page 35)

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Description</th>
<th>MD-81</th>
<th>MD-11</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>KS1</td>
<td>(steering valve spool displacement) / (cmd steering error)</td>
<td>0.0211</td>
<td>0.00873</td>
<td>in/degree</td>
</tr>
<tr>
<td>KS2</td>
<td>(steering rate) / (valve flow)</td>
<td>1.023</td>
<td>0.965</td>
<td>(deg/s)/(in/sec)</td>
</tr>
<tr>
<td>KS3</td>
<td>(steering actuator pressure) / (strut ground moment)</td>
<td>0.0897</td>
<td>0.00842</td>
<td>psi/in-lb</td>
</tr>
</tbody>
</table>

### Rudder Actuation
(NASA Report 195026 page 36)

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Description</th>
<th>MD-81</th>
<th>MD-11</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>mod piston LVDT gain</td>
<td>1/6.43</td>
<td>1/6.43</td>
<td>in/volts</td>
</tr>
<tr>
<td>G3</td>
<td>mod piston position limit</td>
<td>0.1</td>
<td>0.1</td>
<td>in/in</td>
</tr>
<tr>
<td>G4</td>
<td>cmd error gain</td>
<td>0.4</td>
<td>0.4</td>
<td>volts/deg</td>
</tr>
<tr>
<td>G5</td>
<td>deadzone</td>
<td>0.002</td>
<td>0.002</td>
<td>in/in</td>
</tr>
<tr>
<td>G10</td>
<td>deadzone</td>
<td>upper 1041.6</td>
<td>1041.6</td>
<td>(deg/sec)</td>
</tr>
<tr>
<td></td>
<td>lower 724.0</td>
<td>724.0</td>
<td>724.0</td>
<td>in</td>
</tr>
<tr>
<td>G11</td>
<td>rudder position limit</td>
<td>0.1835</td>
<td>0.1835</td>
<td>in/in</td>
</tr>
<tr>
<td>G14</td>
<td>rudder position limit</td>
<td>+/- 23</td>
<td>+/- 23</td>
<td>degrees</td>
</tr>
<tr>
<td>G16</td>
<td>rudder rate limit</td>
<td>0.06</td>
<td>0.06</td>
<td>in/in</td>
</tr>
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### Hysteresis in Steering System in terms of Nose Gear Degrees

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Description</th>
<th>MD-81</th>
<th>MD-11</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>autoland rudder to rudder pedal cable hys</td>
<td>2</td>
<td>2</td>
<td>degrees</td>
</tr>
<tr>
<td>-</td>
<td>rudder pedal to nose gear hysteresis</td>
<td>1</td>
<td>1</td>
<td>degrees</td>
</tr>
<tr>
<td>-</td>
<td>tiller cable hysteresis</td>
<td>1</td>
<td>1</td>
<td>degrees</td>
</tr>
</tbody>
</table>
## Autobrake Actuation (NASA Report 195026 page 37)

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Description</th>
<th>MD-81</th>
<th>MD-11</th>
<th>Units</th>
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</thead>
<tbody>
<tr>
<td>RRPHAS1</td>
<td>phase 1 brake pressure ramp rate</td>
<td>400</td>
<td>400</td>
<td>psi/sec</td>
</tr>
<tr>
<td>RRPHAS2</td>
<td>phase 2 brake pressure ramp rate</td>
<td>1200</td>
<td>1200</td>
<td>psi/sec</td>
</tr>
<tr>
<td>KBPHASE1</td>
<td>phase 1 brake pressure gain</td>
<td>600</td>
<td>600</td>
<td>(psi/sec)/(ft/sec²)</td>
</tr>
<tr>
<td>KBPHASE2</td>
<td>phase 2 brake pressure gain</td>
<td>1800</td>
<td>1800</td>
<td>(psi/sec)/(ft/sec²)</td>
</tr>
<tr>
<td>TMGD</td>
<td>main gear touchdown time</td>
<td>0</td>
<td>0</td>
<td>sec</td>
</tr>
<tr>
<td>TNGD</td>
<td>nose gear touchdown time</td>
<td>6</td>
<td>6</td>
<td>sec</td>
</tr>
<tr>
<td>TSOIL</td>
<td>time between nose gear touchdown and spoiler deployment</td>
<td>1.3</td>
<td>1.3</td>
<td>sec</td>
</tr>
<tr>
<td>TDELAY</td>
<td>time between spoiler deployment and start of brake ramp</td>
<td>3</td>
<td>3</td>
<td>sec</td>
</tr>
<tr>
<td>MUROLL</td>
<td>rolling friction</td>
<td>.15</td>
<td>.15</td>
<td>-</td>
</tr>
<tr>
<td>ASEFF</td>
<td>anti-skid efficiency</td>
<td>0.75</td>
<td>0.75</td>
<td>-</td>
</tr>
</tbody>
</table>

### Hydraulic System

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Description</th>
<th>MD-81</th>
<th>MD-11</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSUP</td>
<td>hydraulic supply pressure</td>
<td>3000</td>
<td>3000</td>
<td>psi</td>
</tr>
<tr>
<td>PRET</td>
<td>hydraulic return pressure</td>
<td>60</td>
<td>60</td>
<td>psi</td>
</tr>
</tbody>
</table>

### Functions

<table>
<thead>
<tr>
<th>Function</th>
<th>Variable Name</th>
<th>Figure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nose gear steering valve flow gain curve</td>
<td>VALVET</td>
<td>3.1</td>
</tr>
<tr>
<td>Nosewheel friction factor vs side slip velocity</td>
<td>MUSKIDT</td>
<td>3.2</td>
</tr>
<tr>
<td>Brake pressure vs brake torque</td>
<td>BDK, BDP, BDEXP</td>
<td>3.3</td>
</tr>
<tr>
<td>Fraction of main gear load supported by center gear</td>
<td>GAMMAT</td>
<td>3.4</td>
</tr>
<tr>
<td>Forward thrust approach idle vs airspeed</td>
<td>THS1T</td>
<td>3.5</td>
</tr>
<tr>
<td>Forward thrust ground idle vs airspeed</td>
<td>THSNT</td>
<td>3.6</td>
</tr>
<tr>
<td>Reverse thrust idle vs airspeed</td>
<td>THSRNT</td>
<td>3.7</td>
</tr>
<tr>
<td>Reverse thrust maximum vs time (initial spool up)</td>
<td>THSTIT</td>
<td>3.8</td>
</tr>
<tr>
<td>Reverse thrust maximum vs airspeed (maximum airspeed when spool-up time ends)</td>
<td>THSRT</td>
<td>3.9</td>
</tr>
<tr>
<td>Rudder to Nosewheel Gearing</td>
<td>STEERT</td>
<td>3.10</td>
</tr>
<tr>
<td>Non-grooved, concrete, surface friction curves</td>
<td>MUMAX</td>
<td>3.11</td>
</tr>
<tr>
<td>Spiral &amp; constant radius, 30 degree, high-speed exit Y coordinate vs X coordinate</td>
<td>YEXIT</td>
<td>3.12</td>
</tr>
</tbody>
</table>
4.0 ROTO DESIGN

The baseline ROTO control law design is documented in reference 2. Prior to beginning the ROT sensitivity study, options were added to the ROTO deceleration control laws to allow for a constant deceleration brake command and a constant reverse thrust command. The ROTO design now allows for four possible combinations of braking and reverse thrust deceleration methods, namely: variable deceleration braking, roll-constant deceleration braking, variable auto reverse thrust and constant reverse thrust. The maximum allowable braking deceleration command for this study was 6.5 ft/sec^2 (medium braking).

The hardware and software costs of the constant braking and constant reverse thrust deceleration methods per aircraft are expected to be less than the variable braking and auto reverse thrust deceleration methods. However, operationally more real-time CPU resources are required by the exit prediction logic as described below, for the constant deceleration methods. The exit prediction logic is essentially an on-board ROTO deceleration simulation, which converges by iteration to the desired constant reverse thrust command and/or runway distance for onset of constant aircraft deceleration.

Autobraking Control Law

For both the variable and constant deceleration braking methods, a commanded deceleration results in brake pressure. The variable braking method uses a PI controller to command a deceleration, such that the aircraft tracks a linearly decreasing speed profile versus runway distance (required deceleration decreases with distance). The constant deceleration braking method, as its name implies, simply commands a constant aircraft deceleration. The logic for both braking methods allows for coasting prior to the onset of braking. However, the coasting period for the constant deceleration braking method is longer. The reasons for this is that the variable braking method currently begins the onset of braking as soon as a ROT less than 53 seconds is assured which generally occurs before the time when a constant 6.5 ft/sec^2 deceleration is required.

Although the exit prediction logic makes use of measured runway friction along the runway length, the variable braking method would be less sensitive to unexpected low friction patches on the runway. There are fewer, last-minute, unexpected, exit aborts; since it is actively tracking a velocity profile and would attempt to correct for aircraft overspeed. The constant deceleration braking method does not adjust for real-time conditions. Its only variability is the runway distance at which constant braking should begin, as determined by the exit prediction logic at or prior to touchdown.

Figures in section 1 of the appendix, on pages 126-127 and 128-129, document variable and constant deceleration method time histories, respectively. Definitions for each plot are contained on the preceding pages 123-125. The ROT for the constant deceleration method is a little less than the variable deceleration method. The methods’ deceleration profiles are quite
different as evidenced by the ground speed graph on the first time history sheet and the main
gear mu (available friction used) graphs on the second time history sheet. The variable
deceleration method brakes earlier than the constant deceleration method. The constant
reverse thrust method and a crosswind of 0 knots were used in each time history.

The simulation results showed that the constant deceleration braking method requires a
constant medium braking deceleration command on the exit for the worse case MD-11/wet
surface condition, in order to stop on the exit. This constant deceleration level on the exit was
used in this study for all aircraft when the constant deceleration braking method was in use.
The constant deceleration braking method required additional deceleration logic for the
situation where the aircraft arrives at the exit with a ground speed much lower than the exit
entrance speed. In this case, the aircraft has very likely coasted all the way to the exit. In this
situation, if medium braking began immediately on the exit, many aircraft would stop on the
exit before they have cleared runway. To account for this circumstance, if an aircraft reaches
the exit entrance having never initiated constant braking, constant braking on the exit will not
begin until a ground speed of no less than \(-40\) knots is assured at runway clearance.

**Auto Reverse Thrust Control Law**

Because reverse thrust is needed for operations under low friction runway conditions, this
study assumed that reverse thrust is engaged soon after touchdown by the pilot moving the
throttle levers through the pedestal inter-locks. The pilot then stows reverse thrust, or at a
minimum sets it to idle, at 70 knots ground speed (exit entrance ground speed).

The auto reverse thrust method varies the reverse thrust to minimize brake pressure, while the
constant reverse thrust method sets reverse thrust to idle, 1/3 maximum, 2/3 maximum or
maximum reverse thrust.

For the constant reverse thrust method the current exit prediction logic finds the minimum
constant reverse thrust level required to decelerate to the earliest available high-speed exit,
thereby not fully minimizing braking as does the auto reverse thrust method. The constant
reverse thrust method would not be recommended for optimum deceleration performance,
unless its thrust level were appropriate for each landing.

**Exit Prediction Logic**

In order to minimize runway occupancy time by controlled deceleration, it is desired to
predict which first available high-speed exit the aircraft is capable of using. This prediction
would most likely occur up to a half minute prior to touchdown. Targeting too early an exit
would cause the exit to be aborted, causing the aircraft to coast to the next exit. Targeting too
late an exit would increase runway occupancy time above what's necessary and perhaps
above the maximum desired ROT. Both of these occurrences may cause a following aircraft to
go-around. If no exit prediction logic is employed, targeting too early an exit occurs often.
The exit prediction logic uses the following predicted/estimated inputs: touchdown location, touchdown ground speed, aircraft weight, aircraft CG, aircraft drag characteristics and aircraft thrust versus airspeed/time profiles. Outer loops were added to the exit prediction logic (see the constant reverse thrust (CRT) loops of figure 4.1); which, for a given exit, first finds the minimum required constant reverse thrust setting and then determines the runway distance for the onset of constant deceleration braking, if these methods are in use. The simulation data shows that improvements to the exit prediction logic algorithm have lowered mis-predictions to less than 1% for all study aircraft and deceleration methods. An updated version of the exit prediction algorithm in MATLAB script code is found in section 2 of the appendix.

To find the desired constant reverse thrust level using the current exit prediction logic, the reverse thrust is decreased from maximum to idle until the simulated exit is aborted, assuming immediate onset of either braking method. The prior reverse thrust level that did not cause a simulated exit abort is the desired constant reverse thrust level. Using the current reverse thrust method, the runway distance at which constant braking should begin is found by delaying the braking onset distance further and further down the runway length until the simulated exit is aborted. The runway distance prior to the simulated exit being aborted is the desired constant braking onset distance.

The values (predicted exit, constant reverse thrust setting, onset distance of constant braking) determined by exit prediction logic would be used directly by auto ROTO or displayed to the pilot by the flight director for manual ROTO.
5.0 CREATING SIMULATED ROT SENSITIVITY DATA

Approach

The requirements of reference 1, the aircraft characteristics of section 3 and the ROTO guidance & control system design of section 4 were used to find the sensitivity of ROT (mean and standard deviation) to various operational factors relative to a ROTO baseline system. A ROTO baseline system was defined to have the following operational factors:

1. 3 high-speed 30 degree exits.
2. Spiral-arc exit geometry.
3. Auto reverse thrust and variable deceleration braking method.
4. Error free exit prediction logic; stow reverse thrust at exit entrance ground speed; no asymmetric braking; aircraft CG stops at exit and taxiway centerline tangent point.
5. 70 knot exit entrance ground speed.
6. Dry and Wet runway/exit surface conditions.
7. Study aircraft landing statistics (mean & stdev) as follows:

<table>
<thead>
<tr>
<th>Longitudinal Dispersion (ft)</th>
<th>Ground Speed (kt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MD-81</td>
<td>1362 +/- 198</td>
</tr>
<tr>
<td>MD-11</td>
<td>1375 +/- 225</td>
</tr>
</tbody>
</table>

(Weight and CG were back calculated from the Airspeed)

8. Positive steady 15 knot crosswind; lateral touchdown location at runway centerline.
9. Normal landing flaps, slats extended, spoilers deployed, elevator constant.
10. Anti-skid efficiency of 75%.
11. A maximum allowed aircraft deceleration limit of 6.5 ft/sec² (medium braking).

Note: Positive crosswind direction is from left to right for landing aircraft. A crosswind of increasing magnitude causes greater lateral centerline deviation. Simulation studies found a positive crosswind caused greater deviation than a negative crosswind for a right side exit.

Note: Runway Exit Location is relative to runway threshold.
Note: Runway Occupancy Time is calculated from the time the aircraft crosses the runway threshold (airborne) until the aircraft wing tip clears the near side of the runway. The aircraft may roll 1000 feet from the start of the turn onto the exit to the point where it has cleared the runway.

Note: Sigma and Standard Deviation (stdev) have equivalent meanings.
The ROT sensitivity data was gathered in the following manner:

1. First, the baseline was used to find the ROT sensitivity of the study aircraft to the location of 3 high-speed exits. Auto reverse thrust and variable deceleration braking were employed for these simulation runs. From this simulation data an approximate optimum location for 3 high-speed exits was selected. The optimum mid exit location was then used to test ROT sensitivity to exit spacing and the number of exits.

Using the optimum baseline location for 3 high-speed exits, each operational factor listed below was varied one at a time, for each study aircraft dispersion, to find its effect on ROT sensitivity.

2. Spiral-arc vs circle-arc exit shape.

3. The type of deceleration profile: constant-level deceleration (no exit prediction logic), roll deceleration (no braking) followed by maximum deceleration acceptable to passengers and variable-level deceleration. Auto (variable) and constant reverse thrust methods were also employed.

4. ROTO System Capability: availability of auto, constant, idle and no reverse thrust on runway; availability of exit prediction logic with or without input errors; possible settings of reverse thrust at exit entrance; availability of auto-asymmetric braking and ability to stop on exit.

5. High-speed exit entrance ground speed (40, 60, 70 & 80 knots).


7. Aircraft longitudinal touchdown dispersion standard deviation (stdev).

8. Aircraft touchdown landing ground speed stdev.

9. Crosswind conditions and lateral touchdown location.

10. Flap setting: normal vs full.

11. Anti-skid efficiency: 60%, 75% and 90%.

12. Maximum allowed deceleration: 6.5 (medium) and 9.0 (heavy) ft/sec\(^2\).

Eight hundred eighty eight and 756 auto ROTO simulations were run to gather data for the MD-11 and MD-81 study aircraft dispersions, respectively. These simulation runs covered the range of expected aircraft touchdown ground speeds and longitudinal touchdown locations, spaced 2 knots and 100 feet apart respectively. Each simulation run recorded the runway occupancy time (ROT) and the ROTO exit location used by the aircraft. A 3-D ROT graph displaying the deterministic ROT results of one aircraft dispersion is described below in the Graph Descriptions section.
Calculating Sensitivity Statistics

ROT Mean & Standard Deviation Calculations

To find an aircraft dispersion's ROT mean and stdev, one must first calculate the relative probability of one run occurring relative to the others. This is accomplished by using the mean and stdev of the two random input variables, landing ground speed and longitudinal touchdown location. Assuming that the aircraft landing ground speed and touchdown location are normally distributed and independent of each other, a simulation run's relative probability of occurrence was calculated as follows:

1. The aircraft landing ground speed mean and standard deviation (stdev) were created by adding an aircraft’s landing airspeed and expected wind means and variances, respectively. The stdev is then obtained by taking the square root of the summed variances.

2. The combined effect of aircraft landing ground speed and longitudinal touchdown location, on the relative probability of an individual simulation run occurring, was calculated by creating a probability distribution (PD) for each of the two individual random variables. This was done by subtracting a normal cumulative density function (CDF) from the next CDF, spaced 2 knots and 100 feet apart for the ground speed variable and touchdown location variables, respectively. A joint PD, based on the two random variables, was created by multiplying the individual PD values together at the intersection values of ground speed and touchdown location for each run. A normal CDF (function provided by the spreadsheet containing the data) is calculated as follows:

\[
\frac{1}{\sqrt{2\pi \sigma}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}
\]

The joint PD represents the relative probability of a run occurring based on the aircraft landing ground speed and touchdown location. A joint 3-D PD graph for one aircraft dispersion is described below in the Graph Descriptions section.

Multiplying a simulation run's output values (ROT and ROTO exit number used) by the probability of the run occurring, allowed output value statistics to be calculated. A spreadsheet was used to manipulate the data. Mean, stdev and PD's were calculated for ROT and ROTO exit number used. 2-D ROT and Exit PD graphs are described below in the Graph Descriptions section.
Graph Descriptions

The 3-D ROT graph (Figure 5.1) plots on the vertical z axis the resulting ROT values from an MD-11 dispersion's 888 simulation runs. Each simulation run varies from each other by the aircraft touchdown ground speed on the y axis and the aircraft longitudinal touchdown location on the x axis. Abrupt steps in the ROT values represent transitions from the usage of one high-speed exit to the next. The optimal high-speed exit locations generally cause slow & early (MD-81 type) and fast & late (MD-11 type) landing aircraft to have the highest ROT values.

The 3-D Exit graph (Figure 5.3) plots on the vertical z axis the exit number used by an aircraft for the same aircraft dispersion as the 3-D ROT graph; the x and y axes are identical. The abrupt steps in the z axis (exit number used value) can be correlated to the abrupt steps in ROT values of the 3-D ROT graph.

The joint 3-D probability distribution (PD) graphs (figures 6.19 and 6.20 for the MD-11 and MD-81 respectively) plot the relative probability of a simulation run's occurrence on the vertical z axis for the same aircraft dispersion as the 3-D ROT graph; the x and y axes are identical. The x and y axis titles, respectively, display the mean and stdev of the aircraft touchdown location and ground speed used in the CDF calculations described above.

