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

Volume I

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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.
6. Runway/exit surface conditions: dry, slush, wet, snow, flood, ice.
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.

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

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

Aircraft Geometry Data

Variable Name	Description		MD-81	MD-11	Units
SW	wing area		1209.3	3647.5	$feet^2$
BW	wing span		107.8	165.37	feet
LMAC	length of mean aerodynamic chord		13.209	24.648	feet
A	distance -- nose gear to CG center of gravity (CG)	(fwd cg) (aft cg)	65.52 70.04	72.932 78.256	feet
B	distance -- main gear to CG	(fwd cg) (aft cg)	6.6b 2.384	7.732 2.457	feet
BC	distance -- center gear to CG	(fwd cg) (aft cg)	0 0	10.234 5.009	feet
C	distance --lift moment arm to CG	(fwd cg) (aft cg)	-3.4 1.110	-3.056 2.218	feet
HCG	CG height	(fwd cg) (aft cg)	8.8 7.32	15.476 15.466	feet
LTAIL	distance -- tail center of pressure to CG	(fwd cg) (aft cg)	62.39 -17.016	83.739 -56.518	feet
IYAW	aircraft yaw moment of inertia		4.1E6	2.56E7	$slug\text{-}ft^2$

Aerodynamic Coefficients
(assumes normal flaps, slats extended, spoilers deployed, elevator = 8 degrees)

Variable Name	Description	MD-81	MD-11	Units
CDRAG	aircraft drag coefficient (fwd cg) (aft cg)	0.227 0.219	0.1746 0.1651	-
CLIFT	aircraft lift coefficient (fwd cg) (aft cg)	0.385 0.550	0.123 0.226	-
CMOM	aircraft pitch moment coefficient (fwd cg) (aft cg)	0.83 0.105	0.515 0.216	-
CMR	rudder yaw moment coefficient	-.0012	-.00262	1/degree
CNB	aircraft side slip moment coefficient	0.00332	0.0037	-
CYB	aircraft side slip force coefficient	-.018	-0.024	-
DCLDE	change in CLIFT due to elevator	0.0083	0.008	-
DMCDE	change in CMOM due to elevator	-.0385	-.025	-

Wing and Center Gear Tire Properties

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

Constants Used to Calculate Nose Gear Cornering Power and Strut Moment

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

Nosewheel Actuation (NASA Report 195026 page 35)

Variable Name	Description	MD-81	MD-11	Units
KS1	(steering valve spool displacement) / (cmd steering error)	0.0211	0.00873	in/degree
KS2	(steering rate)/(valve flow)	1.023	0.965	(deg/s)/ (in^3/sec)
KS3	(steering actuator pressure) / (strut ground moment)	0.0897	0.00842	psi/in-lb

Rudder Actuation (NASA Report 195026 page 36)

Variable Name	Description	MD-81	MD-11	Units
G1	mod piston LVDT gain	1/6.43	1/6.43	in/volts
G3	mod piston position limit	0.1	0.1	in/in
G4	cmd error gain	0.4	0.4	volts/deg
G5	deadzone	0.002	0.002	in/in
G10	upper lower	1041.6 724.0	1041.6 724.0	(deg/sec)/ in
G11		0.1835	0.1835	in/in
G14	rudder position limit	+/- 23	+/- 23	degrees
G16	rudder rate limit	0.06	0.06	in/in

Hysteresis in Steering System in terms of Nose Gear Degrees

Variable Name	Description	MD-81	MD-11	Units (nose wheel)
-	autoland rudder to rudder pedal cable hys	2	2	degrees
-	rudder pedal to nose gear hysteresis	1	1	degrees
-	tiller cable hysteresis	1	1	degrees

Autobrake Actuation (NASA Report 195026 page 37)

Variable Name	Description	MD-81	MD-11	Units
RRPHASE1	phase 1 brake pressure ramp rate	400	400	psi/sec
RRPHASE2	phase 2 brake pressure ramp rate	1200	1200	psi/sec
KBPHASE1	phase 1 brake pressure gain	600	600	(psi/sec)/ (ft/sec^2)
KBPHASE2	phase 2 brake pressure gain	1800	1800	(psi/sec)/ (ft/sec^2)
TMGD	main gear touchdown time	0	0	sec
TNGD	nose gear touchdown time	6	6	sec
TSPOIL	time between nose gear touchdown and spoiler deployment	1.3	1.3	sec
TDELAY	time between spoiler deployment and start of brake ramp	3	3	sec
MUROLL	rolling friction	.15	.15	-
ASEFF	anti-skid efficiency	0.75	0.75	-

Hydraulic System

Variable Name	Description	MD-81	MD-11	Units
PSUP	hydraulic supply pressure	3000	3000	psi
PRET	hydraulic return pressure	60	60	psi

Functions

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

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 is 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:

	Longitudinal Dispersion (ft)	Ground Speed (kt)
MD-81	1362 +/- 198	116.44 +/- 10.36
MD-11	1375 +/- 225	141 +/- 11.5

   (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/sec^2 (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 the 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).
6. Runway/exit surface conditions: dry, slush, wet, snow, flood, ice.
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:

$$\frac{1}{\sqrt{2\pi\sigma}}\exp^{-\left(\frac{(x-\mu)^2}{2\sigma^2}\right)}$$

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:

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

The deceleration method abbreviations found in tabular column 1 are as follows:

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

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/sec^2 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 of 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 6.1a, 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

Aircraft Type (dry/wet averaged)	**ROT Mean (sec)**	**ROT STDEV (sec)**	**Exit numb er (#) Mean**	**Exit number (#) STDEV**	**% of aircraft using the end of runway**	**% of aircraft having a ROT greater than 53.4 seconds**
MD-11	47.0	4.09	2.27	0.63	2.02	2.01
MD-81	41.2	3.22	1.21	0.42	0	0.1
MD-11 & MD-81 (averaged)	44.1	3.65	1.74	0.52	1.01	1.05

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/sec^2, whereas reference 2 allowed a maximum deceleration of 9 ft/sec^2. 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/sec^2 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.

<u>Constant radius-arc high-speed exit</u> (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.

<u>Reverse thrust not stowed prior to exit, limit to idle</u> (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.

<u>Reverse thrust not stowed prior to exit, do not limit to idle</u> (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.

<u>Stop aircraft CG on exit</u> (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/sec^2 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:

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

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).

<u>Auto reverse thrust/variable deceleration</u> (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.

<u>Constant reverse thrust/roll-constant deceleration</u> (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.

<u>Auto reverse thrust/roll-constant deceleration</u> (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.

<u>Constant reverse thrust/variable deceleration</u> (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.

<u>Immediate (medium&maximum) constant reverse thrust/immed. medium constant deceleration</u>

(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.

Mid Exit Location	Exit Entrance Ground Speed			
	40 knots	60 knots	70 knots	80 knots
4950 feet		page 38 of volume 2	page 1 of volume 2	page 15 of volume 2
5350 feet	page 48 of volume 2			
5950 feet	page 39 of volume 2	page 12 of volume 2	page 3 of volume 2 (baseline)	page 13 of volume 2
6550 feet			page 26 of volume 2	
6950 feet		page 14 of volume 2		

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.

<u>Averaged Aircraft Dispersion ROT Sensitivity</u> (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*(operational factor ROT mean - baseline ROT mean)/(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:

ROT Sensitivity Measure	Aircraft Type		
	MD-11+MD-81	MD-81	MD-11
Mean	F7.1a	F7.1b	F7.1c
Stdev	F7.2a	F7.2b	F7.2c
Mean+Stdev	F7.3a	F7.3b	F7.3c
Mean+Stdev, F7.3a ranking		F7.3d	F7.3e

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

Operational Factor Ranking (ranking gives MD-11,MD-81,mean,stdev equal weight; ranked in descending order)	**Figure**	**Changes to existing System**				**Recommendations for ROT Improvement**
		Aircraft			**Runway**	
		Software	**Hardware**	**Procedure**	**Exits**	
Ice/flood runway surface condition	F6.7a					Avoid ice/flooded runway surface conditions
Exit entrance ground speed*	F6.6a	steering control laws	DGPS, HUD	auto(monitor) /manual	high-speed	Use highest exit entrance ground speed allowed by exit requirements; 70 knots is suggested
Number of exits	F6.1a				high-speed	3 exits are recommended for a MD-11/MD-81 population mix
High-speed exit locations and spacing	F6.1a,4				high-speed	Locate exits at 4500, 5950 & 7350 ft for a MD-11/ MD-81 population mix
A/C type, baseline@mid exit loc 5950 ft	pg 3,vol2					Optimize exit locations for expected aircraft types
Touchdown ground speed stdev	F6.9a			X		Investigate lowering wind and approach airspeed stdev
Reverse thrust and braking method*	F6.3a	deceleration control laws	DGPS, HUD	auto(monitor) /manual		An optimum deceleration profile would benefit from auto or flight-directed brakes and reverse thrust
Accurate exit prediction capability	F6.5a	algorithm		ATC ops	measure friction	Use exit prediction logic to select optimum available exit and minimize exit aborts
Maximum Reverse Thrust availability	F6.12a	suggest level		X		Assist pilot in selecting optimum reverse thrust level
Spiral-arc vs circle-arc exit geometry	F6.2a				high-speed	Reference 3
Dry/slush/wet/snow surface condition	F6.7a			X		Extend high-speed dry operations to wet surface cond.
Maximum allowed deceleration	F6.11a					Use highest deceleration that passenger comfort allows
Auto asymmetric braking on exit	F6.2a	brake-by-wire	brake-by-wire			Any method to improve centerline tracking is desired
Do not stow reverse thrust before exit	F6.2a			X		Stow reverse thrust at exit entrance **ground** speed
Touchdown longitudinal location stdev	F6.8					AC 20-57A allowable 2-sigma=1500ft is acceptable
Flap setting	F6.11a					Current use of normal flaps is acceptable
Anti-skid efficiency	F6.11a					Anti-skid efficiency greater than 75% is recommended
Crosswind conditions	F6.10					AC 20-57A CATIIIB allowable of 15 kts is acceptable
Stopping on exit	F6.2a					Aircraft should be able to stop on last 1/3 of exit
Touchdown lateral offset	F6.10					AC 20-57A CATIIIB allowable of 27 feet is acceptable