The 2-D ROT PD graph (Figure 5.2) plots the probability (y axis) of the ROT times (vertical lines, rounded to the nearest second) listed on the x axis for each high-speed exit. The legend defines the line style for each high-speed exit number and all exits. The line containing the most area under it would represent the exit used by most of the aircraft in the dispersion.

The 2-D Exit PD graph (Figure 5.4) plots the probability (y axis) of the high speed exit number being used by aircraft in the dispersion, listed on the x axis. The probability of exit usage can be related to the area under the lines of the 2-D ROT PD graph.
Tabular Statistics

Section 3 of the appendix contains a table, which lists by row the statistics calculated for each aircraft simulation dispersion included in this sensitivity study. The average rows contain the averaged statistics from a set of aircraft dispersions differing only in aircraft type and runway/exit surface condition for one operational factor variation from the operational factor baseline.

The table’s columns from left to right, applying to a simulated aircraft dispersion, are as follows:

<table>
<thead>
<tr>
<th>Column from left to right</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Deceleration method, exit prediction logic usage &amp; difference from baseline</td>
</tr>
<tr>
<td>2</td>
<td>3 exit locations</td>
</tr>
<tr>
<td>3</td>
<td>aircraft type</td>
</tr>
<tr>
<td>4</td>
<td>data row # referenced by the legend in ROT sensitivity figures 6.1-12 and figures beginning on page 1 of volume 2</td>
</tr>
<tr>
<td>5</td>
<td>runway/exit surface condition</td>
</tr>
<tr>
<td>6</td>
<td>runway occupancy time, mean</td>
</tr>
<tr>
<td>7</td>
<td>percent of aircraft dispersion stopping at the end of the runway resulting in a non, high-speed ROTO landing</td>
</tr>
<tr>
<td>8</td>
<td>percent of aircraft dispersion having a ROT greater than 53.4 seconds</td>
</tr>
<tr>
<td>9</td>
<td>runway occupancy time, stdev</td>
</tr>
<tr>
<td>10</td>
<td>exit number used by aircraft, mean</td>
</tr>
<tr>
<td>11</td>
<td>exit number used by aircraft, stdev</td>
</tr>
<tr>
<td>12</td>
<td>Report page number(s) containing figures which graph that row of data</td>
</tr>
</tbody>
</table>
The deceleration method abbreviations found in tabular column 1 are as follows:

<table>
<thead>
<tr>
<th>Deceleration Method</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auto reverse thrust (variable)</td>
<td>auto rev thr</td>
</tr>
<tr>
<td>Constant reverse thrust setting</td>
<td>const rev thr</td>
</tr>
<tr>
<td>Variable deceleration braking</td>
<td>var dec</td>
</tr>
<tr>
<td>Roll, then constant deceleration braking</td>
<td>roll-const dec</td>
</tr>
<tr>
<td>Exit Prediction Logic in use</td>
<td>w/ PRED</td>
</tr>
<tr>
<td>Exit Prediction Logic not used</td>
<td>w/o PRED</td>
</tr>
</tbody>
</table>

Tabular columns 4 and 12 can be used to link tabular data to graphical data. Column 4 is referenced by the legend in the ROT sensitivity figures found in figures 6.1-12 and page 1 of volume 2. Column 12 lists the report figure numbers and page numbers, which graph that row of tabular data. The page numbers are preceded by a P and refer to volume 2. The x axis lists the statistic, while its magnitude is plotted on the y axis. There are two y axes in order to increase the scale resolution of ROT stdev, exit number (#) mean and exit number (#) stdev. The left three x axis statistics use the y axis left of center. The right three x axis statistics use the y axis on the right.

ROT sensitivity figures 6.1-12 (a), described below, graph the averaged statistics found on the tables rows (wet/dry/MD-81 and wet/dry/MD-11 dispersions are averaged together). When present, figures 6.1b-12b and 6.1c-12c graph the statistics for the wet/dry/MD-81 and wet/dry/MD-11 dispersions separately. The graphs on pages 1-48 of volume 2 allow you to graphically see the statistics for each aircraft dispersion individually, pertaining to a single operational factor variation from the operational factor baseline.

The graphs on pages 49-288 of volume 2 (set of two graphs) display the raw ROT data used to create the data row’s dispersion statistics. The first 3-D graph and second 2-D graph are described in the previous Graph Descriptions section as the 3-D ROT graph and 2-D ROT PD graph, respectively.
6.0 ROT SENSITIVITY RESULTS

The ROT (runway occupancy time) sensitivity of each operational factor studied in this report can be found in the ROT sensitivity graphs of figures 6.1-12, described below. The x axis lists statistics described in the Tabular Statistics section above. The magnitude of each statistic is plotted on one of two y axes, named ‘value’. There are two y axes in order to increase the scale resolution of ROT stdev, exit number (#) mean and exit number (#) stdev. The left three x axis statistics use the y axis left of center. The right three x axis statistics use the y axis on the right.

The sensitivity discussion below attempts to describe the ROT trends seen in the ROT sensitivity graphs of figures 6.1-12 and pages 1-48 of volume 2. For each data series, the legend of the ROT sensitivity graph gives a data row number listed in column 4 of the tabular data in section 3 of the appendix, from which the data originated. The tabular data can then be traced to the raw ROT simulation data (3-D ROT & 2-D ROT PD graphs) by using the table’s right-most column listing page numbers (Pxxx) of volume 2. The raw ROT simulation graphs are found in volume 2 in the same order as the tabular row data referring to them.

Improved ROTO performance is indicated by smaller magnitudes for all of the x axis statistics. It is desired that the greatest percent of the landing aircraft dispersion not pass the 3rd high-speed exit and have a ROT less than 53.4 seconds, because a violation of these items would very likely cause a following aircraft to go-around. Go-arounds for current operations occur as rarely as 0.1% of the landings. Two and three sigma make up 95.5% and 99.8% of the landing aircraft dispersion, respectively. The best ROTO performance would be to achieve a low ROT mean and a low percent of aircraft using the end of the runway and/or having a ROT greater than 53.4 seconds. Both the ROT mean and the ROT stdev affect the percent of aircraft having a ROT greater than 53.4 seconds.

Of the various deceleration methods, the auto reverse thrust/variable deceleration braking method has the lowest combined ROT mean and percent of aircraft having a ROT greater than 53.4 seconds. For the baseline ROTO system described earlier, using this deceleration method and a mid exit location at 5950 feet results in 1% of the aircraft having a ROT greater than 53.4 seconds. This is due partly to its low ROT stdev and the low percent of aircraft (1%) exiting at the end of the runway. Several operational factors would improve these statistics, such as: requiring a smaller touchdown ground speed stdev, allowing a maximum deceleration of 9 ft/sec² and using an exit entrance ground speed greater than 70 knots. The auto reverse thrust/variable deceleration braking method does not have the lowest ROT mean, alone, among the various deceleration methods.
The two operational factors, aircraft type (MD-11 & MD-81) and runway/exit surface condition (wet & dry), were given equal weight in these studies by averaging their four dispersions, as a third operational factor was varied from the baseline. As a general rule, operational factors cause ROT sensitivity to aircraft type and runway/exit surface condition (wet & dry) to increase if the required deceleration is not available. Unless otherwise noted in these results, ROT has a large sensitivity to aircraft type but does not have a large sensitivity to wet and dry runway/exit surface conditions.
ROT Sensitivity to Aircraft Type - Figures on pages 1-48 of Volume 2

ROT is sensitive to aircraft type for any given set of operational factors. The figures on pages 1-48 of volume 2 list ROT statistics of each studied aircraft dispersion type, for one set of operational factors. Acknowledging ROT sensitivity to aircraft type, it is then desired to determine ROT sensitivity to an operational factor when averaging the ROT statistics of four wet/dry/MD-11/MD-81 aircraft dispersions together. If ROT sensitivity to an operational factor is mainly due to one aircraft type, figures 6.X b and c are included below to show the ROT statistics of averaged wet/dry/MD-81 and wet/dry/MD-11, respectively. The MD-11 aircraft type appears to be more sensitive to operational factors, which causes the selected high-speed mid exit position of 5950 feet to become less optimal for the MD-11.

Figure 6.10 (ROT Sensitivity to Crosswind Conditions and Lateral Touchdown Offset), described later in the report, is an example of averaged wet/dry/MD-11/MD-81 dispersions having a low ROT sensitivity to an operational factor (crosswind conditions). Individual ROT sensitivity figures b and c are not shown because the MD-81 and MD-11 did not individually contribute to ROT sensitivity for this operational factor. Page 20 in volume 2 still shows ROT sensitivity to aircraft type for the no crosswind condition.
ROT Sensitivity to Exit Location, Spacing & Number of Exits (Figures 6.1a, b & c)

The auto reverse thrust/variable deceleration braking method with exit prediction logic was used to determine the sensitivity of ROT to exit location, exit spacing and number of exits. In the headings, the page number of the volume 2 graph(s) pertaining to each section is given in parenthesis.

Exit Location (Pages 1-3, 25, 26 of volume 2)

The locations of 3 high-speed exits, having 70 knot entrance ground speeds, were shifted to find the sensitivity of ROT to exit location; for MD-81 to MD-11 type aircraft dispersions on dry and wet surface conditions. This report usually refers to the mid exit location of a 3 exit set. For a given set of operational factors, ROT decreases as exit locations are moved closer to the runway threshold up to a point. ROT then begins to increase when a significant number of landing aircraft cannot stop by the 3rd exit, resulting in NON-ROTO landings with aircraft exiting at the end of the runway.

A set of three exit locations was chosen by first selecting the mid (2nd) exit location. The location of the 1st exit is moved nearer to the runway threshold until any studied dispersion aircraft, on a wet surface condition, begin to reach the next (2nd) exit with a ROT greater than 53 seconds. As the first exit is moved closer to the threshold, the exit prediction logic selects it for fewer aircraft having the required deceleration capability. As the distance between exits widens, some of the aircraft just on the border of not being selected for the first exit may take longer than 53 seconds to reach the next (2nd) exit. With the first exit located, the third exit location is then pushed down the runway in a like manner until aircraft begin to arrive at the third exit with a ROT greater than 53 seconds. The selected spacing of the first and third exits would have been different if it had been desired to optimize for a single aircraft type or surface condition. A too-wide exit spacing example is described below.

It was found that the 2nd exit was not equally spaced between the 1st and 3rd exits. When positioning 3 exit sets down the runway, the distance between the 1st and 2nd exit held constant at 1450 feet. The distance between the 2nd and 3rd exits ranged from 1600 feet down to 1200 feet, for short and long positioned exits respectively. The second column in the table in section 3 of the appendix lists the set of three exit locations for each simulation dispersion. The position of the text in this column is positioned to help the reader visualize the relative position of the exits. A fourth high-speed exit was placed at 10000 feet to represent the end of the runway.

ROT sensitivity to wet and dry runway/exit surface conditions and aircraft type increase as exit locations are moved nearer to the runway threshold, as seen on page 25 of volume 2. This is due to aircraft, especially MD-11's, not being able to stop by the 3rd exit. ROT sensitivity to aircraft type virtually disappears for exits located far down the runway as seen on pages 14 and 26 of volume 2.
**Wider Exit Spacing** (Page 4 of volume 2)

The 1st and 3rd exit locations, for the wider exit location example, were each moved 200 feet further from the mid exit location. The MD-11 dispersion on a wet surface condition, shown on page 65 in volume 2, is an example of aircraft not quite getting to the next exit (3rd) with a ROT under 53 seconds. This is due to the 3rd exit being too far from the 2nd exit.

Wider exit spacing decreases ROT stdev sensitivity to aircraft type as seen on page 4 of volume 2.

**Exit Number** (Pages 30-32 of volume 2)

The baseline condition employed three runway exits. The ROT sensitivity to the number of exits was studied by creating a runway with 1, 2, and 4 exits(s). The 2-exit runway was created by placing the two exits at the midpoints of the 1st & 2nd and the 2nd & 3rd exits, respectively, of the 3-exit baseline runway having the mid exit location at 5950 feet. The 1-exit runway placed the single high-speed exit at 5950 feet. The 4-exit runway included the set of three exits having a mid exit location at 5350 feet and added a fourth high-speed exit at 8300 feet.

ROT mean sensitivity to aircraft type decreases as the number of high-speed exits decrease, as seen in the 1-exit runway example on page 31 of volume 2.

**Averaged Aircraft Dispersion ROT Sensitivity** (Figures 6.1 a, b & c)

Figure 6.1a shows that ROT is sensitive to exit location, exit spacing and the number of exits. This study determined that the mid exit location should be placed at 5950 feet (page 3 of volume 2) past the runway threshold for the baseline runway, when all studied aircraft dispersions are averaged. The 1st and 3rd exit locations were placed at 4500 and 7350 feet, respectively. This position gave the lowest ROT mean, ROT stdev and percent of aircraft with a ROT greater than 53.4 seconds. The mid exit location at 5950 feet resulted in the following aircraft dispersion ROT statistics.

**ROT statistics with mid exit location at 5950 feet**

<table>
<thead>
<tr>
<th>Aircraft Type (dry/wet averaged)</th>
<th>ROT Mean (sec)</th>
<th>ROT STDEV (sec)</th>
<th>Exit numb er (#) Mean</th>
<th>Exit number (#) STDEV</th>
<th>% of aircraft using the end of runway</th>
<th>% of aircraft having a ROT greater than 53.4 seconds</th>
</tr>
</thead>
<tbody>
<tr>
<td>MD-11</td>
<td>47.0</td>
<td>4.09</td>
<td>2.27</td>
<td>0.63</td>
<td>2.02</td>
<td>2.01</td>
</tr>
<tr>
<td>MD-81</td>
<td>41.2</td>
<td>3.22</td>
<td>1.21</td>
<td>0.42</td>
<td>0</td>
<td>0.1</td>
</tr>
<tr>
<td>MD-11 &amp; MD-81 (averaged)</td>
<td>44.1</td>
<td>3.65</td>
<td>1.74</td>
<td>0.52</td>
<td>1.01</td>
<td>1.05</td>
</tr>
</tbody>
</table>
The mid exit location at 5950 feet was placed so that some slowest/earliest landing aircraft gave a high ROT at the 1st exit and some fastest/latest landing aircraft gave high ROT values by using the end of the runway. The ROT statistics increased on both sides of this 5950 optimum mid exit position. The statistics also increased if the spacing of the 1st and 3rd exits around mid exit location 5950 was increased. The mid exit location at 5950 feet with wider exit spacing and the mid exit location at 6550 feet had smaller percentages of aircraft using the end of the runway because of the 3rd exit being further down the runway.

The 2 and 1 exit runways centered at 5950 feet have unacceptable ROT statistics for the studied aircraft dispersions. The 4 exit example with the 2nd mid exit at 5350 feet only improves over the baseline 5350 exit set by having fewer aircraft using the end of the runway.

The 5950 foot optimum mid exit location is further down the runway than that recommended by reference 2. This study allowed a maximum deceleration of 6.5 ft/sec², whereas reference 2 allowed a maximum deceleration of 9 ft/sec². Figures 6.11a, b & c, discussed below, show a lower ROT mean for the mid exit location at 5350 feet when a maximum deceleration of 9 ft/sec² is allowed. Any operational factor affecting deceleration capability affects the selection of optimum exit locations.

The sensitivity of ROT to exit location and exit spacing is due mainly to the MD-11 type aircraft (figure 6.1c) versus the MD-81 type aircraft (figure 6.1b). MD-81 ROT sensitivity did not appear until the mid exit location at 6550 feet. The mid exit location at 4950 feet is slightly more optimum for the MD-81. The mid exit location at 6550 feet is slightly more optimum for the MD-11, especially decreasing the number of MD-11s using the end of the runway.
ROT Sensitivity to ‘on-exit’ Operational Factors (Figures 6.2a, b & c)

The ‘on-exit’ operational factors discussed in this section only contribute to ROT from the time the aircraft passes the entrance of the high-speed exit until it clears the runway. They do not affect the exit number (#) mean, exit number (#) stdev or percent of aircraft using the end of the runway. In the headings, the page number of the volume 2 graph(s) pertaining to each section is given in parenthesis. The results (page 3 of volume 2) of the operational factor baseline (see beginning of section 5.0) can be compared with all other results.

Constant radius-arc high-speed exit (Page 24 of volume 2)

Figure 3.12 illustrates how the constant (2900 ft) radius-arc high-speed exit compares to a spiral-arc exit (reference 3). For simulation purposes, the constant radius-arc exit entrance was placed at the same location as its spiral-arc counterpart. The constant radius-arc exit veers away from the runway centerline in a shorter path distance than the spiral-arc high-speed exit, but also has less stopping distance prior to the aircraft entering onto the taxiway. Also steering logic should to be employed to minimize a theoretically infinite lateral jerk at the abrupt entrance to the constant radius-arc exit.

Reverse thrust not stowed prior to exit, limit to idle (Page 29 of volume 2)

Coasting (i.e. no braking or reverse thrust including idle reverse thrust) after the aircraft speed decreases to the exit entrance ground speed minimizes ROT. Thus, it was recommended that reverse thrust be stowed by the pilot at the exit entrance ground speed (usually 70 knots) or prior to entering the high-speed exit. However, some pilots have voiced the preference of only setting reverse thrust to idle and stowing reverse thrust after the aircraft comes to a complete stop. Therefore, ROT sensitivity to idle reverse thrust on the exit was studied.

The ROT stdev loses its sensitivity to aircraft type when reverse thrust is not stowed prior to the exit. The MD-81 stdev increases to that of the MD-11 stdev.

Not stowing reverse thrust prior to the exit, while limiting it to idle, caused some MD-81 aircraft to come to a stop before they cleared the runway. Higher ROT values can be seen on page 207 of volume 2, when compared to page 61 of volume 2.

Reverse thrust not stowed prior to exit, do not limit to idle (Page 40 of volume 2)

This is a variation of the preceding case where the reverse thrust is also not stowed; but, in addition, reverse thrust is allowed to be driven to idle while on the exit rather than being at idle reverse thrust when entering the exit. In this case, auto reverse thrust decreases the reverse thrust magnitude as brake pressure decreases. The stated results for the previous case are more pronounced for this case.

Stop aircraft CG on exit (Page 34 of volume 2)

The baseline ROTO system, with variable deceleration braking, stops the aircraft CG where the high-speed exit centerline is tangent to the parallel taxiway centerline (see figure 3.12). The modeled parallel taxiway centerline has a lateral offset of 600 feet from the runway centerline. ROT sensitivity to the aircraft CG stopping prior to reaching the parallel taxiway
near a lateral offset of 480 feet from the runway centerline was tested. Stopping at this location on the exit may increase braking on the exit prior to the aircraft clearing the runway and thus potentially increase ROT. The results show (compare page 34 with page 3 in volume 2) that this factor has only a slight effect on ROT. The constant deceleration braking method with a deceleration of 6.5 ft/sec^2, based on the braking needs of an MD-11 on a wet surface condition, appears to consistently stop the aircraft CG on the exit.

**Auto-asymmetric braking on exit (Page 46 of volume 2)**

Auto asymmetric braking on the exit is a steering technology that could backup auto nosewheel steering. This function was tested for its negative affect on ROT due the deceleration caused by its added asymmetric braking command. Its positive affect on ROT would be the improved exit centerline tracking capability, causing the aircraft to clear the runway sooner.