* 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

1. Goldthorpe, Kernik, McBee, Preston, GUIDANCE AND CONTROL REQUIREMENTS FOR HIGH-SPEED ROLLOUT AND TURNOFF (ROTO), NASA CR 195026, January 1995, NAS1-19703 Task 3, Langley Research Center, Hampton, VA, NASA.
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.
3. Anon, AIRPORT DESIGN STANDARDS - AIRPORTS SERVED BY AIR CARRIERS - TAXIWAYS, Advisory Circular AC No. 150/5300 - B, US Department of Transportation, Federal Aviation Administration, Washington DC, 5/9/80.

Nosewheel Steering Valve Flow Coefficient

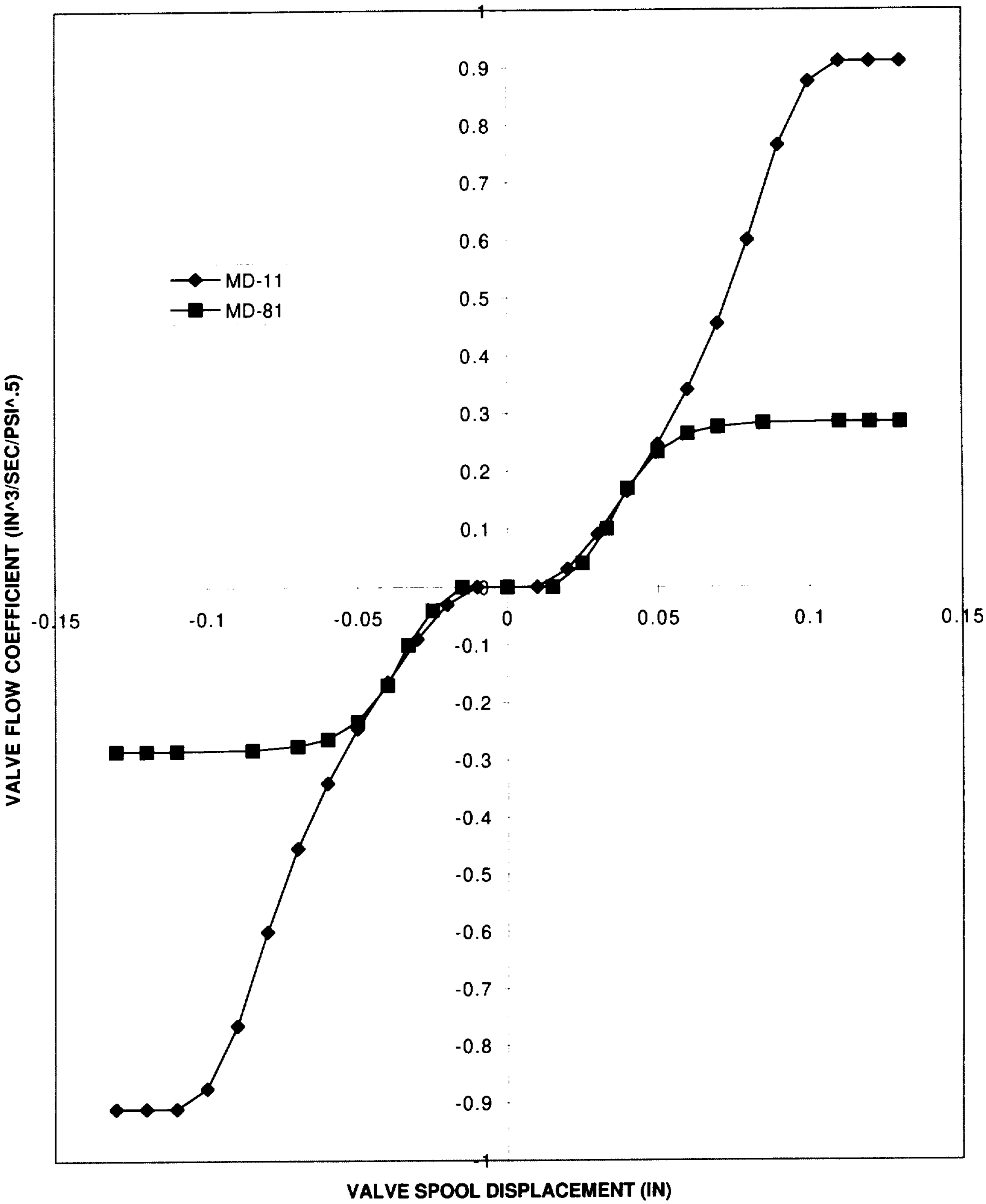


Figure 3.1

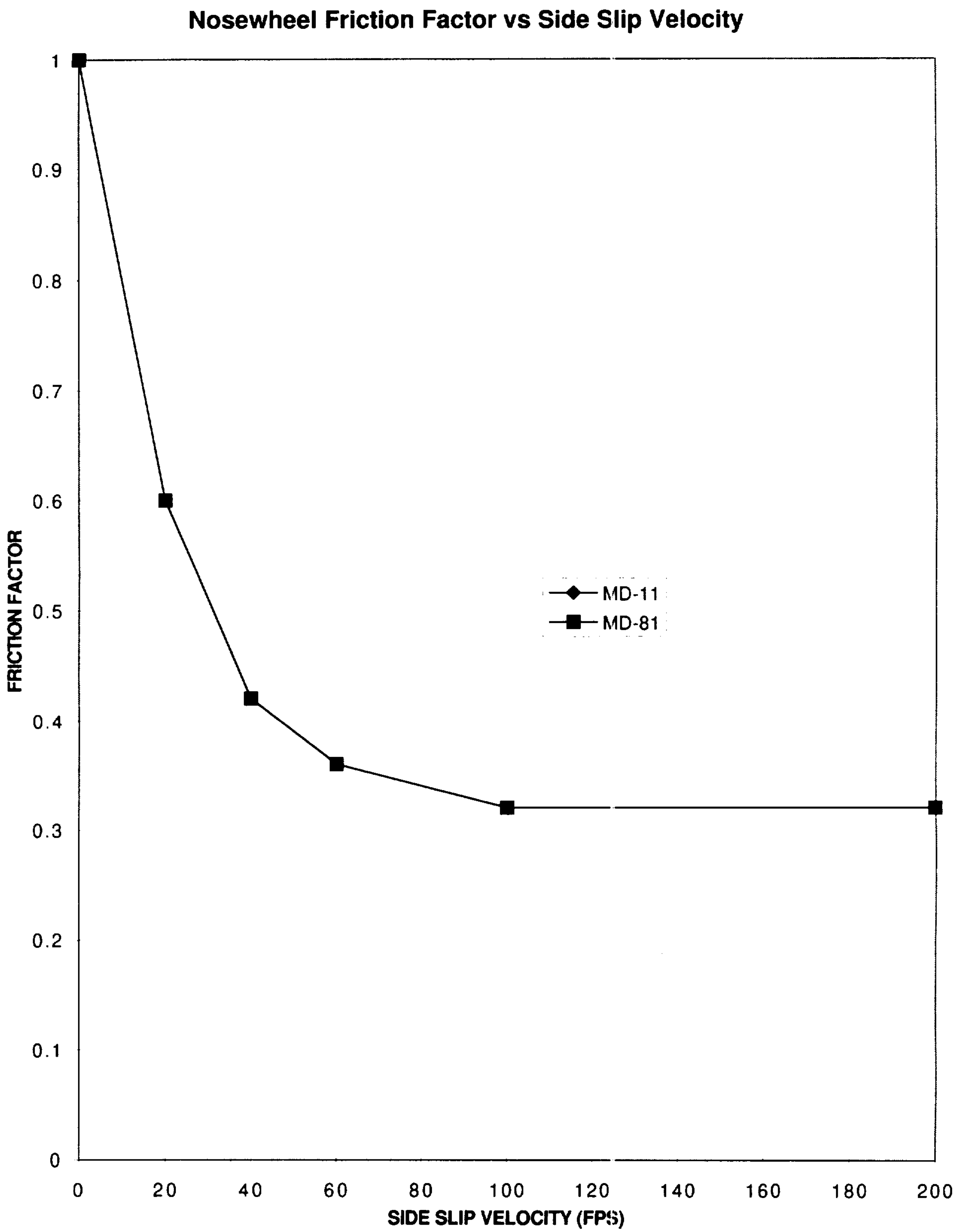

Nosewheel Friction Factor vs Side Slip Velocity
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
FRICTION FACTOR
MD-11
MD-81
0
20
40
60
80
100
120
140
160
180
200
SIDE SLIP VELOCITY (FPS)