**Averaged Aircraft Dispersion ROT Sensitivity (Figures 6.2a, b & c)**

Figure 6.2a shows that the constant radius-arc exit geometry and auto asymmetric braking decrease the ROT mean by several seconds. It is believed that other improvements in steering performance would have a similar positive effect on the ROT mean, as did auto asymmetric braking. Not stowing reverse thrust at the exit entrance ground speed did increase the ROT mean slightly. ROT was not sensitive to the aircraft CG stopping on the exit at a lateral distance of 480 feet from the runway centerline. The MD-81 ROT stdev is more sensitive to this operational factor than the MD-11, as seen in figures 6.2b & c respectively.
ROT Sensitivity to Reverse Thrust & Braking Deceleration Methods
(Figures 6.3a, b & c)

The legend of figure 6.3 lists possible ROTO deceleration method combinations and whether exit prediction logic was used. The 5th and 6th legend entries represent the non-ROTO method with immediate constant (medium and maximum) reverse thrust and immediate constant 6.5 ft/sec² braking onset, without exit prediction logic. The abbreviations used in the tabular data in section 3 of the appendix and the legends of the ROT sensitivity graphs are listed below:

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>auto rev thr</td>
<td>Auto reverse thrust (variable)</td>
</tr>
<tr>
<td>const rev thr</td>
<td>Constant reverse thrust setting</td>
</tr>
<tr>
<td>var dec</td>
<td>Variable deceleration braking</td>
</tr>
<tr>
<td>roll-const dec</td>
<td>Roll, then constant deceleration braking</td>
</tr>
<tr>
<td>with PRED</td>
<td>Exit Prediction Logic in use</td>
</tr>
<tr>
<td>NO PRED</td>
<td>Exit Prediction Logic not used</td>
</tr>
</tbody>
</table>

It is believed that auto reverse thrust/variable braking and constant reverse thrust/roll-constant braking would require the most and least ROTO cost per aircraft, respectively. Auto reverse thrust/variable braking has additional benefits over constant reverse thrust/roll-constant braking as follows:

1. The current exit prediction logic algorithm requires higher real-time CPU resources for determination of the correct constant reverse thrust setting and the appropriate onset distance of constant braking, due to its iterative implementation. The auto reverse thrust/variable braking method does not require iteration.

2. Auto reverse thrust and variable deceleration braking do not require exit prediction logic (but it is recommended). Constant reverse thrust and roll-constant braking require exit prediction logic or some type of on-line algorithm to suggest to the pilot the level of constant reverse thrust and the runway distance at which to initiate constant deceleration braking.

3. The current exit prediction logic algorithm gives approximately 1% mis-predictions for the constant reverse thrust/roll-constant braking method (see ROT spikes and discontinuities in 3-D ROT graph on page 93 of volume 2), when the runway/exit surface condition is uniform. The auto reverse thrust/variable braking method results in approximately 0.1% mis-predictions. Mis-predictions most likely would cause following aircraft to go-around.
4. If the runway surface has unmeasured low friction patches, which could conceivably increase the chance of an aircraft aborting an exit, variable braking attempts to adjust in real-time to the increasing speed error; thereby minimizing the chance of aborting the predicted exit. The constant deceleration method, implemented here, does not compensate for lost deceleration due to unexpected low friction patches.

5. Auto reverse thrust, as implemented, minimizes brake pressure.

The exit prediction logic may not predict the same set of exits for an aircraft dispersion using different deceleration methods.

In the headings, the page number of the volume 2 graph(s) pertaining to each section is given in parenthesis. The first heading below is the baseline reverse thrust braking method (see beginning of section 5.0).

**Auto reverse thrust/variable deceleration** (Page 3 of volume 2)
Variable deceleration does not show a large ROT sensitivity to wet and dry runway/exit surface conditions. The ROT mean, stdev and Exit number (#) mean are sensitive to aircraft type.

**Constant reverse thrust/roll-constant deceleration** (Page 9 of volume 2)
Constant deceleration does show a large ROT mean sensitivity to wet and dry runway/exit surface conditions. The ROT stdev is not sensitive to aircraft type.

**Auto reverse thrust/roll-constant deceleration** (Page 10 of volume 2)
Constant deceleration does show a large ROT mean sensitivity to wet and dry runway/exit surface conditions. The ROT stdev is not sensitive to aircraft type, except for the higher value of the MD-11 dispersion on a wet runway/exit surface condition.

**Constant reverse thrust/variable deceleration** (Page 11 of volume 2)
Variable deceleration does not show a large ROT sensitivity to wet and dry runway/exit surface conditions. The ROT statistics of the MD-81 dispersion on a wet runway surface are now grouped with the both MD-11 dispersions.

**Immediate (medium&maximum) constant reverse thrust/immed, medium constant deceleration**
(Pages 8 and 45 of volume 2)
Constant deceleration does show a large ROT sensitivity to wet and dry runway/exit surface conditions. Maximum immediate constant reverse thrust decreases the ROT mean sensitivity.

With the constant medium reverse thrust setting, 32% of the NON-ROTO MD-11 cases aborted at least one high-speed exit, which is believed to be unacceptable for airport operations. The 1st exit is always selected by default with no exit prediction logic in use. As stated above, the exit prediction logic algorithm causes approximately 0.1% of the exits to be aborted for the auto reverse thrust/variable deceleration braking method. Without reverse thrust flight guidance, it is unknown what constant reverse thrust setting a pilot might select.
The non-ROTO method's immediate constant deceleration is excessive for some aircraft landings and causes higher maximum ROT values for each exit when compared with the auto reverse thrust/variable deceleration method as seen on pages 81 and 57 of volume 2, respectively. The effect of these two deceleration methods on ROT stdev is seen on pages 82, 84, 86, & 88 and 58, 60, 62 & 64 of volume 2 respectively; reflected by the width of and area under the ROT curves for each exit.

**Averaged Aircraft Dispersion ROT Sensitivity (Figures 6.3a, b & c)**

Figure 6.3a shows that ROT is moderately sensitive to the ROTO deceleration methods and highly sensitive to the non-ROTO deceleration methods. The roll-constant deceleration braking method had a slightly lower ROT mean and stdev. This might be expected because this method allows the aircraft to coast for a longer runway distance before braking is initiated. The exit number (#) mean and stdev are very similar for all deceleration methods. The auto reverse thrust/variable deceleration braking method results in the fewest aircraft using the end of the runway and the fewest aircraft having a ROT greater than 53.4 seconds.

The constant reverse thrust/variable deceleration braking method had the highest ROT mean. The auto reverse thrust/roll-constant deceleration braking method had the highest percent of aircraft using the end of the runway. Both of these methods mix variable and constant deceleration techniques.

The 5th and 6th deceleration methods, non-ROTO immediate medium/maximum reverse thrust/constant medium deceleration without exit prediction, have the highest ROT stdev of the deceleration methods studied. They have a slightly lower ROT mean and exit number (#) mean when compared to the auto reverse thrust/variable deceleration method. Possibly the exit prediction logic used with the auto reverse thrust/variable deceleration method is a little cautious in selecting exits.

The MD-81 ROT mean is more sensitive to this operational factor, while the MD-11 ROT stdev is more sensitive; as seen in figures 6.3b & c respectively.
ROT Sensitivity to Exit Location for non-ROTO/NO Exit Prediction (Figure 6.4)

The exit location studies were repeated for three mid exit locations using the non-ROTO deceleration method. This method uses no exit prediction with immediate (medium & maximum) reverse thrust and immediate medium constant deceleration. The general ROT characteristics of this deceleration method were described in the previous section. The medium and maximum reverse thrust ROT data are found on pages 7-9 and 43-45 of volume 2, respectively. Graphs on pages 7-9 of volume 2 show a ROT mean sensitivity to wet and dry runway/exit surface conditions.

The use of maximum constant reverse thrust lessens ROT mean sensitivity to runway/exit surface conditions. Maximum reverse thrust causes a higher ROT mean and higher ROT values for the 1st exit as seen on page 276 of volume 2, when compared to medium reverse thrust on page 88 of volume 2.

Averaged Aircraft Dispersion ROT Sensitivity (Figure 6.4)

When all studied aircraft dispersions are averaged, a mid exit location at 5950 feet again appears to be optimum because it results in the fewest aircraft using the end of the runway and fewest aircraft having a ROT greater than 53.4 seconds. The percent of aircraft having a ROT greater than 53.4 seconds does not follow a trend for the mid exit location at 5350 feet. This value would lie between the mid exit locations of 4950 and 5950 if exits were not aborted due to the use of exit prediction logic, as seen in figure 6.1a.
ROT Sensitivity to ROTO/Exit Prediction Capability (Figures 6.5a, b & c)

This study was performed to show the sensitivity of ROT to the presence of properly functioning exit prediction logic. The 5th and 6th legend data items represent an example of exit prediction not being available. Even if exit prediction is available, it is still possible to input inaccurate data to the algorithm. This decreases the ability to select the optimum exit for aircraft or may cause a mis-predicted exit abort. The variable and constant deceleration methods with exit prediction logic were compared with and without an estimated aircraft longitudinal touchdown location input error of +300 feet. This exit prediction input error is representative of other possible input errors, such as: aircraft touchdown ground speed, aircraft touchdown weight, measured runway friction coefficient and other aircraft characteristics used to model aircraft deceleration.

In the headings, the page number of the volume 2 graph(s) pertaining to each section is given in parenthesis. The first heading is the operational factor baseline (see beginning of section 5.0).

Variable deceleration with exit prediction (Page 3 of volume 2)
This deceleration method is described in the section describing figure 6.3 (two sections earlier).

Variable deceleration with exit prediction input error (Page 22 of volume 2)
ROT remains insensitive to wet and dry runway/exit surface conditions.
The higher exit number (#) mean, caused by the exit prediction input error, resulted in the MD-11 aircraft dispersions having a higher percentage of aircraft using the end of the runway and higher ROT values for each exit as seen on page 169 of volume 2. The figure on page 169 of volume 2 can be compared to the figure on page 57 of volume 2, which included no exit prediction input error.

Constant deceleration with exit prediction (Page 9 of volume 2)
This deceleration method is described in the section describing figure 6.3 (two sections earlier).

Constant deceleration with exit prediction input error (Page 23 of volume 2)
ROT remains sensitive to wet and dry runway/exit surface conditions. Similar ROT effects as described for the auto deceleration method.

Immediate (medium&maximum) constant reverse thrust/immed, medium constant deceleration (Pages 8 & 45 of volume 2)
This deceleration method is described in the section describing figure 6.3 (two sections earlier).

Averaged Aircraft Dispersion ROT Sensitivity (Figures 6.5a, b & c)
Figure 6.5a shows that the ROT mean is sensitive to exit prediction input error. For both variable and constant deceleration methods, the +300 longitudinal aircraft touchdown location input error caused the exit prediction logic to recommend later exits causing the ROT and exit number (#) means to increase for all studied aircraft dispersions.

The ROT mean and stdev is sensitive to the non-use of exit prediction logic by the non-ROTO immediate constant deceleration method. It has a larger percent of aircraft with a ROT
greater than 53.4 seconds. This is due to the percent (32%) of aircraft dispersions aborting at least one high-speed exit.

The MD-11 ROT mean and stdev are more sensitive to this operational factor compared to the MD-81, as seen in figures 6.5c & b respectively. The higher exit number (#) mean, caused by the exit prediction error, especially increased the number of MD-11 aircraft using the end of the runway causing a higher percentage of MD-11 aircraft to have a ROT greater than 53.4 seconds.
ROT Sensitivity to High-speed Exit Entrance Ground Speed (Figures 6.6a, b & c)

Aircraft dispersions using 40, 60, 70 and 80 knot exit entrance ground speeds for the optimum mid exit location at 5950 feet were simulated using the auto reverse thrust/variable deceleration method with exit prediction. Faster exit entrance speeds allow for the optimum exit location to be somewhat nearer to the runway threshold, without increasing the percent of aircraft using the end of the runway (passing the 3rd exit); and visa versa. Therefore, a faster 80 knot exit entrance speed was simulated with an earlier mid exit location at 4950 feet and slower 60 knot exit entrance speed was simulated with a later mid exit location at 6950 feet. 40 and 60 knot exit entrance speeds were also simulated with mid exit locations earlier than 5950 feet to document the results.

The maximum allowed exit entrance ground speed is constrained by the following: the steering performance must be capable of controlling the position of the aircraft gear within the bounds of the exit, lateral acceleration must remain below 0.15 G's and the aircraft must be able to stop on the exit prior to entering the taxiway. An exit entrance ground speed much greater than 70 knots (plus 2 knots allowed over-speed at the exit entrance) cannot be recommended from the steering performance studies thus far completed for worse case conditions (MD-11, aft CG, wet surface condition, 15 knot steady crosswind, no asymmetric braking).

The table below lists the page numbers of volume 2 graphs pertaining to each mid exit location/exit entrance ground speed data series in figures 6.6a, b & c.

<table>
<thead>
<tr>
<th>Mid Exit Location</th>
<th>Exit Entrance Ground Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>40 knots</td>
</tr>
<tr>
<td>4950 feet</td>
<td></td>
</tr>
<tr>
<td></td>
<td>page 38 of volume 2</td>
</tr>
<tr>
<td>5350 feet</td>
<td>page 48 of volume 2</td>
</tr>
<tr>
<td>5950 feet</td>
<td>page 39 of volume 2</td>
</tr>
<tr>
<td>6550 feet</td>
<td></td>
</tr>
<tr>
<td>6950 feet</td>
<td></td>
</tr>
</tbody>
</table>

Using the mid exit location at 5950 feet as an example; graphs on pages 39 (40kt), 12 (60kt), 3 (70kt) & 13 (80kt) of volume 2 show that ROT sensitivity to wet and dry runway/exit surface conditions and aircraft type increases as exit entrance ground speed decreases. All aircraft
dispersions had a similar ROT mean and stdev for the 60 knot exit entrance speed at the 6950 foot mid exit location, as seen on page 14 of volume 2. This is mainly due to the late exit location. For the mid exit location at 5950 feet, the MD-11 had high ROT values for the 60 knot exit entrance speed, as seen on pages 113 and 115 of volume 2.
Averaged Aircraft Dispersion ROT Sensitivity (Figures 6.6a, b & c)

ROT is highly sensitive to the exit entrance ground speed. Figure 6.6a shows that as the exit entrance speed increases, the ROT mean decreases. When averaging all aircraft dispersions, the only ROT improvement over the baseline was the use of an 80 knot exit entrance speed at the 5950 foot mid exit location. The 80 knot exit entrance speed at the 4950 foot mid exit location increased the percentage of aircraft using the end of the runway and the percentage having a ROT greater than 53.4 seconds.

When all aircraft dispersions are averaged, a high percentage of aircraft having a ROT greater than 53.4 seconds was found for 40 and 60 knot exit entrance speeds at all studied mid exit locations. For the 60 knot exit entrance speed at the 6950 foot mid exit location, this was due to aircraft taking longer to reach the exit, rather than aircraft passing the 3rd exit and exiting at the end of the runway.

Figure 6.6c shows that the unacceptability of an 80 knot exit entrance speed at the 4950 foot mid exit location is due to a high percentage of MD-11's using the end of the runway. The MD-11 only benefited over the baseline for the 80 knot exit entrance speed at the 5950 foot mid exit location.

Figure 6.6b shows that the MD-81 benefited from both 80 knot exit entrance speed cases. Mid exit locations 4950 and 5950 with the 60 knot exit entrance speed are acceptable for the MD-81, even though their ROT mean (approx. 44.5 seconds) is higher than the MD-81 baseline. The 40 knot exit entrance speed greatly degraded ROT performance for the MD-81.
ROT Sensitivity to Runway/Exit Surface Condition (Figures 6.7a, b & c)

Friction coefficient versus aircraft ground speed is illustrated in figure 3.11 for the runway/exit surface conditions used in this study. The simulation runtime was limited to 99 seconds, which for some aircraft landings on ice and flood runway/exit surface conditions, sufficient time was not available to decelerate the aircraft to exit speed. Therefore, these landings gave lower ROT mean values than in actuality. ROT sensitivity to runway/exit surface conditions was studied with the mid exit location at 5950 feet using the auto reverse thrust/variable deceleration method with exit prediction. The legend of figures 6.7a, b & c list surface condition in descending order of friction coefficient.

The surface conditions used in this study are considered to be uniform along the entire runway length, with no patches of differing surface condition. Unmeasured patches of surface friction would affect the accuracy of the exit prediction logic, as represented by the exit prediction error discussed in the ROT Sensitivity to ROTO/Exit Prediction Capability section above. A constant deceleration method, that does not track a speed error, would not be able to adjust its deceleration for the effects of unexpected friction patches.

The MD-11 & MD-81 3-D ROT graphs for these runway/exit surface condition studies are found on pages 57-63 (wet and dry) and 189-203 (ice, snow, slush & flood) of volume 2. Aft CG, heavy MD-81 and MD-11 do not have adequate steering performance on an exit with a snow surface condition and a crosswind of 15 knots. Therefore, if the ROTO system determines that the snow surface condition provides adequate deceleration on the runway, the snow surface condition should not extend onto the exit. Adequate exit steering performance can be attained on dry, slush and wet surface conditions.

Averaged Aircraft Dispersion ROT Sensitivity (Figures 6.7a, b & c)

For this set of operational factors, figures 6.7a, b & c show that the ROT mean is not sensitive to dry, slush and wet runway/exit surface conditions. The ROT mean is somewhat sensitive to the snow runway/exit surface condition. ROT is very sensitive to flood and ice runway/exit surface conditions.

Figure 6.7a shows that ice and flood runway/exit surface conditions increased all of the ROT statistics, requiring a high-speed exit at or greater than 15000 feet past the runway threshold for some MD-81 and MD-11 aircraft landings. Also, exit steering performance on ice and flooded surface conditions is not adequate at high speeds. The snow surface condition mainly increased the percent of aircraft using the end of the runway and percent of aircraft having a ROT greater than 53.4 seconds.

The MD-11 (figure 6.7c) dispersion was solely responsible for the high percentage of aircraft with a ROT higher than 53.4 seconds, on a snow runway/exit surface condition. The MD-81 (figure 6.7b) has good ROT statistics for the snow runway/exit surface condition.
ROT Sensitivity to Touchdown Longitudinal Location stdev (feet) (Figure 6.8)

This study investigated ROT sensitivity to touchdown longitudinal location stdev (feet) as described in the dispersion requirements of AC 20-57A. ROT sensitivity to the touchdown longitudinal location mean was not studied, because it is similar to the sensitivity of varying the high-speed exit locations.

Probability distributions for MD-11 and MD-81 touchdown longitudinal location stdev's of ~200 (baseline), 100 and 375 feet are found in figures 6.13, 15 & 17 and 6.14, 16 & 18 respectively. These figures are joint probability distributions for the two simulation random inputs: aircraft touchdown ground speed and location.

For this operational factor, graphs on pages 3 (baseline), 16 and 17 of volume 2 do not show a large ROT sensitivity to wet and dry runway/exit surface conditions, but do show a sensitivity to aircraft type.

All of the ROT 3-D graphs, beginning on page 49 of volume 2, show the ROT ‘valley’ running parallel to the touchdown location x axis. This characteristic is responsible for the lack of ROT sensitivity to the touchdown longitudinal location stdev stated below.

Averaged Aircraft Dispersion ROT Sensitivity (Figure 6.8)

ROT has very little sensitivity to touchdown longitudinal location stdev in the range of 100 to 375 (maximum requirement of AC 20-57A) feet. The middle data series of figure 6.8’s legend lists the current (baseline) touchdown longitudinal location stdev for the studied aircraft. If the high-speed exits are optimally located, it appears that a large touchdown longitudinal location stdev is acceptable.
ROT Sensitivity to Touchdown Ground Speed stdev (kts) (Figures 6.9a, b & c)

This study investigated ROT sensitivity to touchdown ground speed stdev (knots). ROT sensitivity to the touchdown ground speed mean was not studied, because it is similar to the sensitivity of varying aircraft weight types.

Probability distributions for MD-11 and MD-81 touchdown ground speed stdev’s of ~11 (baseline), 5 and 17 knots are found in figures 6.13, 19 & 21 and 6.14, 20 & 22 respectively. These figures are joint probability distributions for the two simulation random inputs: aircraft touchdown ground speed and location.

For this operational factor, graphs on pages 3 (baseline), 18 and 19 of volume 2 do not show a large ROT sensitivity to wet and dry runway/exit surface conditions, but do show a sensitivity to aircraft type. As the touchdown ground speed stdev decreases: all aircraft type ROT means and stdevs are decreasing, ROT mean sensitivity to aircraft type is increasing and ROT stdev sensitivity to aircraft type is decreasing.

The touchdown ground speed stdev affect on the MD-11 ROT stdev can for seen on pages 146 and 154 (area under ROT curves) of volume 2, for the 17 and 5 knot stdev respectively.

All of the ROT 3-D graphs, beginning on page 49 of volume 2, show a ROT ‘valley’ running perpendicular to the touchdown ground speed y axis. This characteristic is responsible for ROT sensitivity to the touchdown ground speed stdev stated below. A smaller touchdown ground speed stdev keeps the aircraft landings, with higher probability of occurrence, on the lower slopes of the ROT ‘valley’.

Averaged Aircraft Dispersion ROT Sensitivity (Figures 6.9a, b & c)

ROT has a great sensitivity to touchdown ground speed stdev for the studied range of 5 to 17 knots. The middle data series of figure 6.9a’s legend lists the current (baseline) ground speed stdev for the studied aircraft.

Figure 6.9a shows that the 5 knot touchdown ground speed stdev decreases the ROT mean and stdev. It also results in virtually no aircraft using the end of the runway or having a ROT greater than 53.4 seconds.

Figures 6.9 b & c show that the MD-11 ROT mean is not very sensitive to this operational factor, compared to the MD-81. The MD-11 ROT stdev and percent of MD-11’s using the end of the runway are more sensitive to this operational factor, compared to the MD-81.
ROT Sensitivity to Crosswind Conditions and Lateral Touchdown Offset
(Figure 6.10)

In the headings, the page number of the volume 2 graph pertaining to each section is given in parenthesis. The first heading is the operational factor baseline (see beginning of section 5.0).

Positive steady 15 knot crosswind (Page 3 of volume 2)
This is the maximum crosswind required by AC 20-57A in determining dispersion limits. A positive crosswind direction is from left to right for a landing aircraft. The simulation studies found that a positive crosswind created greater steering difficulty on a right-hand exit, than a negative crosswind.

No crosswind (Page 20 of volume 2)
A no-crosswind condition improves centerline tracking on the exit, allowing the aircraft to clear the runway sooner.

Positive gusting crosswind (12.5 mean, 2.5 sigma knots) & sensor noise (Page 21 of volume 2)
The gusting sigma portion of the crosswind was set at 1/5 of the mean. The assumed navigational source accuracy of +/- 2 feet was created by passing a random number of Normal Distribution 4 feet * (0 mean, 1 unity variance) through a first-order filter with a 30 second time constant.

Less uniform ROT values due to a gusting crosswind can be compared to ROT values resulting from a steady crosswind on pages 165 and 57 of volume 2, respectively.

Lateral touchdown offset of +27 feet and steady 15 knot crosswind (Page 33 of volume 2)
This is the maximum lateral dispersion allowed by AC 20-57A.

Averaged Aircraft Dispersion ROT Sensitivity (Figure 6.10)
ROT has very little sensitivity to runway crosswind conditions (up to 15 knots) or lateral touchdown offset (up to 27 feet). A slightly lower ROT mean resulted from crosswind means less than 15 knots. A slightly higher ROT mean resulted from the lateral touchdown offset of 27 feet. The exit prediction logic accounts well for the crosswind effect on drag in predicting exits.
ROT Sensitivity to Full Flaps, Anti-Skid Efficiency and 9 ft/sec$^2$ Allowed Deceleration (Figures 6.11a, b & c)

In the headings, the page number of the volume 2 graph(s) pertaining to each section is given in parenthesis. The first heading is the operational factor baseline (see beginning of section 5.0).

Baseline (Pages 3 of volume 2)
The operational factor baseline includes normal flaps, an anti-skid efficiency of 75% and a maximum allowed deceleration of 6.5 ft/sec$^2$.

Anti-skid efficiency of 60 & 90% (Pages 37 & 47 of volume 2)
The anti-skid system reduces the maximum available brake drag by reducing brake pressure as it senses main gear skidding. The effect of reduced brake pressure was modeled by limiting the maximum available brake drag to the anti-skid efficiency percent of its original value. Lowering anti-skid efficiency increases ROT sensitivity to wet and dry runway/exit surface conditions (compare 90% on page 47 to 60% on page 37 in volume 2).

Maximum allowed deceleration of 9 ft/sec$^2$ (Page 35 of volume 2)
A higher allowed maximum deceleration of 9 ft/sec$^2$ over its baseline value of 6.5 ft/sec$^2$ allows the use of an earlier mid exit location at 5350 feet. Increasing maximum allowed deceleration increases ROT sensitivity to wet and dry runway/exit surface conditions (compare 9 ft/sec$^2$ on page 35 to 6.5 ft/sec$^2$ on page 2 in volume 2, for a mid exit location at 5350 feet).

Full flaps (Page 5 of volume 2)
An aircraft’s normal and full flap settings are defined in the first table of section 3. Full flaps provide more aero drag deceleration to the aircraft.

Averaged Aircraft Dispersion ROT Sensitivity (Figures 6.11a, b & c)
Figure 6.11a shows a moderate ROT mean sensitivity to flap setting and a high sensitivity to maximum allowed deceleration. Use of full flaps and an allowed deceleration 9 ft/sec$^2$ decreased ROT mean and the percent of aircraft using the end of the runway. A higher anti-skid efficiency of 90% did not have a measurable benefit. A lower anti-skid efficiency of 60% increased the percent of aircraft using the end of the runway and having a ROT greater than 53.4 seconds.

Figures 6.11b & c show that the percent of MD-11 using the end of the runway and having a ROT greater than 53.4 seconds was more sensitive to this operational factor than the MD-81. Full flaps slightly increased the MD-81 ROT stdev and the number of MD-81 having a ROT greater than 53.4 seconds, due to excessive deceleration; whereas full flaps helped the MD-11.
ROT Sensitivity to Variations of Reverse Thrust Usage on Runway and Exit (Figures 6.12a, b & c)

In the headings, the page number of the volume 2 graph(s) pertaining to each section is given in parenthesis. The first heading is the operational factor baseline (see beginning of section 5.0).

**Baseline** (Page 3 of volume 2)

The baseline uses auto reverse thrust, which minimizes commanded brake pressure. Reverse thrust is stowed by the pilot prior to the exit or earlier if the aircraft ground speed decreases to the exit entrance ground speed.

**Reverse thrust not stowed prior to exit, limit to idle** (Page 29 of volume 2)

See discussion in the *ROT Sensitivity to ‘on-exit’ Operational Factors* section above.

**Reverse thrust not stowed prior to exit, do not limit to idle** (Page 40 of volume 2)

See discussion in the *ROT Sensitivity to ‘on-exit’ Operational Factors* section above.

**Reverse thrust limited to Idle on the runway and exit** (Page 41 of volume 2)

This case reflects the circumstances required by some airports. Limiting reverse thrust causes a large ROT sensitivity to wet and dry runway/exit surface conditions.

**No reverse thrust on the runway and exit** (Page 42 of volume 2)

This case was run to investigate the effect of not using reverse thrust. Using no reverse thrust causes a large ROT sensitivity to wet and dry runway/exit surface conditions.

**Averaged Aircraft Dispersion ROT Sensitivity** (Figures 6.12a, b & c)

Figure 6.12a shows that ROT mean is very sensitive to not using reverse thrust on the runway. The ROT stdev and the percent of aircraft having a ROT greater than 53.4 seconds is sensitive to all reverse thrust variations from the baseline, especially no reverse thrust. The exit locations were optimized for the operational factor baseline.

Figures 6.12b & c show that the MD-81’s ROT is less sensitive to limiting reverse thrust on the runway. The MD-11’s ROT is less sensitive to not stowing reverse thrust prior to the exit.
7.0 ROT SENSITIVITY RANKING

This section describes the ranking of operational factors in terms of their ROT sensitivity to the ROT mean, stdev and combined mean&stdev. The quantitative measure of ROT mean sensitivity, for instance, is calculated as:

\[ \% = 100 \times \frac{\text{operational factor ROT mean} - \text{baseline ROT mean}}{\text{baseline ROT mean}} \]

The mean values used in the above calculation were obtained from figures 6.1-12a, b & c. The % may be positive or negative; meaning that the ROT mean has increased (worsened) or decreased, respectively. If an operational factor has a range of values above and below the baseline value, such as exit entrance ground speed, there may be positive and negative %’s making up the total sensitivity. These calculations were repeated for stdev and combined mean&stdev. These three ROT sensitivity measures were documented for the MD-81, MD-11 and the combined MD-11/MD-81 aircraft in figures 7.1-3a, b & c as shown below:

<table>
<thead>
<tr>
<th>ROT Sensitivity Measure</th>
<th>MD-11+MD-81</th>
<th>Aircraft Type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MD-81</td>
<td>MD-11</td>
</tr>
<tr>
<td>Mean</td>
<td>F7.1a</td>
<td>F7.1b</td>
</tr>
<tr>
<td>Stdev</td>
<td>F7.2a</td>
<td>F7.2b</td>
</tr>
<tr>
<td>Mean+Stdev</td>
<td>F7.3a</td>
<td>F7.3b</td>
</tr>
<tr>
<td>Mean+Stdev, F7.3a ranking</td>
<td>F7.3d</td>
<td>F7.3e</td>
</tr>
</tbody>
</table>

In these figures, the y axis displays the positive and negative magnitudes of ROT sensitivity to a operational factor. The x axis ranks the operational factors in terms of their ROT sensitivity magnitude (including positive and negative). The operational factor labels list the variation from the operational factor baseline described in section 5.0. The operational factor ranking order varies with aircraft type and ROT sensitivity measure. The sensitivity of most operational factors is near 10% or 1%, with a few highly sensitive operational factors. The MD-11 aircraft appears to cause operational factors to have a larger ROT sensitivity, especially for the ROT stdev sensitivity measure.

Figures 7.3d & e display the same MD-81 and MD-11 sensitivity data as found in figures 7.3b & c, except that they use the operational factor ranking as found in Figure 7.3a. These two figures can be used to easily compare ROT sensitivity differences between the two aircraft types for a common operational factor.
8.0 CONCLUSIONS AND RECOMMENDATIONS

The operational factors are ranked in descending order according to ROT sensitivity (see figure 7.3a) in table 8.1 below. Suggested system changes relating to ROT recommendations are also shown in this table.
Table 8.1 Ranking of ROTO Operational Factors in Descending Order According to ROT Sensitivity

<table>
<thead>
<tr>
<th>Operational Factor Ranking (ranking gives MD-11, MD-81, mean, stdev equal weight; ranked in descending order)</th>
<th>Figure</th>
<th>Changes to existing System</th>
<th>Runway Exits</th>
<th>Recommendations for ROT Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice/flood runway surface condition</td>
<td>F6.7a</td>
<td>steering control laws</td>
<td>DGPS, HUD</td>
<td>auto (monitor) / manual</td>
</tr>
<tr>
<td>Exit entrance ground speed*</td>
<td>F6.6a</td>
<td>steering control laws</td>
<td>DGPS, HUD</td>
<td>auto (monitor) / manual</td>
</tr>
<tr>
<td>Number of exits</td>
<td>F6.1a</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High-speed exit locations and spacing</td>
<td>F6.1a, 4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A/C type, baseline@mid exit loc 5950 ft</td>
<td>pg 3, vol2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Touchdown ground speed stdev</td>
<td>F6.9a</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reverse thrust and braking method*</td>
<td>F6.3a</td>
<td>deceleration control laws</td>
<td>DGPS, HUD</td>
<td>auto (monitor) / manual</td>
</tr>
<tr>
<td>Accurate exit prediction capability</td>
<td>F6.5a</td>
<td>algorithm</td>
<td></td>
<td>ATC ops</td>
</tr>
<tr>
<td>Maximum Reverse Thrust availability</td>
<td>F6.12a</td>
<td>suggest level</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Spiral-arc vs circle-arc exit geometry</td>
<td>F6.2a</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Maximum allowed deceleration</td>
<td>F6.11b</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Auto asymmetric braking on exit</td>
<td>F6.2a</td>
<td>brake-by-wire</td>
<td>brake-by-wire</td>
<td>X</td>
</tr>
<tr>
<td>Do not stow reverse thrust before exit</td>
<td>F6.2a</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Touchdown longitudinal location stdev</td>
<td>F6.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flap setting</td>
<td>F6.11a</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anti-skid efficiency</td>
<td>F6.11a</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crosswind conditions</td>
<td>F6.10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stopping on exit</td>
<td>F6.2a</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Touchdown lateral offset</td>
<td>F6.10</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Pilots are already performing manual, 70 knot, high-speed turnoffs under daylight and dry surface conditions with standard aircraft systems
It is believed that procedural and software-only changes would be the least costly method of improving ROT for existing systems. Aircraft hardware and runway structural additions would be more costly. The results of this report assume that all aircraft have an anti-skid system. The following outlines recommendations of increasing cost to minimize ROT.

Procedures and Training
Regardless of the availability of high-speed exits, training may improve optimum braking procedure and extend current technique to night and wet surface conditions. Training may improve the optimal use and stowing of reverse thrust.

Software
Decreasing an aircraft population’s touchdown ground speed standard deviation decreases the ROT standard deviation. Operational winds and the recommended approach air speed of an aircraft population contribute to the ground speed standard deviation. As safety permits, lowering the maximum recommended approach air speed would require a FMS software change for FMS equipped aircraft. A great benefit to continuous ROTO operations would be to add a new software module (exit prediction logic) to recommend to the pilot an available exit that minimizes ROT and exit aborts. Optimal exit prediction logic requires runway-length friction measurements.

Hardware and Software
A great benefit to minimizing ROT would be derived from retrofitting aircraft with a head-up-display (HUD), DGPS guidance and adding additional software to give braking, reverse thrust and steering flight guidance. If flight-directed manual ROTO is not felt to be adequate, software and hardware additions could be added for auto variable braking and auto (variable) reverse thrust.

Software and hardware additions to improve steering performance would allow for higher exit entrance ground speeds for existing exits. Auto asymmetric braking is currently not state-of-the-art.

Runway Exits
One of the greatest benefits to minimizing ROT would be to add new high-speed exits to a runway, whose locations are optimized for the aircraft population expected to use that runway. Reference 2 recommends that all high-speed exits be grooved.

It is understandable that pilots desire to minimize their time to the gate. Minimizing time to the gate will not necessarily minimize ROT (runway occupancy time), such as in the situation of a distant runway exit being nearer to an aircraft’s destination gate. Airlines and ATC may have the stronger impetus to minimize ROT and maximize a runway’s continuous throughput, rather than the pilot of a single aircraft. The goal of continuous ROTO operation is to guarantee a ROT below a desired value for nearly 3 sigma (99.8%) of the landing aircraft population. Violating the ROT maximum may cause a following aircraft to go-around. Section 4 in the appendix illustrates that today, without any changes to current systems, pilots can achieve good ROT results. This example documents daylight landings on a dry runway having one high-speed exit. Pilots received no official training beyond their own experience.
REFERENCES


2. Goldthorpe, Dangaran, Dwyer, McBee, Norman, Shannon, Summers, GUIDANCE AND CONTROL DESIGN FOR HIGH-SPEED ROLLOUT AND TURNOFF (ROTO), NASA CR 201602, August 1996, NAS1-19703 Task 7, Langley Research Center, Hampton, VA, NASA.

Nosewheel Steering Valve Flow Coefficient

Figure 3.1
Figure 3.2

Nosewheel Friction Factor vs Side Slip Velocity

Figure 3.2
54
Brake Pressure vs Brake Torque

Figure 3.3
Figure 3.4

Fraction of Main Gear Load Supported by Center Gear

- MD-11
- MD-81

TOTAL LOAD ON WINGS & CENTER GEAR (KLBS)

FRACTION OF TOTAL LOAD ON CENTER GEAR
Forward Thrust Approach Idle vs Airspeed

Figure 3.5
Reverse Thrust Idle vs Airspeed

Figure 3.7
59
Reverse Thrust Maximum vs Time

Figure 3.8
Reverse Thrust Maximum vs Airspeed

VEAS (kt)

THRUST (LBS)

Figure 3.9

61
Figure 3.10
MD-11
MAXIMUM GROUND COEFFICIENT OF FRICTION VS. GROUND SPEED
TIRE INFLATION = 187.9 LBS

Figure 3.11
Exit Prediction Logic Path

- Initialize Aircraft at time = 0, main gear touchdown using predicted touchdown ground speed and location.
- If active, calculate braking decel cmd based on decel methodology.
- Process Logic to determine whether braking has been activated yet.
- Calculate Friction fraction used at Main Gear using Aircraft Parameters (Gear Loading, Anti-skid Eff. & decel).
- Limit Required Deceleration.
- Calculate Friction needed taking into account Aircraft Drag and Thrust.
- Calculate Friction available from surface at Main Gear.
- Calculate Aircraft Drag.
- Calculate Thrust using Airspeed and whether braking has begun.
- Calculate Airspeed assuming constant winds.
- Calculate Required Deceleration.
- If active, calculate braking decel cmd based on decel methodology.
- Increment logic time by 0.25 s.
- Delay Decel Cmd after T.D.
- Rate Limit Decel Cmd.
- Limit Total Decel (brakes, thrust, drag).
- Calculate new runway location.
- Calculate new ground speed.
- If CRT and CRT not yet FOUND, decrease CRT setting by 1/3.
- If CRT and CRT not yet FOUND, decrease CRT setting by 1/3.
- If CRT and CRT not yet FOUND, decrease CRT setting by 1/3.
- If CRT and CRT not yet FOUND, decrease CRT setting by 1/3.
- Calculate desired Speed Profile for the current ground speed.
- Lower limit ground speed to Speed Profile for the current ground speed.
- Calculate new decel and runway location.
- Aircraft Past Roto Exit?
- Constant Decel? (variable decel)
- CRT or RD?
- Needed friction > Available friction?
- CRT and CRT < 0.9 or (RD and dondist > predicted TD location)?
Figure 5.1

Predict exit prior to TD

Weight = 340K + (480K - 340K)*(VEAS - 130)/36
CG = 0.12 + (0.34 - 0.12)*(VEAS - 130)/36

Runway Occupancy Time

MD-11 ROTO Occupancy Time

Wet Exits = 4500, 5950, 7350, 10000
Auto reverse Thrust/Variable Deceleration
Slow Reverse Thrust = 70 kt gd

TD Ground Speed = Airspeed + Average Tailwind

TD X Location Past Threshold
Figure 5.2
MD-11 ROTO ROT Probability Distribution
Wet, Auto reverse thrust/variable decel
Mean=47.2, STDEV=4.16

MD-11 Runway Occupancy Time (ROT) seconds
Curves Represent Exits at 4500, 5950, 7350 & 10000 feet
Predict exit prior to TD
Weight = 340K + (480K - 340K) * (VEAS - 130) / 36
CG = 0.12 + (0.34 - 0.12) * (VEAS - 130) / 36

MD-11 ROTO Exit Used
Wet, Exits = 4500, 5950, 7350, 10000
Autoreverse Thrust/Variable Deceleration
Stow Reverse Thrust = 70 kt gd

Figure 5.3

ROTO Exit Location feet

10000
7350
5950
4500

162 +7
158 +3
154 -1
150 -5
146 -9
142 -13
138 -17
134 -21
130 -25
250

T.D. Ground Speed = Airspeed + Average Tailwind

T.D. X Location
Past Runway Threshold
Figure 5.4

MD-11 ROTO Exit Probability Distribution
Wet, Auto reverse thrust/variable decel
Mean=2.3, STDEV=0.63
ROT sensitivity to exit location, spacing & number of exits

Autoreverse thrust/variable braking

Statistics average wet/dry/MD-11/MD-81 dispersions

Figure 6.1a
ROT sensitivity to exit location, spacing & number of exits (MD-81 only)
Autoreverse thrust/variable braking
Statistics average wet/dry/MD-81 dispersions