Figure 3.2

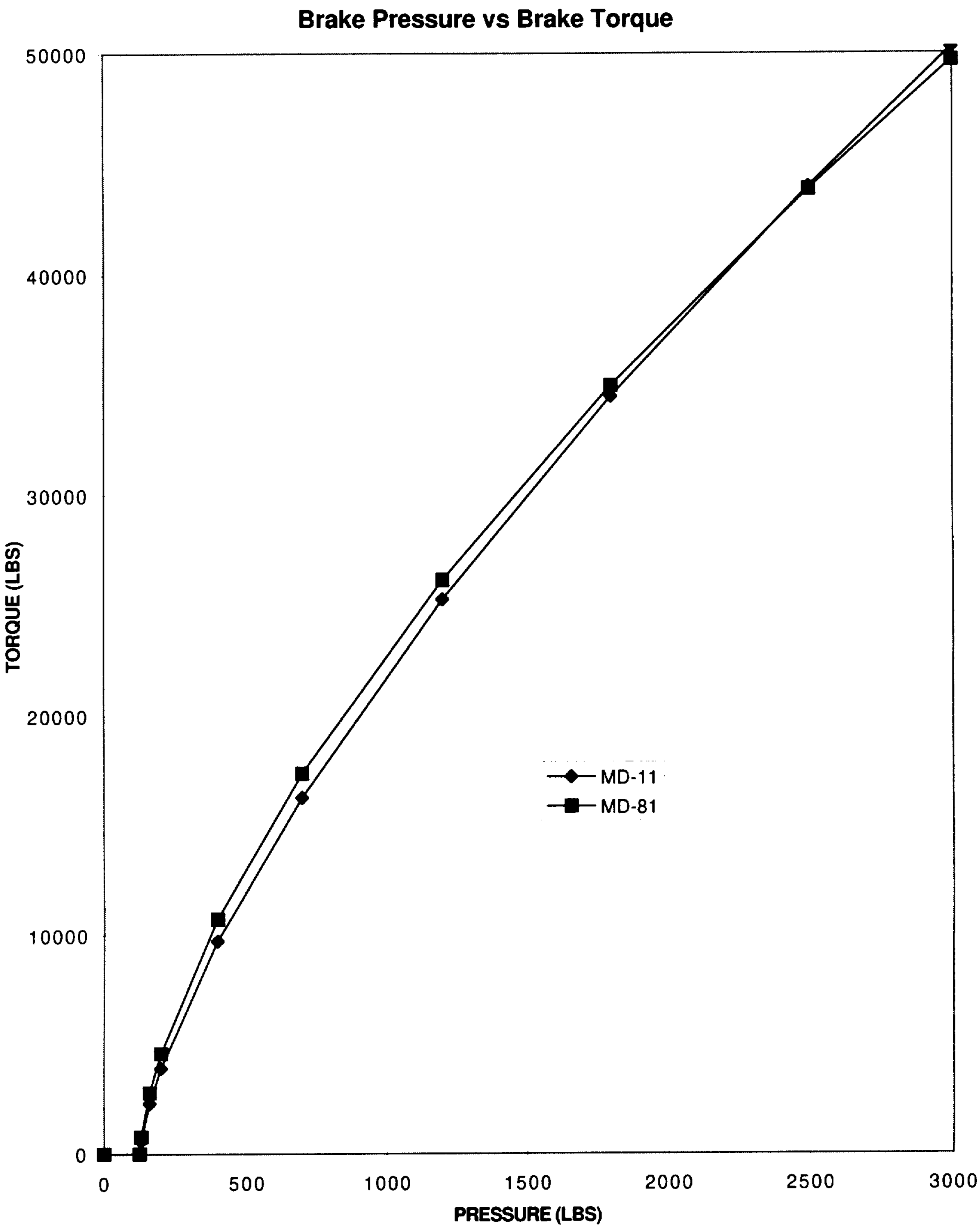

Brake Pressure vs Brake Torque
50000
40000
30000
20000
10000
0
TORQUE (LBS)
0
500
1000
1500
2000
2500
3000
PRESSURE (LBS)
MD-11
MD-81