Figure 6.1b
• 5350ft(mid exit) ; avg Table data rows 6,7
• 5950ft(mid exit); wider exit spacing ; avg Table data rows 16,17
2 exits at 5225ft & 6650ft ; avg Table data rows 46,147
1 exit at 5950ft ; avg Table data rows 151,152
5350ft(mid exit) with 4th exit at 8300ft ; avg Table data rows 156,157

Statistics

ROT sensitivity to exit location, spacing & number of exits (MD-11 only)
Autoreverse thrust/variable braking
Statistics average wet/dry/MD-11 dispersions

Figure 6.1c
72
- Baseline ; Table data row 15
- Constant 2900 ft exit radius ; Table data row 120
- Aircraft CG stop on exit at Y=480 ft ; Table data row 170
- Reverse Thrust (idle) on Exit, not stowed ; Table data row 145
- Reverse Thrust (auto) on Exit, not stowed ; Table data row 200
- Auto asymmetric braking on Exit ; Table data row 230

Figure 6.2a
■ Baseline ; avg Table data rows 13,14
■ Constant 2900 ft exit radius ; avg Table data rows 118,119
■ Aircraft CG stop on exit at Y=480 ft ; avg Table data rows 168,169
□ Reverse Thrust (idle) on Exit, not stowed ; avg Table data rows 143,144
□ Reverse Thrust (auto) on Exit, not stowed ; avg Table data rows 198,199
■ Auto asymmetric braking on Exit ; avg Table data rows 228,229

Figure 6.2b
- Baseline; avg Table data rows 11,12
- Constant 2900 ft exit radius; avg Table data rows 116,117
- Aircraft CG stop on exit at Y=480 ft; avg Table data rows 166,167
- Reverse Thrust (idle) on Exit, not stowed; avg Table data rows 141,142
- Reverse Thrust (auto) on Exit, not stowed; avg Table data rows 196,197
- Auto asymmetric braking on Exit; avg Table data rows 226,227

Figure 6.2c
ROT sensitivity to reverse thrust and braking deceleration methods

Statistics

Mid exit location at 5950
Statistics average wet/dry/MD-11/MD-81 dispersions

Figure 6.3a

76
- auto rev thr & var dec, with PRED (baseline); avg Table data rows 13,14
- const rev thr & roll-const dec, with PRED; avg Table data rows 43,44
- auto rev thr & roll-const dec, with PRED; avg Table data rows 48,49
- const rev thr & var dec, with PRED; avg Table data rows 53,54
- immediate medium rev thr & immed. const 6.5 decel, then coast after 70 kts, NO PRED; avg Table data rows 38,39
- immediate maximum rev thr & immed. const 6.5 decel, then coast after 70 kts, NO PRED; avg Table data rows 223,224

Statistics

ROT sensitivity to thrust and braking deceleration methods (MD-81 only)
Mid exit location at 5950
Statistics average wet/dry/MD-81 dispersions

Figure 6.3b

77
- auto rev thr & var dec, with PRED (baseline); avg Table data rows 11,12
- cnst rev thr & roll-const dec, with PRED; avg Table data rows 41,42
- auto rev thr & roll-const dec, with PRED; avg Table data rows 46,47
- const rev thr & var dec, with PRED; avg Table data rows 51,52

Immediate medium rev thr & immed. const 6.5 decel, then coast after 70 kts, NO PRED; avg Table data rows 36,37
Immediate maximum rev thr & immed. const 6.5 decel, then coast after 70 kts, NO PRED; avg Table data rows 221,222

Figure 6.3c
Figure 6.4

ROT sensitivity to exit location for NON-ROTO/NO Exit Prediction
Immediate reverse thrust & immediate 6.5 constant deceleration
Statistics average wet/dry/MD-11/MD-81 dispersions
- auto rev thr & var dec, with PRED (baseline); Table data row 15
- auto rev thr & var dec, with PRED, exit predict TD location error +300ft; Table data row 110
- cnst rev thr & roll-const dec, with PRED; Table data row 45
- immediate medium rev thr & immed. const 6.5 decel, then coast after 70 kts, NO PRED; Table data row 40
- immediate maximum rev thr & immed. const 6.5 decel, then coast after 70 kts, NO PRED; Table data row 225

Statistics
ROT sensitivity to ROTO/Exit Prediction Capability
Mid exit location at 5950
Statistics average wet/dry/MD-11/MD-81 dispersions

Figure 6.5a
- auto rev thr & var dec, with PRED (baseline); avg Table data rows 13,14
- auto rev thr & var dec, with PRED, exit predict TD location error +300ft; avg Table data rows 108,109
- const rev thr & roll-const dec, with PRED; avg Table data rows 43,44
- const rev thr & roll-const dec, with PRED, exit predict TD location error +300ft; avg Table data rows 113,114
- immediate medium rev thr & immed. const 6.5 decel, then coast after 70 kts, NO PRED; avg Table data rows 38,39
- immediate maximum rev thr & immed. const 6.5 decel, then coast after 70 kts, NO PRED; avg Table data rows 223,224

Figure 6.5b
• auto rev thr & var dec, with PRED (baseline); avg Table data rows 11,12

• auto rev thr & var dec, with PRED, exit predict TD location error +300ft; avg Table data rows 106,107

• cnst rev thr & roll-const dec, with PRED; avg Table data rows 41,42

• cnst rev thr & roll-const dec, with PRED, exit predict TD location error +300ft; avg Table data rows 111,112

• immediate medium rev thr & immed. const 6.5 decel, then coast after 70 kts, NO PRED; avg Table data rows 36,37

• immediate maximum rev thr & immed. const 6.5 decel, then coast after 70 kts, NO PRED; avg Table data rows 221,222

Statistics

ROT sensitivity to ROTO/Exit Prediction Capability (MD-11 only)
Mid exit location at 5950
Statistics average wet/dry/MD-11 dispersions

Figure 6.5c
4950 ft (mid exit); 60 kt exit speed; Table data row 190
4950 ft (mid exit); 70 kt exit speed; Table data row 5
4950 ft (mid exit); 80 kt exit speed; Table data row 75
5350 ft (mid exit); 40 kt exit speed; Table data row 240
5950 ft (mid exit); 40 kt exit speed; Table data row 195
5950 ft (mid exit); 60 kt exit speed; Table data row 60
5950 ft (mid exit); 70 kt exit speed (baseline); Table data row 15
5950 ft (mid exit); 80 kt exit speed; Table data row 65
6550 ft (mid exit); 70 kt exit speed; Table data row 130
6950 ft (mid exit); 60 kt exit speed; Table data row 70

Figure 6.6a
Figure 6.6b

84
- 4950ft (mid exit); 60 kt exit speed; avg Table data rows 186,187
- 4950ft (mid exit); 70 kt exit speed; avg Table data rows 1,2
- 4950ft (mid exit); 80 kt exit speed; avg Table data rows 71,72
- 5350ft (mid exit); 40 kt exit speed; avg Table data rows 236,237
- 5950ft (mid exit); 40 kt exit speed; avg Table data rows 191,192
- 5950ft (mid exit); 60 kt exit speed; avg Table data rows 56,57
- 5950ft (mid exit); 70 kt exit speed (baseline); avg Table data rows 11,12
- 5950ft (mid exit); 80 kt exit speed; avg Table data rows 61,62
- 6550ft (mid exit); 70 kt exit speed; avg Table data rows 126,127
- 6950ft (mid exit); 60 kt exit speed; avg Table data rows 66,67

Figure 6.6c

Statistics
ROT sensitivity to exit entrance ground speed (MD-11 only)
Autoreverse thrust/variable braking
Statistics average wet/dry/MD-11 dispersions
 ROT sensitivity to runway surface condition
 Autoreverse thrust/variable braking
 Mid exit location at 5950
 Statistics average MD-11/MD-81 dispersions

Figure 6.7a

86
- dry surface condition; Table data row 14
- slush surface condition; Table data row 138
- wet surface condition; Table data row 13
- snow surface condition; Table data row 137
- flood surface condition; Table data row 139
- ice surface condition; Table data row 136

**Statistics**

ROT sensitivity to runway surface condition (MD-81 only)
Autoreverse thrust/variable braking
MD-81 dispersions with mid exit location at 5950

Figure 6.7b
- dry surface condition; Table data row 12
- slush surface condition; Table data row 133
- wet surface condition; Table data row 11
- snow surface condition; Table data row 132
- flood surface condition; Table data row 134
- ice surface condition; Table data row 131

Statistics

ROT sensitivity to runway surface condition (MD-11 only)
Autoreverse thrust/variable braking
MD-11 dispersions with mid exit location at 5950

Figure 6.7c

88
100 td location stdev; Table data row 85

Baseline td location stdev; 198 for MD-81; 225 for MD-11; Table data row 15

375 (AC 20-57A) td location stdev; Table data row 80

Figure 6.8

Statistics
ROT sensitivity to touchdown longitudinal location stdev (ft)
Autoreverse thrust/variable braking
Mid exit location at 5950
Statistics average wet/dry/MD-11/MD-81 dispersions
5 kt td gnd speed stdev; Table data row 95

baseline td gnd speed stdev; 10.5 kt for MD-81; 11.5 kt fcr MD-11; Table data row 15

17 kt td gnd speed stdev; Table data row 90

---

**Figure 6.9a**

**Statistics**

ROT sensitivity to touchdown ground speed stdev (kts)
Autoreverse thrust/variable braking
Mid exit location at 5950
Statistics average wet/dry/MD-11/MD-81 dispersions
5 kt td gnd speed stdev; avg Table data rows 93,94

Baseline td gnd speed stdev; 10.5 kt for MD-81; avg Table data rows 13,14

17 kt td gnd speed stdev; avg Table data rows 88,89

**Figure 6.9b**

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Statistics

ROT sensitivity to touchdown ground speed std (kts) (MD-11 only)
Autoreverse thrust/variable braking
Mid exit location at 5950
Statistics average wet/dry/MD-11 dispersions

Figure 6.9c
baseline (15 kt constant crosswind) ; Table data row 15

no crosswind ; Table data row 100

gusting crosswind 12.5+/-2.5 kt & sensor noise ; Table data row 105

lateral touchdown offset of +27 feet ; Table data row 165

Statistics

ROT sensitivity to crosswind conditions and lateral touchdown offset
Autoreverse thrust/variable braking
Mid exit location at 5950
Statistics average wet/dry/MD-11/MD-81 dispersions

Figure 6.10
Figure 6.11a
- 5350ft (mid exit); max 9 ft/s/s ; avg Table data rows 173,174
- 5950ft (mid exit); Baseline ; avg Table data rows 13,14
- 5950ft (mid exit); Full Flaps ; avg Table data rows 23,24
- 5950ft (mid exit); Anti-skid Eff. 60% ; avg Table data rows 183,184
- 5950ft (mid exit); Anti-skid Eff. 90% ; avg Table data rows 233,234

![Figure 6.11b](image)

**Statistics**

ROT sensitivity to full flaps, anti-skid eff. & max 9ft/s/s decel (MD-81 only)

Autoreverse thrust/variable braking

Statistics average wet/dry/MD-81 dispersions
5350 ft (mid exit); max 9 ft/s/s; avg Table data rows 171,172

5950 ft (mid exit); Baseline; avg Table data rows 11,12

5950 ft (mid exit); Full Flaps; avg Table data rows 21,22

5950 ft (mid exit); Anti-skid Eff. 60%; avg Table data rows 181,182

5950 ft (mid exit); Anti-skid Eff. 90%; avg Table data rows 231,232

Figure 6.11c
 Baseline (auto reverse thrust, stowed at exit entrance) ; Table data row 15

 Reverse Thrust (idle) on Exit, not stowed ; Table data row 145

 Reverse Thrust (auto) on Exit, not stowed ; Table data row 200

 Reverse Thrust Idle on Runway ; Table data row 205

 NO Reverse Thrust ; Table data row 210

 ROT sensitivity to variations of reverse thrust usage on runway and exit
 Autoreverse thrust/variable braking
 Mid exit location 5950
 Statistics average wet/dry/MD-11/MD-81 dispersions

Figure 6.12a
- Baseline (auto reverse thrust, stowed at exit entrance); avg Table data rows 13, 14
- Reverse Thrust (idle) on Exit, not stowed; avg Table data rows 143, 144
- Reverse Thrust (auto) on Exit, not stowed; avg Table data rows 198, 199
- Reverse Thrust Idle on Runway; avg Table data rows 203, 204
- NO Reverse Thrust; avg Table data rows 208, 209

**ROT sensitivity to reverse thrust settings (MD-81 only)**

*Autoreverse thrust/variable braking*

Mid exit location 5950

Statistics average wet/dry/MD-81 dispersions

**Figure 6.12b**

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Basel ine (auto reverse thrust, stowed at exit entrance) ; avg Table data rows 11,12

Reverse Thrust (idle) on Exit, not stowed ; avg Table data rows 141,142

Reverse Thrust (auto) on Exit, not stowed ; avg Table data rows 196,197

Reverse Thrust Idle on Runway ; avg Table data rows 201,202

NO Reverse Thrust ; avg Table data rows 206,207

ROT sensitivity to reverse thrust settings (MD-11 only)
Autoreverse thrust/variable braking
Mid exit location 5950
Statistics average wet/dry/MD-11 dispersions

Figure 6.12c

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MD-11 Joint Probability Distribution based on 2 touchdown independent, normal, random input variables

Weight = 340K + (480K - 340K) * (VEAS - 130) / 36
CG = 0.12 + (0.34 - 0.12) * (VEAS - 130) / 36

(888 data points)

Figure 6.13

TD Ground Speed = Airspeed + Average Tailwind
141 +/- 11.5 knots

TD X Location
Past Runway Threshold
1375 +/- 225 feet
MD-81 Joint Probability Distribution based on 2 touchdown independent, normal, random input variables

Weight = 82K + (128K - 82K) * (VEAS - 110) / 33  
CG = -0.008 + (0.334 - (-0.008)) * (VEAS - 110) / 33

(756 data points)

Figure 6.14

TD Ground Speed = Airspeed + Average Tailwind  
116.44 +/- 10.36 knots

TD X Location
Past Runway Threshold  
1362.6 +/- 198 feet
MD-11 Joint Probability Distribution based on 2 touchdown independent, normal, random input variables

Weight = 340K + (480K - 340K) * (VEAS - 130) / 36
CG = 0.12 + (0.34 - 0.12) * (VEAS - 130) / 36

(888 data points)

Figure 6.15

TD Ground Speed = Airspeed + Average Tailwind
141 +/- 11.5 knots

TD X Location Past Runway Threshold
1375 +/- 100 feet
MD-81 Joint Probability Distribution based on 2 touchdown independent, normal, random input variables

Weight=82K+(128K-82K)*(VEAS-110)/33
CG=-0.008+(0.334-(-0.008))*(VEAS-110)/33

(756 data points)

Figure 6.16

Figure 6.16

TD Ground Speed = Airspeed + Average Tailwind
116.44 +/- 10.36 knots

TD X Location Past Runway Threshold
1362.6 +/- 100 feet
MD-11 Joint Probability Distribution based on 2 touchdown independent, normal random input variables

Weight = 340K + (480K - 340K) * (VEAS - 130) / 36
CG = 0.12 + (0.34 - 0.12) * (VEAS - 130) / 36

(888 data points)
MD-81 Joint Probability Distribution based on 2 touchdown independent, normal, random input variables

Weight = 82K + (128K - 82K) * (VEAS - 110) / 33
CG = -0.008 + (0.334 - (-0.008)) * (VEAS - 110) / 33

(756 data points)

Figure 6.18

TD Ground Speed = Airspeed + Average Tailwind
116.44 +/- 10.36 knots

TD X Location Past Runway Threshold
1362.6 +/- 375 feet
MD-11 Joint Probability Distribution based on 2 touchdown independent, normal, random input variables

Weight = 340K + (480K - 340K) * (VEAS - 130) / 36
CG = 0.12 + (0.34 - 0.12) * (VEAS - 130) / 36

(888 data points)

Figure 6.19

TD X Location
Past Runway Threshold
1375 +/- 225 feet

TD Ground Speed = Airspeed + Average Tailwind
141 +/- 5 knots
MD-81 Joint Probability Distribution based on 2 touchdown independent, normal, random input variables

Weight = 82K + (128K - 82K) * (VEAS - 110)/33
CG = 0.008 + (0.334 - (-0.008)) * (VEAS - 110)/33

Figure 6.20

TD Ground Speed = Airspeed + Average Tailwind
116.44+/-5 knots

TD X Location
Past Runway Threshold
1362.6+/-198 feet

(756 data points)
MD-81 Joint Probability Distribution based on 2 touchdown independent, normal, random input variables

Weight=82K+(128K-82K)*(VEAS-110)/33
CG=-0.008+(0.334-(-0.008))*(VEAS-110)/33

(756 data points)
Figure 7.1a
Figure 7.1b
Figure 7.1c: MD-11 ROT Mean Sensitivity Ranking
% Stddev Variation from Baseline Stddev (avg MD-11 & MD-81)

Ice/flood runway surface condition
Number of exits (1-4)
Exit entrance gnd speed (40-80kt)
High-speed exit locations & spacing
Touchdown ground speed stddev
Reverse thrust/brake method
Inaccurate exit prediction
No Reverse Thrust
A/C type, baseline @ mid 5950
Dry, Slush, Wet, Snow surface cond
Do not stow reverse thrust @ exit
Touchdown longitudinal loc. stddev
Max allowed deceleration (9ft/s/s)
Full flap setting
Anti-skid efficiency (60%–90%)
Auto asymmetric braking
Circle instead of spiral-arc exit
Touchdown lateral offset (27 feet)
Stop on last third of exit
No crosswind

Figure 7.2a

MD-11 & MD-81 ROT Stddev Sensitivity Ranking
MD-81 ROT Stdev Sensitivity Ranking

Operational Factor

Figure 7.2b

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Figure 7.2c

Operational Factor

% Stdev Variation from Baseline MD-11 Stdev

- Ice/flood runway surface condition
- Number of exits (1-4)
- Exit entrance gnd speed (40-80kt)
- High-speed exit locations & spacing
- Touchdown ground speed stdev
- Reverse thrust/brake method
- Inaccurate exit prediction
- No Reverse Thrust
- Dry, Slush, Wet, Snow surface cond
- Touchdown longitudinal loc. stdev
- Full flap setting
- Anti-skid efficiency (60%-90%)
- Circle instead of spiral-arc exit
- Auto asymmetric braking
- Touchdown lateral offset (27 feet)
- Max allowed deceleration (9ft/s/s)
- Stop on last third of exit
- Do not stow reverse thrust @ exit
- No crosswind
MD-11 & MD-81 ROT Sensitivity Ranking

Operational Factor
(Ranking gives Mean and Stdev equal weight)

Figure 7.3a

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MD-81 ROT Sensitivity Ranking

% (Mean & Stdev) Variation from Baseline MD-81 (Mean & Stdev)

-20% -10% 0% 10% 20% 30% 40% 50%

Ice/flood runway surface condition
Exit entrance gnd speed(40-80kt)
Number of exits(1-4)
Touchdown ground speed std dev
Reverse thrust/brake method
High-speed exit locations&spacing
Inaccurate exit prediction
Circle instead of spiral-arc exit
No Reverse Thrust
Max allowed deceleration(9ft/s/s)
Dry,Slush,Wet,Snow surface cond
Do not stow reverse thrust@exit
Auto asymmetric braking
Touchdown longitudinal loc. std dev
Full flap setting
Anti-skid efficiency (60%-90%)
No crosswind
Stop on last third of exit
Touchdown lateral offset(27 feet)

Figure 7.3b

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MD-11 ROT Sensitivity Ranking

Operational Factor
(Ranking gives Mean and Stdev equal weight)

Figure 7.3c
Figure 7.3d

Operational Factor

MD-81 ROT Sensitivity

(94.3

% (Mean & Stdev) Variation from Baseline MD-81 (Mean & Stdev)

- Ice/flood runway surface condition
- Exit entrance gnd speed(40-80kt)
- Number of exits(1-4)
- High-speed exit locations&spacing
- A/C type, baseline@mid5950
- Touchdown ground speed stdev
- Reverse thrust/brake method
- Inaccurate exit prediction
- No Reverse Thrust
- Circle instead of spiral-arc exit
- Dry,Slush,Wet,Snow surface cond
- Max allowed deceleration(9ft/s/s)
- Auto asymmetric braking
- Do not stow reverse thrust@exit
- Touchdown longitudinal loc. stdev
- Full flap setting
- Anti-skid efficiency (60%-90%)
- No crosswind
- Stop on last third of exit
- Touchdown lateral offset(27 feet)

(With ranking of Figure 7.3a)
APPENDIX

1. TIME HISTORIES...........................................................................................................123
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3. TABULATED ROT SENSITIVITY DATA .......................................................................141
4. DALLAS/FT. WORTH HIGH-SPEED EXIT DATA.........................................................165
TIME HISTORIES

Figures on pages 126-127 and 128-129 document variable and constant deceleration method time histories, respectively. Definitions for each plot follow. The ROT for the constant deceleration method is a little less than the variable deceleration method. The methods’ deceleration profiles are quite different as evidenced by the ground speed graph on the first time history sheet and the main gear mu (available friction used) graphs on the second time history sheet. The variable deceleration method brakes earlier than the constant deceleration method. The constant reverse thrust method and a crosswind of 0 knots were used in each time history.

Each simulation run is documented with two pages of time histories. When a plot shares more than one variable, the second variable is usually plotted on the right hand Y axis. The zero origin of the left and right axis are usually offset so that the variable time histories do not cross each other. The X axis of all plots is the runway longitudinal axis in feet. 0 feet is at the runway threshold.

Page 1; Bottom Plot

This plot shows two views of the aircraft position relative to the runway with a right hand ROTO turnoff. The left axis shows the aircraft Y position in feet. The runway centerline is along the top of the plot. The desired path (dashed line) is along the centerline and then curves to the right as the right-handed ROTO exit. Any small perturbations in the dashed curves represent exit entrances which the aircraft did not enter. The solid line represents the aircraft position. For MD-81 and MD-11 simulation runs the first ROTO exit is at position 3300 feet and 4950 feet, respectively.

The right axis shows the aircraft Y lateral displacement (solid line) in feet from the runway centerline and exit path. The straight-lined funnel shape represents the allowable lateral width in which the aircraft can move without running off the pavement. The funnel width is the runway and ROTO exit widths minus the aircraft main gear offset, which varies with aircraft type.

Page 1; 2nd from Bottom Plot

The left axis plots the aircraft ground speed in knots (decreasing trace). The right axis plots the aircraft runway occupancy time in seconds. The runway occupancy time at touchdown begins at a value greater than zero because it begins counting at the runway threshold. The runway occupancy time stops increasing when the aircraft wing tip clears the near side of the runway.
The left axis plots the aircraft lateral acceleration in G's (lower trace). The right axis plots the aircraft lateral jerk in G/sec. Gust cases do not plot the lateral jerk because it is too excessive. This study did not ascertain the cause of the gust related jerk (simulation model, control laws, sensors) or find a solution for this occurrence.

The left axis plots the aircraft longitudinal acceleration in G's (lower trace). The right axis plots the aircraft longitudinal jerk in G/sec. Gust cases do not plot the longitudinal jerk because it is too excessive. This study did not ascertain the cause of the gust related jerk (simulation model, control laws, sensors) or find a solution for this occurrence.

The left axis plots the percent of main gear brake supply pressure commanded (lower trace). When the plot shows 100%, the deceleration command is commanding all of the brake supply pressure. The percent of brake supply pressure commanded does not reflect the amount of brake supply pressure in use if anti-skid (required by ROTO) is active.

The right axis plots the aircraft total thrust in pounds (upper trace).

The left axis plots the aircraft rudder position in degrees (lower trace). The right axis plots the nose gear position in degrees.

The left axis plots the amount of \( \mu \) being used by the aircraft nose gear (lower trace). The right axis plots the available aircraft nose gear \( \mu \).

The left axis plots the amount of \( \mu \) being used by the aircraft main right gear \( \mu \) (lower trace). The right axis plots the available aircraft main right gear \( \mu \).
Page 2; 4th from Bottom Plot
The left axis plots the amount of $\mu$ being used by the aircraft main center gear $\mu$ (lower trace). The right axis plots the available aircraft main center gear $\mu$.

Page 2; 3rd from Top Plot
The left axis plots the aircraft track angle relative to the aircraft heading in degrees. The right axis plots the aircraft elevator angle in degrees (gradually rising trace).

Page 2; 2nd from Top Plot
The left axis plots the steady tailwind in knots. A headwind would have a negative value. The right axis plots the crosswind in knots. If the crosswind is steady it will have a straight line value. Gust cases will show a varying crosswind. A positive crosswind blows in a negative Y to positive Y direction (left to right as viewed by a landing aircraft).

Page 2; Top Plot
The left axis plots the navigation X position data noise content (lower trace). The right axis plots the navigation Y position data noise content.
VAR BRK, CONST IDLE REV THR, MD-11 CAT IIIB AUTO ROTO (PG 1 OF 2)

WET SURFACE CONDITION, 0 KNOT CRS WIND

30 DEG SPIRAL EXIT, STOW @ 70 KTS GND, 4500, 5950, 7350 EXITS

A/C X POSITION (FT)

A/C Y POS. (FT)

GROUND SPD (KT)

LAT. ACCEL (G)

LONG. ACCEL (G)

PERCENT BRAKE

THRUST (LBS)

RUNWAY TIME (S)

Y DISPL. (FT)
VAR BRK, CONST IDLE REV THR, MD-11 CAT IIIb AUTO ROTO (PG 2 OF 2)

WET SURFACE CONDITION, 0 KNOT CROSSWIND

30 DEG SPIRAL EXIT, STOW@70 KTS GND, 4500, 5950, 7350 EXITS
CONST BRK, CONST IDLE REV THR, MD-11 CATIIIIB AUTO ROTO (PG 2 OF 2)

WET SURFACE CONDITION, 0 KNOT CROSSWIND

30 DEG SPIRAL EXIT, STOW@70 KTS GND, 4500, 5950, 7350 EXITS

A/C X POSITION (FT)
EXIT PREDICTION LOGIC

FUNCPREDICTABORT.M is a MATLAB script function file called from RUNROTO.M once, containing the exit prediction algorithm. The parameters passed to it are variables predicted prior to touchdown.

```matlab
function abortearly = funcpredictabort(upre,utpre,xnavpre,wpre,cgpre,vwsspre,vexit,exitpos,nexit)
% these inputs are predicted values at touchdown
% in the simulation time=0 at maingear touchdown
% used if USEMUABORT is true

global SW RWFC ASEFF REVERSE AUTOREV
global CDFWD CDAFT CGAFT CGFWD PCTMAC DECLIM TMGD TNGD
global USEMUABORT TIMEOCCLAG
global thstmulast BRKBUF DRATE DTIME MD11
  global AUREVCONST
  global DRLM

  global DECLOW DECMED DECMAX DECSel DOND1ST DECRATELAG
  global CONSTDEC ROLL1ST CREVTHRLOOP VEXITSPD

  global lenxdefmult

% initialize Aircraft variables
%L111:
  while (1)
    thstmulast=0;
    abortearly=0;
    decelpreon=0;
    futt=0;
    if(MD11)
      if(wpre>480000)wpre=480000;end;
      if(wpre<340000)wpre=340000;end;
      if(cgpre>.34)cgpre=.34;end;
      if(cgpre<.12)cgpre =.12;end;
      if(xnavpre>2500)xnavpre=2500;end;
      if(xnavpre<250)xnavpre=250;end;
    else
      if(wpre>128000)wpre=128000;end;
      if(wpre<82000)wpre=82000;end;
      if(cgpre>.34)cgpre=.34;end;
    end
```

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if(cgpre<-0.008) cgpre=-.008; end;
if(xnavpre>2313) xnavpre=2313; end;
if(xnavpre<333) xnavpre=333; end;
end;

runtimepre=1/(upre/xnavpre);
tempw = utpre*1.689-upre;
futut = utpre;
deccnstu = upre;
deccnstx = xnavpre;
deccnstbd = exitpos-xnavpre;
futu = upre;
futut = (futu+tempw)/1.689;
disfcms = 0;
lenfcms = 250;
lenxdef = 50;
timepre = 0;
dtpre = 0.25;
temp = 1+xnavpre/lenfcms;

% See note at bottom for why 0.5 is subtracted
i=xnavpre-0.5;

thstmu = functhrust(REVERSE,AUTOREV,futt,futut,i,exitpos,0.,futu,dtpre/0.5);
CDRAG = CDFWD + ((CDAFT-CDFWD)/(CGAFT-CGFWD))*(PC1MAC-CGFWD);
adragmu = (utpre^2)/295.37*CDRAG*SW;
if(DONDIST<1)
    DONDIST = xnavpre;
end;

% CALCULATE NEW cgpre VARIABLES BASED ON FRACTION CG
if(MD11)
    cginpre = 1311.947+cgpre*295.779;
apre = (cginpre-473.437)/12.;
bpre = (1442-cginpre)/12.;
bcpre = (1472.62-cginpre)/12.;
hcgpre = (209.32-(sqrt(cginpre^2+(-21)^2))*sin(atan(21/cginpre)+0.0193))/12.;
else
    cginpre = 885.547+cgpre*158.512;
apre = (cginpre-97.998)/12.;
bpre = (967.1-cginpre)/12.;
bccpre = 0;
hcgpre = (83.029-(sqrt(cginpre^2+(5.1)^2))*sin(atan(-5.1/cginpre)+0.118))/12.;
end;
temp = apre+bpre;
[mumax,mumaxx] = funcfc(RWFC(itemp),upre,xnavpre,temp);
% drag contributions due to crosswind
dragcrs=abs(vwsspre)/57.3/4;

% drag contributions
otherd=((+thstmu-adragmu)/wpre)*32.2+dragcrs;
tempdlast=0;
tempdlagset=tempdlast;
tempd = (vexit^2 - futu^2)/(exitpos-xnavpre)/2.0;
if(nexit>=3 | ROLLIST==1 | ...
 (-tempd>7.0/9.0*DECLIM ))
   DRATE=8.0/9.0*DECLIM;
else
   DRATE=6.0/9.0*DECLIM;
end;
tempd=0;
timeocclag=TIMEOCCLAG;
timepreocclag=timeocclag;
decelprerate=0;
lastprexnav=xnavpre;
lastpredeccalc=0;

% LOOP L112:
while(1)
% Increment logic time by dtpre
  timepre=timepre+dtpre;
  futt=timepre;
  futulast=futu;
% delay decel cmd after touchdown
  if(-TMGD+futt < TNGD)tempd=0;end;
% rate limit for the decel command as well as the actual decel
% a compromise is to rate limit increases in decel but not rate limit
% decreases in decel, such as caused by ice patch
  if(abs(-tempd-tempdlast) > DRLM*dtpre)
    if(-tempd-tempdlast > 0.)
      tempdset=tempdlast+DRLM*dtpre;
    else
      tempdset=-tempd;
    end;
  else
    tempdset=-tempd;
  end;
if(ROLL1 ST)
  % this represents the autobrake lag, too conservative for var braking
  tempdlagset=tempdset+(tempdlagset-tempdset)*exp(-dtpre/0.4);
tempdset=tempdlagset;

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end;
tempdlast=tempdset;
accpre=-tempdset+otherd;
%
Limit total decel (brakes,thrust,drag)
if(accpre<-DECLIM)accpre=-DECLIM;end;
lasti=i;
%
Calculate new runway location
i=i+futu*dtpre+0.5*accpre*dtpre*dtpre;
%
See note at bottom for why 0.5 is subtracted
i=i-0.5;
%
Calculate new ground speed
futu=sqrt(futu*futu+2*accpre*(i-lasti));

if(~CONSTDEC)
%
calculate desired speed profile ground speed
if(decelpreon)
  temp=deccnstu-(i+BRKBUF-deccnstx)*(deccnstu-vexit)/deccnstbd;
else
  temp=0;
end;
%
limit ground speed at or above speed profile ground speed
if(temp<vexit)temp=vexit;end;
if(futu < temp)
  futu=temp;
%
Calculate new decel and runway location based on limited ground speed
accpre=(futu-futulast)/dtpre;
i=lasti+futulast*dtpre+0.5*accpre*dtpre*dtpre;
%
See note at bottom for why 0.5 is subtracted
i=i-0.5;
end;
%
Is aircraft past ROTO exit?
if(i>exitpos)break;end;
%
calculate required deceleration
temdpd = ((vexit)^2- futu^2)/(exitpos-i)/2.0;
decelempre=-temdpd;
%
calculate airspeed, assumes winds are constant
futut=(futu+tempw)/1.689;
%
constant rev thrust is a little overestimated, subtract small value
tempr=0;
if(~AUTOREV&ROLLIST)tempr=0.1;end;
if(AUREVCONST-temp<0) temp=AUREVCONST;end;

% calculate rev thrust using airspeed & whether braking is engaged
  temp=1;
  if((decelpreon&-ROLL1ST)--AUTOREV)
    thstmu=functhrust(REVERSE,AUTOREV,futt,futut,temp,exitpos,AUREVCONST-temp,futu,dtpre/0.5);
  else
    % roll decel and auto rev thrust and braking not initiated, idle rev thrust
    thstmu=functhrust(REVERSE,AUTOREV,futt,futut,temp,exitpos)
      ,futu,dtpre/0.5);
  end;
% calculate aircraft drag along runway using airspeed
  adragmu = (futut^2)/295.37*CDRAG*SW;

% calculate friction available from surface at main gear (mumaxx)
% lenxdef step size may be smaller than friction measurement spacing
  if(disfcms<=0)
    disfcms=lenfcms;
    itemp=1+i/lenfcms;
    temp=1;
    temp2=apre+bpre;
  % fcerr & psip for patches not implemented yet
    [mumax,mumaxx]=funcfc(RWFC(itemp),futu,temp,temp2,0,0);
  end;
% For this study lenxdefmult equaled 0. This causes the use of the friction coefficient
% for the ground speed at touchdown only. This algorithm may need some more retuning
% to minimize mis-predictions while allowing the friction coefficient to vary with ground
% speed, which is more accurate.
  disfcms=disfcms-lenxdef*lenxdefmult;
% calculate NEEDED friction taking into account aircraft drag and thrust
  muneedarr=-tempd/32.2-(-thstmu+adragmu)/wpre)*1;
% limit required decel
  if(tempd<-DECLIM) tempd=-DECLIM;end;
% calculate friction fraction USED at main gear using
% aircraft parameters (gear loading & avg anti-skid eff)
  muavailarr=mumaxx*ASEFF*...
    (apre+hcgpre-(-adragmu/wpre+tempd/32.2))/(-apre+(8*bpre+2*bcpre)/10.);
  otherd=((+thstmu-adragmu)/wpre)*32.2+dragcrs;

% logic to determine onset of variable braking
  temp=((exitpos-i)*(-tempd -lastpredeccalc)/...
    ( i-lastprexnav-tempd );
  decelprerate = temp;
  lastprexnav= i;
  lastpredeccalc=-tempd;
timepreocclast = timepreocclag;
timepreocc = (exitpos - i)/((vexit + futu)/2.2) + futu + runtimepre;

% TIME FOR DECEL AT DECMED
tempt = (futu - vexit)/DECMED;

% DISTANCE OF DECEL AT DECMED
tempdis = -(vexit^2 - futu^2)/2.0/DECMED;

% TIME REQUIRED
temp = BRKBUF/vexit + (exitpos - i - BRKBUF - tempdis)/futu + tempt;

% TIME REMAINING
dtemp = DTIME - futt - runtimepre;

timepreocclag = timepreocc + (timepreocclag - timepreocc)*exp(-dtpre/0.6);

if (~ROLL IST)
dpreon = ((decelprerate > DRATE | timepreocc < DTIME | temp > dtemp...
| (timepreocclag > timepreocclast & futt > 6)));
else
dpreon = (i >= DONDIST);
end;

% If braking has begun, the tempd calculated below is what brake decel will
% provide, decel methodology affects how tempd is created
if (decelpreon | dpreon)
    if (~CONSTDEC)
        % variable braking
        % With variable braking the decel by braking only has to decrease the aicraft speed down
        % to the desired speed profile. The autoreverse thrust is modeled as max at all times.
        % Constant reverse thrust is modeled at its correct value.
        if (~decelpreon)
            deccnstu = futu;
            deccnstx = i;
            deccnstbd = exitpos - i;
        end;
        % assume braking uses all available friction
        tempd = -muavailarr * 32.2;
        % special case for md-81 and constant rev thrust: subtract otherd, normally would
        % allow braking to be as big as possible to drive speed down to speed profile
        if (~MD11 & ~AUTOREV) tempd = tempd - otherd; end;
        % limit braking to DECLIM
        if (tempd < -DECLIM) tempd = -DECLIM; end;
        else
            % constant braking
            if (futu > vexit)
                % assumed that DECSEL <= DECLIM
                % constant decel braking (auto or manual) will be less based on decel
            end;
        end;
    end;
end;
% provided by other (rev thrust, drag)
    tempd = DECSEL- otherd;
% constant decel will never give more than available friction
    if(abs(tempd)>abs(muavailarr*32.2))tempd=-muavailarr*32.2; end;
else
% represents coasting below exit entrance ground speed
    tempd=0;
end;
end;
decelpreon = 1;
else
    tempd=0;
end;
if(tempd>0)tempd=0; end;
end; %L12

% exit for loop if aircraft is past ROTO exit
% ABORT EXIT if NEEDED friction > AVAILABLE friction
    if(~ROLL1ST)
        abortearly=(muneedarr > muavailarr) | (deceltemppre>DECLIM);
    else
        abortearly=((muneedarr > muavailarr) | (deceltemppre>DECLIM))...
            & (futu>vexit);
    end;
repL121=0;
if(~ROLL1ST & CREVTHRLOOP)
% not roll deceleration or trying to find constant reverse thrust setting
% if(abortearly & ~OCCSTOP)fprintf(fid,'%13.6e %s %i
','predict abort, nexit=',nexit);end;
else
% Logic was added for roll- then deceleration (could be constant or variable)
% Start with brake onset (DONDIST) at runway threshold. If exit is not aborted
% increase DONDIST repeatedly down the runway until the exit is aborted. Then
% back up DONDIST as calculated below. DONDIST is found after constant rev thrust
% is found if AUTOREV=false
if(abortearly)
    if(DONDIST>xnavpre)
        abortearly=0;
% md-81 needs more distance for the autorev=false case.
% may have to do with its slower reverse thrust spool up.
% not needed if reverse thrust is at idle
    if(~MD11 & ~AUTOREV & (AUREVCONST>0.1))}
if(\(-\text{MD11} \& \neg \text{-AUTOREV}\))
  \(\text{DONDIST}=\text{DONDIST}-350\times(1+nexit)-1600\times\text{dragcrs}-\text{lenxdef}^2;\)
else
  \(\text{DONDIST}=\text{DONDIST}-125-1600\times\text{dragcrs}-\text{lenxdef}^2;\)
end;
else
  \% exit abort is final
  \(\text{DONDIST}=0;\)
end;
break;%L111
else
  \(\text{DONDIST}=\text{DONDIST}+\text{lenxdef}^2;\)
  if(\(\text{DONDIST}<\text{exitpos}\))
    \(\text{newexit}=1;\)
    \(\text{lastdeccalc}=0;\)
    \(\text{repL111}=1;\)
  end;
end;
end;

if(\(-\text{repL111}\))
  \% LOGIC WAS ADDED FOR CONSTANT REVERSE THRUST SO THAT THE CORRECT
  \% CONSTANT REV COULD BE RECOMMENDED BY EXIT PREDICTION LOGIC.
  \% INITIALLY MAXIMUM REVERST THRUST
  \% IS ASSUMED & IF AN EXIT IS ABORTED IT IS ALLOWED. IF AN EXIT IS NOT
  \% ABORTED, CONSTANT REV IS DECREASED AND THE EXIT PREDICTION LOGIC IS
  \% RUN AGAIN UNTIL AN EXIT IS ABORTED AGAIN. THEN THE CONSTANT REV
  \% IS INCREASED TO ITS PREVIOUS LEVEL AND THE REV THRUST PREDICTION IS OVER.
  if(abortearly)
    \% This is final constant reverse thrust (AUREVCONST) factor if AUTOREV=false
    \% reverse thrust = AUREVCONST\times(\text{max rev thrust} - \text{idle rev thr ist}) + \text{idle rev thrust};
    \% assumes four levels of constant reverse thrust
    \% AUREVCONST=(1, .66, .33, 0)
    \else

if(-AUTOREV)
    if(AUREVCONST>0.1 & CREVTHRLOOP)
        AUREVCONST=AUREVCONST-0.33;
        abortearly=1;
        %repeat L111
    else
        % if(-OCCSTOP)fprintf(fid,'%s %13.6e
','constant rev thr setting',AUREVCONST);end;
        % no need to decrease AUREVCONST any further since it is near 0
    end;
end;
end;

% THIS IS FOR ROLL1ST,DO CONST REV THR FIRST, THEN BRAKE ONSET
if(-abortearly)
    if(-AUTOREV & ROLL1ST & CREVTHRLOOP )
        CREVTHRLOOP=0;
        %repeat L111 to find roll deceleration brake onset distance
    else
        break;%L111
    end;
end;
end;%L111

% The DONDIST value for roll deceleration and the AUREVCONST value for constant rev thrust
% are not calculated until an exit is not aborted with DONDIST=0 (immediate braking)
% and AUREVCONST=1 (max rev thrust). Then the algorithm finds the smallest allowable
% AUREVCONST value down to idle reverse thrust (=0), then using that the largest DONDIST
% value up to the current exit's position.