Figure 3.3

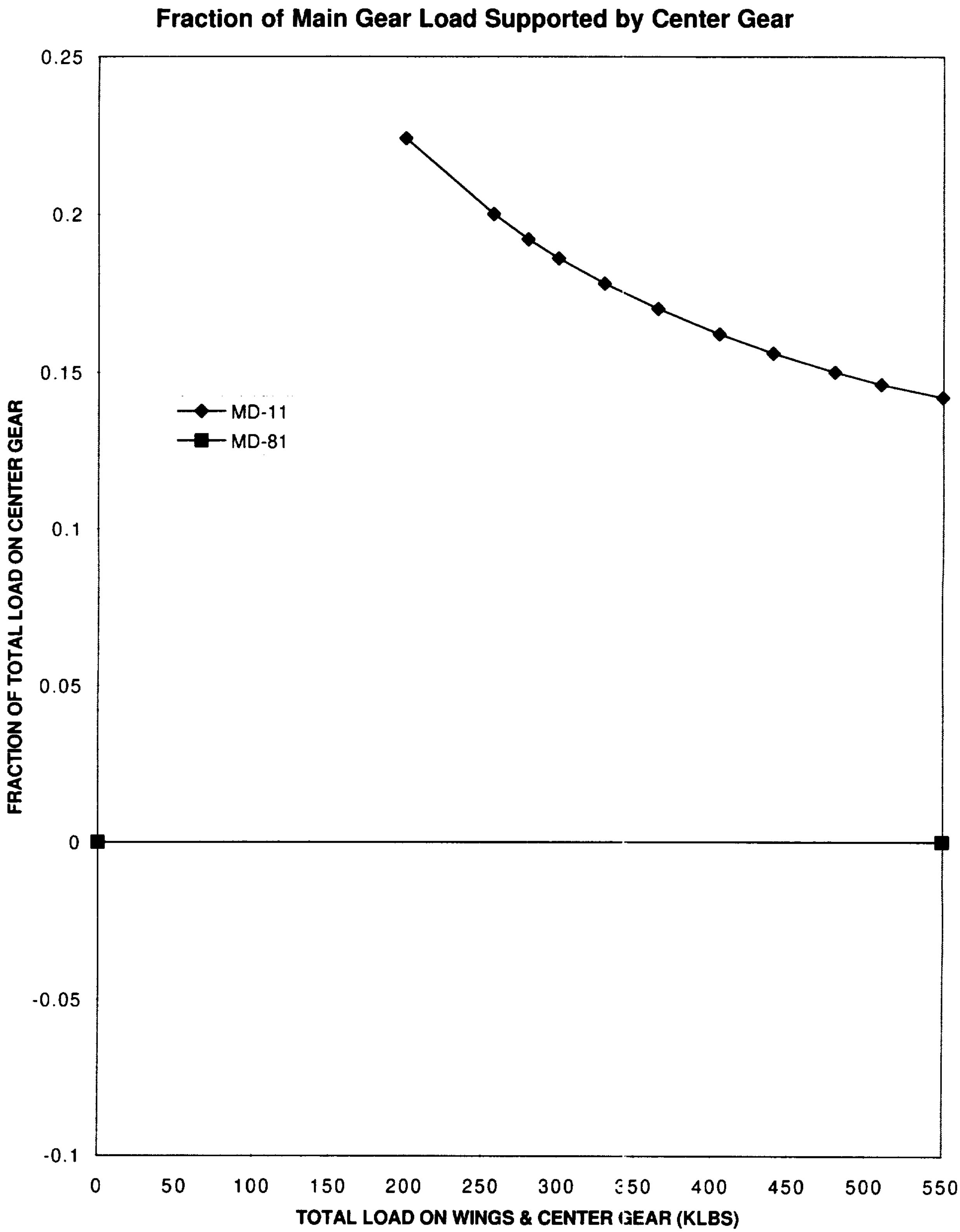

Fraction of Main Gear Load Supported by Center Gear
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
FRACTION OF TOTAL LOAD ON CENTER GEAR
MD-11
MD-81
0
50
100
150
200
250
300
350
400
450
500
550
TOTAL LOAD ON WINGS & CENTER GEAR (KLBS)