% Roll deceleration exit prediction logic needs much more CPU resources. Exit predicted
% constant reverse thrust also requires some more CPU time.

% The ROTO FORTRAN code uses some integer values.
% So that the MATLAB exit prediction logic gets the same results as the FORTRAN
% code I need to truncate the real variable i. Matlab's fix() function gives me
% unexplained runtime divide by zero errors, so this is my compromise.
% Subtract 0.5 from desired integer value, as a statistical solution.
% The i value represents the aircraft longitudinal runway location in the exit
% prediction logic. When it is an integer value, with the current algorithm
% it has a small tendency to predict an earlier exit.
Baseline is: 70 kt spiral exit, normal flaps, no exit prediction estimation input data errors, reverse thrust stowed at 70 kt, 15 kts crosswind, touchdown lateral offset = 0 ft, 6.5 ft/sec/sec decel limit, stop tangent to taxiway centerline, antiskid eff. = 75%

Each row of data obtained from an aircraft's dispersion of 756 (MD-81), 888 (MD-11) simulation runs

| Deceleration method, exit prediction usage and difference from baseline | First 3 high-speed exit locations | Aircraft type | Runway surface condition | ROT = Runway Occupancy Time at end of runway | % using end of runway | % ROT > 53.4 sec | ROT STDEV (sec) | Exit number used by aircraft | Exit # MEAN | Exit # STDEV | Page or Figure Number |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Auto rev thr & var dec, w/ PRED | 3500 4950 6550 | MD-11; wet surf | 1 | 49.00 | 13.70 | 13.70 | 34.10 | 14.70 | 2.90 | P1, P49 | F6.1c, 5c |
| Auto rev thr & var dec, w/ PRED | 3500 4950 6550 | MD-11; dry surf | 2 | 48.50 | 11.40 | 11.40 | 32.55 | 14.45 | 2.85 | P1, P51 | F6.1c, 6c |
| Auto rev thr & var dec, w/ PRED | 3500 4950 6550 | MD-81; wet surf | 3 | 41.00 | 0.01 | 0.00 | 19.45 | 9.50 | 2.60 | P1 | F6.1b, 6b |
| Auto rev thr & var dec, w/ PRED | 3500 4950 6550 | MD-81; dry surf | 4 | 40.60 | 0.00 | 0.00 | 19.33 | 9.30 | 2.55 | P1, P51 | F6.1b, 6b |

**EXIT LOCATION**

| Auto rev thr & var dec, w/ PRED | 3900 5350 6950 | MD-11; wet surf | 6 | 48.00 | 6.11 | 6.11 | 26.70 | 13.40 | 3.00 | P2, P53 | F6.1c, 11c |
| Auto rev thr & var dec, w/ PRED | 3900 5350 6950 | MD-11; dry surf | 7 | 47.50 | 4.86 | 4.86 | 25.50 | 13.15 | 3.00 | P2 | F6.1c, 11c |
| Auto rev thr & var dec, w/ PRED | 3900 5350 6950 | MD-81; wet surf | 8 | 41.10 | 0.00 | 0.00 | 19.83 | 8.15 | 2.65 | P2, P55 | F6.1b, 11b |
| Auto rev thr & var dec, w/ PRED | 3900 5350 6950 | MD-81; dry surf | 9 | 40.40 | 0.00 | 0.00 | 19.10 | 7.90 | 2.65 | P2 | F6.1b, 11b |

**EXIT LOCATION**

<p>| Auto rev thr &amp; var dec, w/ PRED | Average | 10 | 44.25 | 2.74 | 2.74 | 22.78 | 10.65 | 2.83 | F6.1a | F6.11a |</p>
<table>
<thead>
<tr>
<th>Deceleration method, exit prediction usage and difference from baseline</th>
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<th>surface condition</th>
<th>Row #</th>
<th>ROT MEAN (sec)</th>
<th>% using end of runway</th>
<th>% ROT &gt; 53.4</th>
<th>ROT STDEV (sec)</th>
<th>Exit # MEAN</th>
<th>Exit # STDEV</th>
<th>Figure or Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>auto rev thr &amp; var dec, w/ PRED</td>
<td>4500 5950 7350</td>
<td>MD-11; wet surf</td>
<td>11</td>
<td>47.20</td>
<td>2.31</td>
<td>2.31</td>
<td>20.80</td>
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<td>auto rev thr &amp; var dec, w/ PRED</td>
<td>4500 5950 7350</td>
<td>MD-11; dry surf</td>
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<td>46.80</td>
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<td>11.20</td>
<td>3.10</td>
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<td>41.20</td>
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<td>16.10</td>
<td>6.05</td>
<td>2.10</td>
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<td>41.20</td>
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<td>16.10</td>
<td>6.05</td>
<td>2.10</td>
<td></td>
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</table>

**BEST EXIT LOCATION, BASELINE**

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| auto rev thr & var dec, w/ PRED | 4300 5950 7550 | MD-11; wet surf | 16 | 47.70 | 1.36 | 6.36 | 20.65 | 11.60 | 2.85 |
| auto rev thr & var dec, w/ PRED | 4300 5950 7550 | MD-11; dry surf | 17 | 47.30 | 0.94 | 4.19 | 20.11 | 11.30 | 2.80 |
| auto rev thr & var dec, w/ PRED | 4300 5950 7550 | MD-81; wet surf | 18 | 41.50 | 0.00 | 0.00 | 20.81 | 6.70 | 2.40 |
| auto rev thr & var dec, w/ PRED | 4300 5950 7550 | MD-81; dry surf | 19 | 41.20 | 0.00 | 0.00 | 19.83 | 6.60 | 2.35 |

**WIDER EXIT SPACING**

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | |
| Average | 44.10 | 1.01 | 1.05 | 18.27 | 8.70 | 2.61 |

<p>| | | | | | | | | | | |
| | | | | | | | | | | |
| F6.1c, F6.1b, 2d, 2c, 3c, 5b, 6b, 7a, 7b, 9b, 11b, 12b |
| P3, P59, P61, P63 |</p>
<table>
<thead>
<tr>
<th>Deceleration method, exit prediction usage and difference from baseline</th>
<th>first 3 high-speed exit locations</th>
<th>aircraft type</th>
<th>surface condition</th>
<th>Row</th>
<th>% using end of runway</th>
<th>% ROT &gt; 53.4</th>
<th>ROT MEAN (sec)</th>
<th>ROT STDEV (sec)</th>
<th>Exit # MEAN</th>
<th>Exit # STDEV</th>
<th>Page or Figure Number</th>
</tr>
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<tr>
<td>auto rev thr &amp; var dec, w/ PRED + full flaps</td>
<td>4500 5950 7350</td>
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<td>21</td>
<td>1.36</td>
<td>1.36</td>
<td>46.40</td>
<td>19.50</td>
<td>10.95</td>
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<td>0.60</td>
<td>41.20</td>
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<tr>
<td>auto rev thr &amp; var dec, w/ PRED + full flaps</td>
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<td>0.50</td>
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<td>FULL FLAPS</td>
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<td>0.85</td>
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<td>3500 4950 6550</td>
<td>MD-11; wet surf</td>
<td>26</td>
<td>8.44</td>
<td>8.44</td>
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<td>7.07</td>
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<td>28</td>
<td>0.02</td>
<td>0.00</td>
<td>41.30</td>
<td>25.50</td>
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<td>0.00</td>
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<td>DECEL METHOD, NON-ROTO</td>
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<td>3.88</td>
<td>3.89</td>
<td>33.83</td>
<td>11.46</td>
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<td>Deceleration method, exit prediction usage and difference from baseline</td>
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**DECEL METHOD, NON-ROTO**

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<tr>
<th>Average</th>
<th>35</th>
<th>43.43</th>
<th>1.51</th>
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<td>36</td>
<td>46.60</td>
<td>2.09</td>
<td>8.50</td>
<td>30.60</td>
<td>10.80</td>
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<td>0.30</td>
<td>20.81</td>
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</table>

**DECEL METHOD, NON-ROTO**

<p>| Average | 40 | 43.68 | 0.72 | 2.51 | 24.20 | 8.30 | 2.55 | F6.3a, F6.4, F6.5a |</p>
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<tr>
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<td>0.10</td>
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<td>P9,P95</td>
<td>F6.3b,5b</td>
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<tr>
<td><strong>DECEL METHOD</strong></td>
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<td>1.34</td>
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<td>2.75</td>
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<tr>
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<td>46</td>
<td>47.10</td>
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<td>7.36</td>
<td>26.35</td>
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<td>F6.3c</td>
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<td>MD-11; dry surf</td>
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<td>43.80</td>
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<td>aircraft type</td>
<td>surface condition</td>
<td>Row #</td>
<td>ROT MEAN (sec)</td>
<td>% using end of runway</td>
<td>% ROT &gt; 53.4</td>
<td>ROT STDEV (sec)</td>
<td>Exit # MEAN</td>
<td>Exit # STDEV</td>
<td>Page or Figure Number</td>
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<td>MD-81; dry surf</td>
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<td>P12,F6.6b</td>
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60 KNOT EXIT ENTRANCE SPEED AT MID EXIT LOCATION 5950 | Average | 60 | 47.58 | 2.16 | 15.48 | 22.16 | 9.68 | 2.85 | F6.6a |
<table>
<thead>
<tr>
<th>Deceleration method, exit prediction usage and difference from baseline</th>
<th>first 3 high-speed exit locations</th>
<th>aircraft type</th>
<th>surface condition</th>
<th>Row #</th>
<th>ROT MEAN (sec)</th>
<th>% using end of runway</th>
<th>% ROT &gt; 53.4</th>
<th>ROT STDEV (sec)</th>
<th>Exit # MEAN</th>
<th>Exit # STDEV</th>
<th>Page or Figure Number</th>
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<td>auto rev thr &amp; var dec, w/ PRED 80 knot high speed exit</td>
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<td>MD-11; wet surf</td>
<td>61</td>
<td>41.80</td>
<td>0.85</td>
<td>0.85</td>
<td>18.90</td>
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<td>P13,P117</td>
<td>F6.6c</td>
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<tr>
<td>auto rev thr &amp; var dec, w/ PRED 80 knot high speed exit</td>
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<td>MD-81; wet surf</td>
<td>63</td>
<td>38.10</td>
<td>0.00</td>
<td>0.00</td>
<td>14.96</td>
<td>5.55</td>
<td>1.60</td>
<td>P13,F6.6b</td>
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<tr>
<td>auto rev thr &amp; var dec, w/ PRED 80 knot high speed exit</td>
<td>4500 5950 7350</td>
<td>MD-81; dry surf</td>
<td>64</td>
<td>37.60</td>
<td>0.00</td>
<td>0.00</td>
<td>14.95</td>
<td>5.50</td>
<td>1.50</td>
<td>P13,F6.6b</td>
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**80 KNOT EXIT ENTRANCE SPEED AT MID EXIT LOCATION 5950**

| auto rev thr & var dec, w/ PRED 60 knot high speed exit | 5500 6950 8350 | MD-11; wet surf | 66 | 50.70 | 0.35 | 21.00 | 21.15 | 9.10 | 3.10 | P14,P121 | F6.6c |
| auto rev thr & var dec, w/ PRED 60 knot high speed exit | 5500 6950 8350 | MD-11; dry surf | 67 | 49.70 | 0.13 | 11.70 | 20.25 | 8.75 | 3.05 | P14,F6.6c |
| auto rev thr & var dec, w/ PRED 60 knot high speed exit | 5500 6950 8350 | MD-81; wet surf | 68 | 48.80 | 0.00 | 10.43 | 20.21 | 5.20 | 1.00 | P14,F6.6b |
| auto rev thr & var dec, w/ PRED 60 knot high speed exit | 5500 6950 8350 | MD-81; dry surf | 69 | 48.60 | 0.00 | 9.60 | 20.29 | 5.15 | 0.90 | P14,F6.6b |

**60 KNOT EXIT ENTRANCE SPEED AT MID EXIT LOCATION 6950**

<p>| auto rev thr &amp; var dec, w/ PRED 60 knot high speed exit | 5500 6950 8350 | MD-81; dry surf | 70 | 49.45 | 0.12 | 13.18 | 20.47 | 7.05 | 2.01 | F6.6a |</p>
<table>
<thead>
<tr>
<th>Deceleration method, exit prediction usage and difference from baseline</th>
<th>first 3 high-speed exit locations</th>
<th>80 KNOT EXIT ENTRANCE SPEED AT MID EXIT LOCATION 4950</th>
<th>TOUCHDOWN DISPERSION SIGMA</th>
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</thead>
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<td>auto rev thr var dec, w/ PRED</td>
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<td>3500</td>
<td>4500</td>
</tr>
<tr>
<td>auto rev thr var dec, w/ PRED</td>
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<td>4950</td>
<td>5950</td>
</tr>
<tr>
<td>auto rev thr var dec, w/ PRED</td>
<td>6550</td>
<td>6550</td>
<td>7350</td>
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<tr>
<td>auto rev thr var dec, w/ PRED</td>
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<td>4500</td>
</tr>
<tr>
<td>auto rev thr var dec, w/ PRED</td>
<td>4950</td>
<td>4950</td>
<td>5950</td>
</tr>
<tr>
<td>auto rev thr var dec, w/ PRED</td>
<td>6550</td>
<td>6550</td>
<td>7350</td>
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<td>4500</td>
</tr>
<tr>
<td>auto rev thr var dec, w/ PRED</td>
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<td>4950</td>
<td>5950</td>
</tr>
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<td>auto rev thr var dec, w/ PRED</td>
<td>6550</td>
<td>6550</td>
<td>7350</td>
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<table>
<thead>
<tr>
<th>Deceleration method, exit prediction usage and difference from baseline</th>
<th>first 3 high-speed exit locations</th>
<th>aircraft type</th>
<th>surface condition</th>
<th>Row #</th>
<th>ROT MEAN (sec)</th>
<th>% using end of runway</th>
<th>ROT STDEV (sec)</th>
<th>Exit # MEAN</th>
<th>Exit # STDEV</th>
<th>Page or Figure Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>auto rev thr &amp; var dec, w/ PRED dispersion sigma = 100</td>
<td>4500 5950 7350</td>
<td>MD-11; wet surf</td>
<td>81 47.20</td>
<td>1.97</td>
<td>1.97</td>
<td>20.10</td>
<td>11.50</td>
<td>3.10</td>
<td>P17,P137</td>
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<tr>
<td>auto rev thr &amp; var dec, w/ PRED dispersion sigma = 100</td>
<td>4500 5950 7350</td>
<td>MD-11; dry surf</td>
<td>82 46.70</td>
<td>1.51</td>
<td>1.50</td>
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<td>11.15</td>
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<td>auto rev thr &amp; var dec, w/ PRED dispersion sigma = 100</td>
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<td>MD-81; wet surf</td>
<td>83 41.10</td>
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<td>15.65</td>
<td>6.00</td>
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<td>84 41.10</td>
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<td>15.65</td>
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**TOUCHDOWN GROUND SPEED SIGMA**

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<th>0.87</th>
<th>0.92</th>
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**TOUCHDOWN GROUND SPEED SIGMA**

<p>|          | Average | 45.03 | 3.29 | 3.98 | 23.42 | 9.06 | 3.34 | F6.9a |</p>
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<th>Deceleration method, exit prediction usage and difference from baseline</th>
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<th>aircraft type</th>
<th>surface condition</th>
<th>Row #</th>
<th>ROT MEAN (sec)</th>
<th>% using end of runway</th>
<th>% ROT &gt; 53.4</th>
<th>ROT STDEV (sec)</th>
<th>Exit # MEAN</th>
<th>Exit # STDEV</th>
<th>Page or Figure Number</th>
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</thead>
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<tr>
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<td>wet surf</td>
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<td>dry surf</td>
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<td>wet surf</td>
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<td>dry surf</td>
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<td>wet surf</td>
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<td>0.10</td>
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<td>dry surf</td>
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<td>F6.10</td>
</tr>
<tr>
<td>Deceleration method, exit prediction usage and difference from baseline</td>
<td>first 3 high-speed exit locations</td>
<td>aircraft type</td>
<td>surface condition</td>
<td>Row #</td>
<td>ROT MEAN (sec)</td>
<td>% using end of runway</td>
<td>% ROT &gt; 53.4</td>
<td>ROT STDEV (sec)</td>
<td>Exit #</td>
<td>Exit # STDEV</td>
<td>Page or Figure Number</td>
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<tr>
<td>auto rev thr &amp; var dec, w/ PRED gusting crosswind 12.5+/−2.5 &amp; sensor noise</td>
<td>4500 5950 7350</td>
<td>MD-11; wet surf</td>
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<td>46.80</td>
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<td>0.10</td>
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<td>% using end of runway</td>
<td>% ROT &gt; 53.4</td>
<td>ROT STDEV (sec)</td>
<td>Exit # MEAN</td>
<td>Exit # STDEV</td>
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<td>0.21</td>
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<td>5350</td>
<td>6950</td>
<td>8300</td>
<td>MD-11; wet surfa</td>
<td>156</td>
<td>47.60</td>
<td>0.08</td>
<td>5.07</td>
<td>19.85</td>
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<td>8300</td>
<td>MD-11; dry surfa</td>
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<td>8300</td>
<td>MD-81; wet surfa</td>
<td>158</td>
<td>41.10</td>
<td>0.00</td>
<td>0.00</td>
<td>19.47</td>
<td>8.15</td>
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<td>6950</td>
<td>8300</td>
<td>MD-81; dry surfa</td>
<td>159</td>
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<td>0.00</td>
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<td>Average</td>
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<td>44.05</td>
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<td>LATERAL TOUCHDOWN OFFSET = 27 FEET</td>
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<tr>
<td>auto rev thr &amp; var dec, w/ PRED</td>
<td>4500, 5950, 7350</td>
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</table>