Figure 3.4

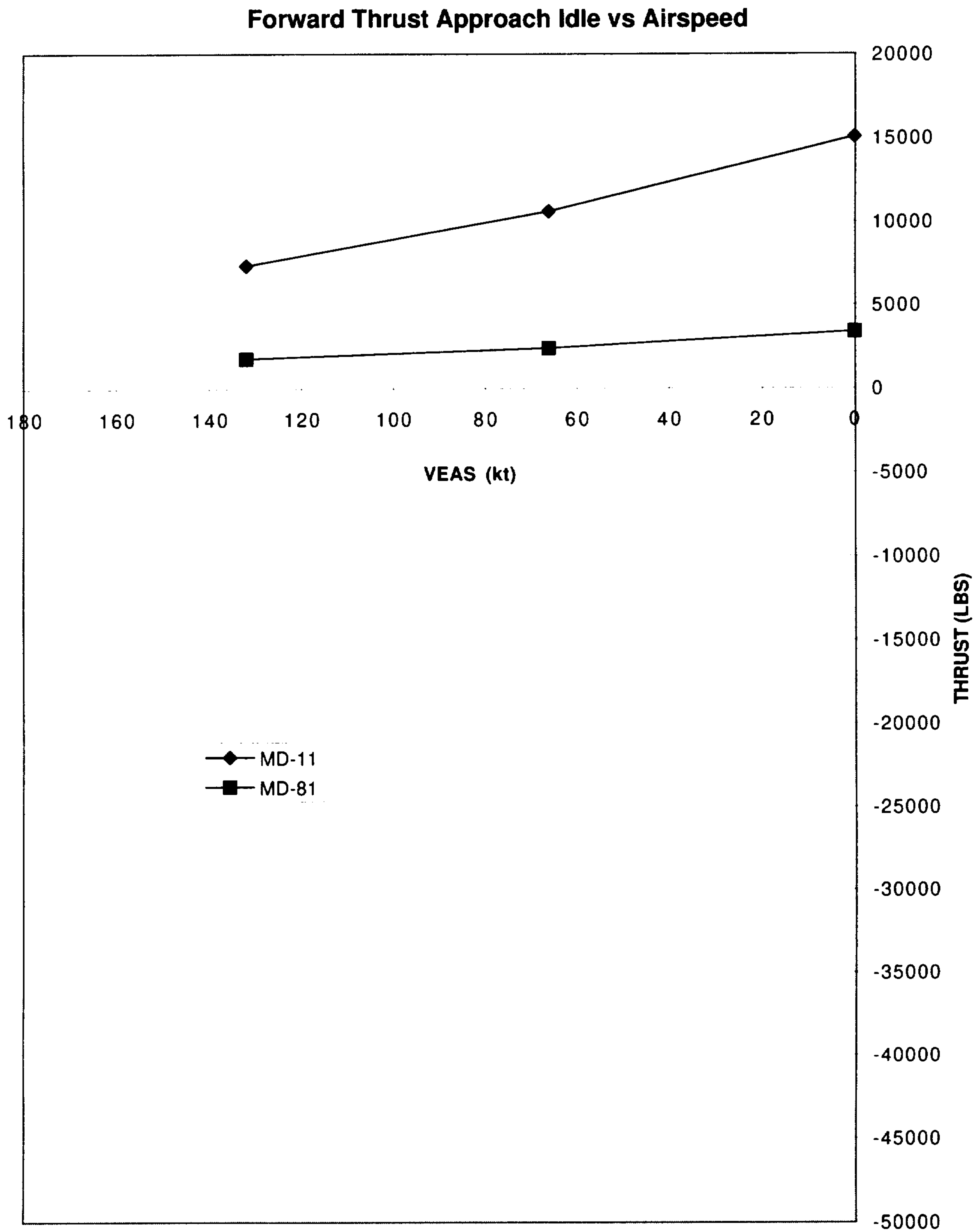
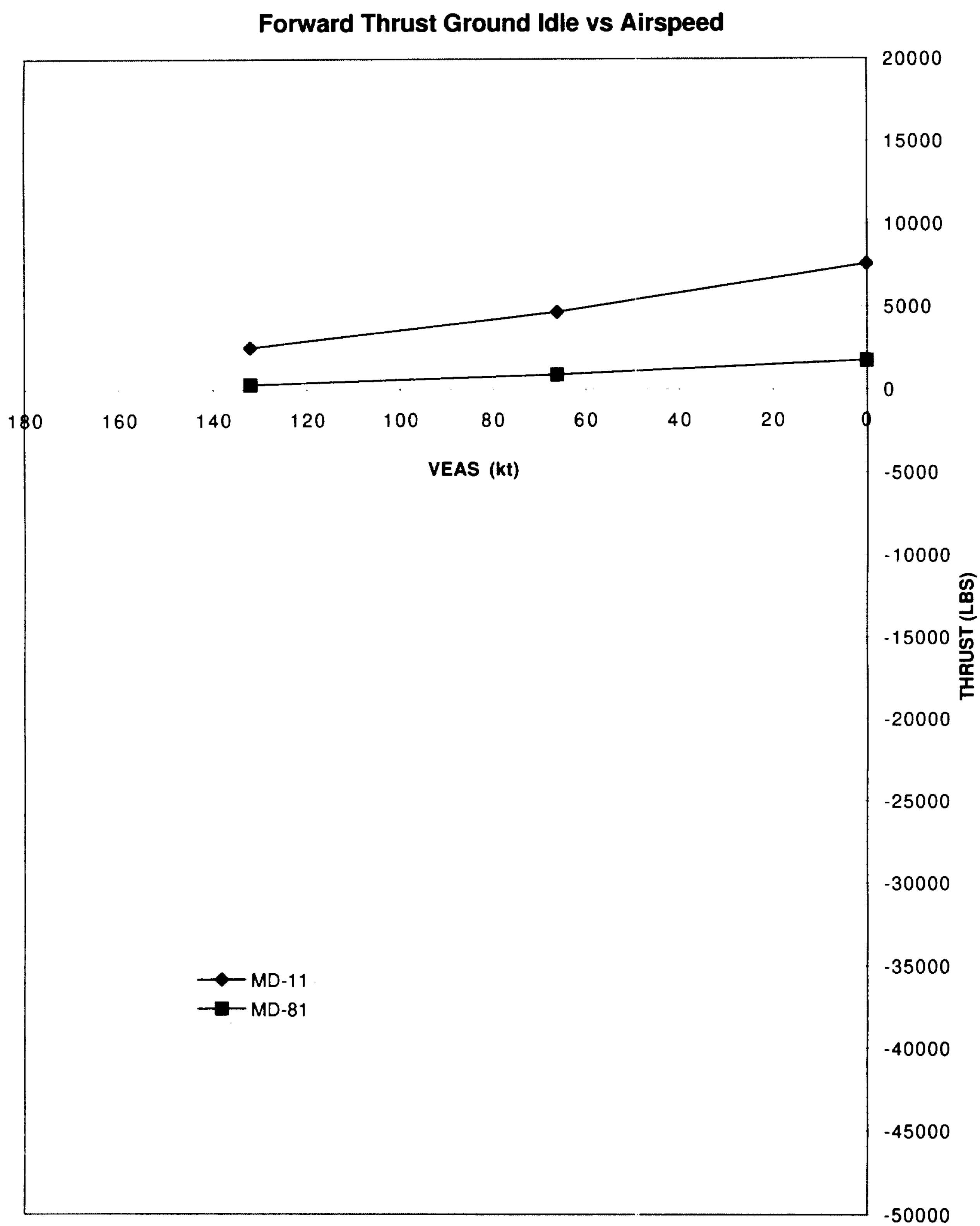