<p>| AIRCRAFT CG STOPS ON EXIT @ Y = 480 FEET |
|------------------------------------------|---------------------------------|
| auto rev thr &amp; var dec, w/ PRED         | 4500                            |
| aircraft cg stops on exit @ Y = 480 ft  | 4500                            |
| auto rev thr &amp; var dec, w/ PRED         | 4500                            |
| aircraft cg stops on exit @ Y = 480 ft  | 4500                            |
| auto rev thr &amp; var dec, w/ PRED         | 4500                            |
| aircraft cg stops on exit @ Y = 480 ft  | 4500                            |</p>
<table>
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<th>% using end of runway</th>
<th>% ROT &gt; 53.4</th>
<th>ROT STDEV (sec)</th>
<th>Exit # MEAN</th>
<th>Exit # STDEV</th>
<th>Page or Figure Number</th>
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</thead>
<tbody>
<tr>
<td>auto rev thr &amp; var dec, w/ PRED max allowable decel=9ft/s/s</td>
<td>3900 5350 6950</td>
<td>MD-11; wet surf</td>
<td>171</td>
<td>45.40</td>
<td>1.72</td>
<td>1.72</td>
<td>22.50</td>
<td>12.10</td>
<td>2.90</td>
<td>P35,P229</td>
<td>F6.11c</td>
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<td>auto rev thr &amp; var dec, w/ PRED max allowable decel=9ft/s/s</td>
<td>3900 5350 6950</td>
<td>MD-11; dry surf</td>
<td>172</td>
<td>43.20</td>
<td>0.07</td>
<td>0.07</td>
<td>17.85</td>
<td>10.95</td>
<td>2.60</td>
<td>P35</td>
<td>F6.11c</td>
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<td>3900 5350 6950</td>
<td>MD-81; wet surf</td>
<td>173</td>
<td>40.50</td>
<td>0.00</td>
<td>0.23</td>
<td>18.51</td>
<td>7.75</td>
<td>2.65</td>
<td>P35,P231</td>
<td>F6.11b</td>
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<td>3900 5350 6950</td>
<td>MD-81; dry surf</td>
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<td>38.50</td>
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<td>17.71</td>
<td>6.85</td>
<td>2.45</td>
<td>P35</td>
<td>F6.11b</td>
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</table>

ALLOW FOR MAXIMUM DECELERATION OF 9 FT/S/S

| Auto rev thr & var dec, w/ PRED anti-skid eff.=90% | 3900 5350 6950 | MD-11; wet surf | 176 | 47.90 | 5.46 | 5.46 | 25.85 | 13.35 | 2.95 | P36,P233 | F6.11c |
|--------------------------------------------------|------------------|---------------|-------|---------------|------------------------|-------------|-------------|-------------|-------------|-----------------------|
| auto rev thr & var dec, w/ PRED anti-skid eff.=90% | 3900 5350 6950 | MD-11; dry surf | 177 | 47.50 | 4.86 | 4.86 | 25.75 | 13.15 | 3.00 | P36 | F6.11c |
| auto rev thr & var dec, w/ PRED anti-skid eff.=90% | 3900 5350 6950 | MD-81; wet surf | 178 | 40.90 | 0.00 | 0.00 | 19.17 | 8.05 | 2.70 | P36,P235 | F6.11b |
| auto rev thr & var dec, w/ PRED anti-skid eff.=90% | 3900 5350 6950 | MD-81; dry surf | 179 | 40.50 | 0.00 | 0.00 | 19.00 | 7.90 | 2.65 | P36 | F6.11b |

ANTI-SKID EFFICIENCY EQUALS 90% AT MID EXIT LOCATION 5350

| Auto rev thr & var dec, w/ PRED anti-skid eff.=90% | 3900 5350 6950 | MD-81; dry surf | 179 | 40.50 | 0.00 | 0.00 | 19.00 | 7.90 | 2.65 | P36 | F6.11b |

| Auto rev thr & var dec, w/ PRED anti-skid eff.=90% | 3900 5350 6950 | MD-11; wet surf | 176 | 47.90 | 5.46 | 5.46 | 25.85 | 13.35 | 2.95 | P36,P233 | F6.11c |
|--------------------------------------------------|------------------|---------------|-------|---------------|------------------------|-------------|-------------|-------------|-------------|-----------------------|
| auto rev thr & var dec, w/ PRED anti-skid eff.=90% | 3900 5350 6950 | MD-11; dry surf | 177 | 47.50 | 4.86 | 4.86 | 25.75 | 13.15 | 3.00 | P36 | F6.11c |
| auto rev thr & var dec, w/ PRED anti-skid eff.=90% | 3900 5350 6950 | MD-81; wet surf | 178 | 40.90 | 0.00 | 0.00 | 19.17 | 8.05 | 2.70 | P36,P235 | F6.11b |
| auto rev thr & var dec, w/ PRED anti-skid eff.=90% | 3900 5350 6950 | MD-81; dry surf | 179 | 40.50 | 0.00 | 0.00 | 19.00 | 7.90 | 2.65 | P36 | F6.11b |

ANTI-SKID EFFICIENCY EQUALS 90% AT MID EXIT LOCATION 5350

<p>| Auto rev thr &amp; var dec, w/ PRED anti-skid eff.=90% | 3900 5350 6950 | MD-81; dry surf | 179 | 40.50 | 0.00 | 0.00 | 19.00 | 7.90 | 2.65 | P36 | F6.11b |</p>
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<th>first 3 high-speed exit locations</th>
<th>aircraft type</th>
<th>surface condition</th>
<th>Row #</th>
<th>ROT MEAN (sec)</th>
<th>% using end of runway</th>
<th>% ROT &gt; 53.4</th>
<th>ROT STDEV (sec)</th>
<th>Exit # MEAN</th>
<th>Exit # STDEV</th>
<th>Page or Figure Number</th>
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<td>MD-11; wet surf</td>
<td>181</td>
<td>47.40</td>
<td>3.39</td>
<td>3.39</td>
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<td>182</td>
<td>46.70</td>
<td>1.72</td>
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<td>20.30</td>
<td>11.20</td>
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<td>4500 5950 7350</td>
<td>MD-81; wet surf</td>
<td>183</td>
<td>41.70</td>
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<td>Average</td>
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<td>18.93</td>
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<td>3500 4950 6550</td>
<td>MD-11; wet surf</td>
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<td>54.00</td>
<td>23.50</td>
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<td>MD-81; wet surf</td>
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<td>Average</td>
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<td>10.95</td>
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<td>12.93</td>
<td>2.65</td>
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<td>Deceleration method, exit prediction usage and difference from baseline</td>
<td>first 3 high-speed exit locations</td>
<td>aircraft type</td>
<td>surface condition</td>
<td>Row #</td>
<td>ROT MEAN (sec)</td>
<td>% using end of runway</td>
<td>% ROT &gt; 53.4</td>
<td>ROT STDEV (sec)</td>
<td>Exit # MEAN</td>
<td>Exit # STDEV</td>
<td>Page or Figure Number</td>
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<td>4500 5950 7350</td>
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<td>15.10</td>
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<td>14.35</td>
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<td>8.65</td>
<td>2.65</td>
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<td>72.00</td>
<td>23.48</td>
<td>8.35</td>
<td>2.65</td>
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<td>P39, F6.6b</td>
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**40 KNOT EXIT ENTRANCE SPEED AT MID EXIT LOCATION 5950**

Average 195 61.25 6.19 86.73 29.66 11.28 2.93 P6.6a

| auto rev thr & var dec, w/ PRED, Reverse Thrust not stowed on Exit | 4500 5950 7350 | MD-11; wet surfa | 196 | 47.30 | 2.31 | 2.31 | 21.05 | 11.50 | 3.15 | P40, P249 | F6.2c, 12c |
| auto rev thr & var dec, w/ PRED, Reverse Thrust not stowed on Exit | 4500 5950 7350 | MD-11; dry surfa | 197 | 46.80 | 1.72 | 1.72 | 20.25 | 11.20 | 3.10 | F6.2c, 12c | P40 |
| auto rev thr & var dec, w/ PRED, Reverse Thrust not stowed on Exit | 4500 5950 7350 | MD-81; wet surfa | 198 | 41.90 | 0.00 | 1.03 | 19.49 | 6.20 | 2.20 | P40, P251 | F6.2b, 12b |
| auto rev thr & var dec, w/ PRED, Reverse Thrust not stowed on Exit | 4500 5950 7350 | MD-81; dry surfa | 199 | 41.60 | 0.00 | 1.03 | 18.92 | 6.10 | 2.10 | F6.2b, 12b | P40 |

**REVERSE THRUST NOT STOWED ON EXIT**

Average 200 44.40 1.01 1.52 19.93 8.75 2.64 F6.2a, 12a
<table>
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<tr>
<th>Deceleration method, exit prediction usage and difference from baseline</th>
<th>first 3 high-speed exit locations</th>
<th>aircraft type</th>
<th>surface condition</th>
<th>Row #</th>
<th>ROT MEAN (sec)</th>
<th>% using end of runway</th>
<th>% ROT &gt; 53.4</th>
<th>ROT STDEV (sec)</th>
<th>Exit # MEAN</th>
<th>Exit # STDEV</th>
<th>Page or Figure Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>auto rev thr &amp; var dec, w/ PRED, Rev Thr Idle on Runway</td>
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<td>201</td>
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<td>2.90</td>
<td>P42,P259</td>
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<td>MD-81; dry surf</td>
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<td>22.83</td>
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<td>aircraft type</td>
<td>surface condition</td>
<td>Row #</td>
<td>ROT MEAN (sec)</td>
<td>% using end of runway</td>
<td>% ROT &gt; 53.4</td>
<td>ROT STDEV (sec)</td>
<td>Exit # MEAN</td>
<td>Exit # STDEV</td>
<td>Page or Figure Number</td>
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<tr>
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<td>MD-11; wet surf</td>
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<tr>
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<td>3900  5350  6950</td>
<td>MD-81; wet surf</td>
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<td>P44, P267</td>
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<td>% ROT STDEV &gt; 53.4</td>
<td>% using end of runway</td>
<td>ROT MEAN (sec)</td>
<td>Row &amp; surface condition</td>
<td>Aircraft type</td>
<td>Deceleration method, exit prediction &amp; difference from baseline</td>
<td>Exit #</td>
<td>Exit #</td>
<td>Exit #</td>
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<td>3.10</td>
<td>F6.3.5c</td>
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<td>P45027</td>
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<td>21.50</td>
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<td>F6.3.5c</td>
<td>P45029</td>
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<td>F6.3.5c</td>
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<td>F6.3.5c</td>
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<td>4.550</td>
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<td>4.550</td>
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<td>F6.3.5c</td>
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<td>4.550</td>
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<td>3.10</td>
<td>F6.3.5c</td>
<td>P45029</td>
<td>P45027</td>
<td>P45029</td>
<td>P45027</td>
<td>P45029</td>
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<tr>
<td>Deceleration method, exit prediction usage and difference from baseline</td>
<td>first 3 high-speed exit locations</td>
<td>aircraft type</td>
<td>surface condition</td>
<td>Row #</td>
<td>ROT MEAN (sec)</td>
<td>% using end of runway</td>
<td>% ROT &gt; 53.4</td>
<td>ROT STDEV (sec)</td>
<td>Exit #</td>
<td>Exit # STDEV</td>
<td>Page or Figure Number</td>
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<tr>
<td>auto rev thr &amp; var dec, w/ PRED anti-skid eff.=90%</td>
<td>4500 5950 7350</td>
<td>MD-11; wet surface</td>
<td>231</td>
<td>47.10</td>
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<td>1.99</td>
<td>20.60</td>
<td>11.40</td>
<td>3.15</td>
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<td>MD-11; dry surface</td>
<td>232</td>
<td>46.70</td>
<td>1.72</td>
<td>1.72</td>
<td>20.30</td>
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<td>41.20</td>
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<td>15.76</td>
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<td>2.10</td>
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ANTI-SKID EFFICIENCY EQUALS 90% AT MID EXIT LOCATION 5950

<table>
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<th>auto rev thr &amp; var dec, w/ PRED 40 knot high speed exit</th>
<th>3900 5350 6950</th>
<th>MD-11; wet surface</th>
<th>236</th>
<th>68.60</th>
<th>27.80</th>
<th>99.30</th>
<th>47.00</th>
<th>15.95</th>
<th>2.85</th>
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<td>auto rev thr &amp; var dec, w/ PRED 40 knot high speed exit</td>
<td>3900 5350 6950</td>
<td>MD-11; dry surface</td>
<td>237</td>
<td>66.30</td>
<td>20.70</td>
<td>96.90</td>
<td>44.20</td>
<td>15.45</td>
<td>2.80</td>
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<tr>
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<td>3900 5350 6950</td>
<td>MD-81; wet surface</td>
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<td>86.10</td>
<td>23.93</td>
<td>10.70</td>
<td>2.50</td>
<td>P48,P287</td>
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<td>MD-81; dry surface</td>
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<td>10.40</td>
<td>2.50</td>
<td>F6.6b</td>
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</table>

40 KNOT EXIT ENTRANCE SPEED AT MID EXIT LOCATION 5350

| auto rev thr & var dec, w/ PRED 40 knot high speed exit | 3900 5350 6950 | MD-81; dry surface | 239 | 57.20 | 0.05 | 81.30 | 23.45 | 10.40 | 2.50 | P48,F6.6b |
DALLAS/FT. WORTH HIGH-SPEED EXIT DATA

30 degree, high-speed exits at Dallas-Ft. Worth International Airport are used by flight crews, at their discretion, under daylight VMC conditions with no runway/exit surface contamination. This applies to both narrow and wide body aircraft at exit entrance ground speeds up to 70 knots. This section will compare actual MD-8x ROT data collected on Dallas-Ft. Worth runway 13R in November, 1993 to simulated auto ROTO ROT data for a MD-81 dispersion on a dry runway surface condition. The simulation used the same single runway high-speed exit location as found on runway 13R.

The figure on page 168 is a map of the airport runways, looking north. Runway 13R is the left most diagonal runway, with aircraft landing from left-top to right-bottom. The high-speed exit is 2/3 of the way down the runway at 5325 feet past the runway threshold, when fitted with a spiral-arc exit geometry.

The figure on page 169 graphs actual MD-8x ROT data for 196 landings. Assuming all landings have equal probability, the ROT mean and stdev are 46.5 and 1.72 seconds respectively. Figures referred to in this section are described in report section 5. The figure on page 170 graphs the probability distribution (PD) for the actual ROT data, assuming all landings have equal probability of occurring. It shows the relative occurrence of ROT values for the actual landings.

The figure on page 171 is a 3-D ROT graph of a auto ROTO simulated MD-81 dispersion on a dry surface condition. Auto ROTO MD-81 modeling is described in report sections 3 and 4. The touchdown ground speed and touchdown longitudinal location statistics of 116.44 +/- 10.36 knots and 1362 +/- 198 feet, respectively; were used to calculate the relative probability of a landing occurring. This relative probability of landings was then used to calculate the simulated ROT mean and stdev of 45.6 and 5.04, respectively. The relative probability of landings was also used in creating the ROT PD graph on page 172 showing the probability of ROT values for the simulated MD-81 dispersion.
The following table summarizes ROT mean and stdev statistics for the actual MD-8x landings and various simulated aircraft dispersions using the runway 13R high-speed exit location. The last four entries list ROT statistics gathered from this report for the optimum 3 exit location having a mid exit location at 5950 feet past the runway threshold.

<table>
<thead>
<tr>
<th>Aircraft Data</th>
<th>Runway &amp; exit #</th>
<th>Surface Condition</th>
<th>ROT mean (sec)</th>
<th>ROT stdev (sec)</th>
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<td>1.72</td>
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<tr>
<td>Each landing does not have equal probability.</td>
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<tr>
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<td>wet</td>
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<tr>
<td>Simulated MD-11 dispersion</td>
<td>study, 3</td>
<td>wet</td>
<td>47.2</td>
<td>4.16</td>
</tr>
</tbody>
</table>

The actual Dallas/Ft. Worth ROT data appears to have a smaller standard deviation than that obtained through simulation and may suggest that pilots are delaying touchdown beyond the box, as needed, to control ROT.

Officially, there are no procedures nor training for the use of high-speed exits, at the flight crew's discretion, under daylight VMC conditions with no runway/exit surface contamination. If runway productivity would benefit, perhaps official training would also allow pilots to apply their manual skills to night VMC conditions with appropriate runway lighting and/or on a wet runway surface condition (no flooding).
Runway 13R’s single high-speed exit appears to be effective for ROTO. Runway 13R is believed to have a lower construction cost than the multiple high-speed exit runways found on the map on page 168. Multiple exit runways are suited for the wide range of aircraft landing ground speeds. Application of recent technology may allow single exit runways to be suitable for a wide range of aircraft landing speeds just as multiple exit runways, irrespective of its operational practicality.

Exit prediction logic could select the appropriate aircraft longitudinal touchdown point based on the predicted aircraft touchdown ground speed and the runway’s high-speed exit location. Unlike ILS’s stationary glideslope beam, DGPS and navigation software could allow for a variable longitudinal touchdown location by shifting the autoland glideslope longitudinally as needed. A HUD could display artificial runway touchdown paint stripes at the appropriate runway location.

In addition to single high-speed exit runways having a lower construction cost, they also benefit from there being no immediate contention on the parallel taxi-way. In this situation, aircraft would not need to stop on the high-speed exit, and should not for continuous ROTO operations with aircraft spacing of approximately 50 seconds.

There would be, however, contention for one parallel taxiway servicing a runway’s multiple high-speed ROTO exits. Continuous ROTO operation, described in Appendix A of reference 2 (Event Timeline Table), assumes that a high-speed exit be clear every 100 seconds in order for every third aircraft to use that exit. This time accounts for the exit being clear as its designated aircraft passes the runway threshold (50 seconds for the preceding aircraft to clear the runway and also 50 seconds for it to clear the exit). Exit clearance every 150 seconds would allow every fourth aircraft to use that exit.
Dallas/Ft. Worth 13R Actual Runway Occupancy Times

MD-8X narrow body aircraft

Runway Occupancy Time (sec)
Dallas/Ft. Worth 13R, 1 high-speed exit
Actual ROT Probability Distribution
Mean=46.5, STDEV=1.72, assumed DRY & daylight
MD-8x narrow body aircraft

All exits
- Exit 1
- End of Runway

Probability

Actual Runway Occupancy Time (ROT) seconds
Curve Represents Exit at 5475 feet
Predict exit prior to TD

Weight = 82K + (128K - 82K) * (VEAS - 110) / 33
CG = -0.008 + (0.334 - (-0.008)) * (VEAS - 110) / 33

Dry, Exits = 5325, 9300
Dallas/Ft. Worth 13R
Autoreverse Thrust
Stow Reverse Thrust = 70 kt gd
The Terminal Area Productivity (TAP) research program was initiated by NASA to increase the airport capacity for transport aircraft operations. One element of the research program is called Low Visibility Landing and Surface Operations (LVLASO). A goal of the LVLASO research is to develop transport aircraft technologies which reduce Runway Occupancy Time (ROT) so that it does not become the limiting factor in the terminal area operations that determine the capacity of a runway. Under LVLASO, the objective of this study was to determine the sensitivity of ROT to various factors associated with the Rollout and Turnoff (ROTO) operation for transport aircraft. The following operational factors were studied and are listed in the order of decreasing ROT sensitivity: ice/flood runway surface condition, exit entrance ground speed, number of exits, high-speed exit locations and spacing, aircraft type, touchdown ground speed standard deviation, reverse thrust and braking method, accurate exit prediction capability, maximum reverse thrust availability, spiral-arc vs. circle-arc exit geometry, dry/slush/wet/snow runway surface condition, maximum allowed deceleration, auto asymmetric braking on exit, do not stow reverse thrust before the exit, touchdown longitudinal location standard deviation, flap setting, anti-skid efficiency, crosswind conditions, stopping on the exit and touchdown lateral offset.