Forward Thrust Approach Idle vs Airspeed
20000
15000
10000
5000
0
-5000
-10000
-15000
-20000
-25000
-30000
-35000
-40000
-45000
-50000
THRUST (LBS)
180
160
140
120
100
80
60
40
20
0
VEAS (kt)
MD-11
MD-81

Figure 3.5



Forward Thrust Ground Idle vs Airspeed
20000
15000
10000
5000
0
-5000
-10000
-15000
-20000
-25000
-30000
-35000
-40000
-45000
-50000
THRUST (LBS)
180
160
140
120
100
80
60
40
20
0
VEAS (kt)
MD-11
MD-81

Figure 3.6

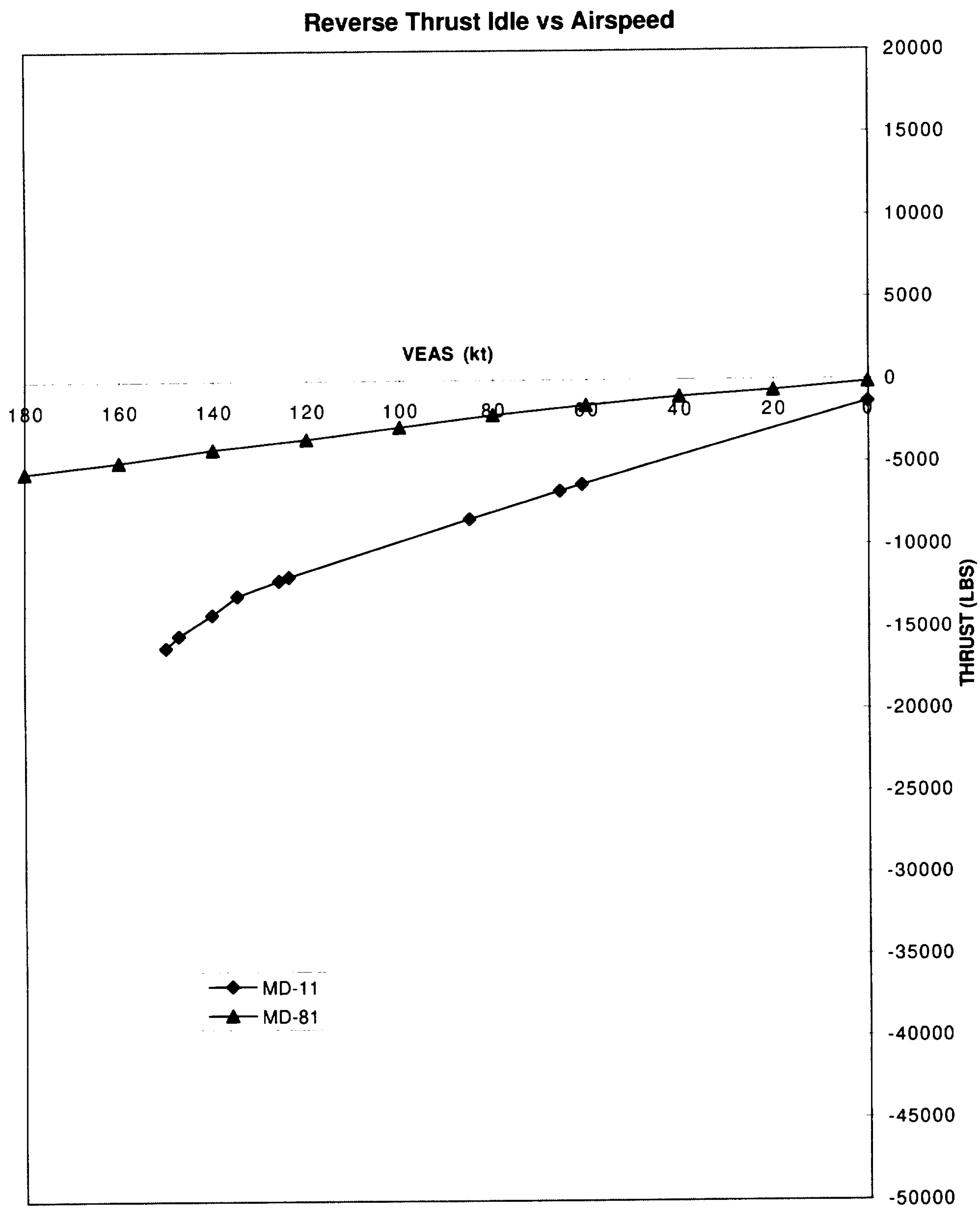

Reverse Thrust Idle vs Airspeed
VEAS (kt)
180
160
140
120
100
80
60
40
20
0
20000
15000
10000
5000
0
-5000
-10000
-15000
-20000
-25000
-30000
-35000
-40000
-45000
-50000
THRUST (LBS)
MD-11
MD-81

Figure 3.7

Reverse Thrust Maximum vs Time

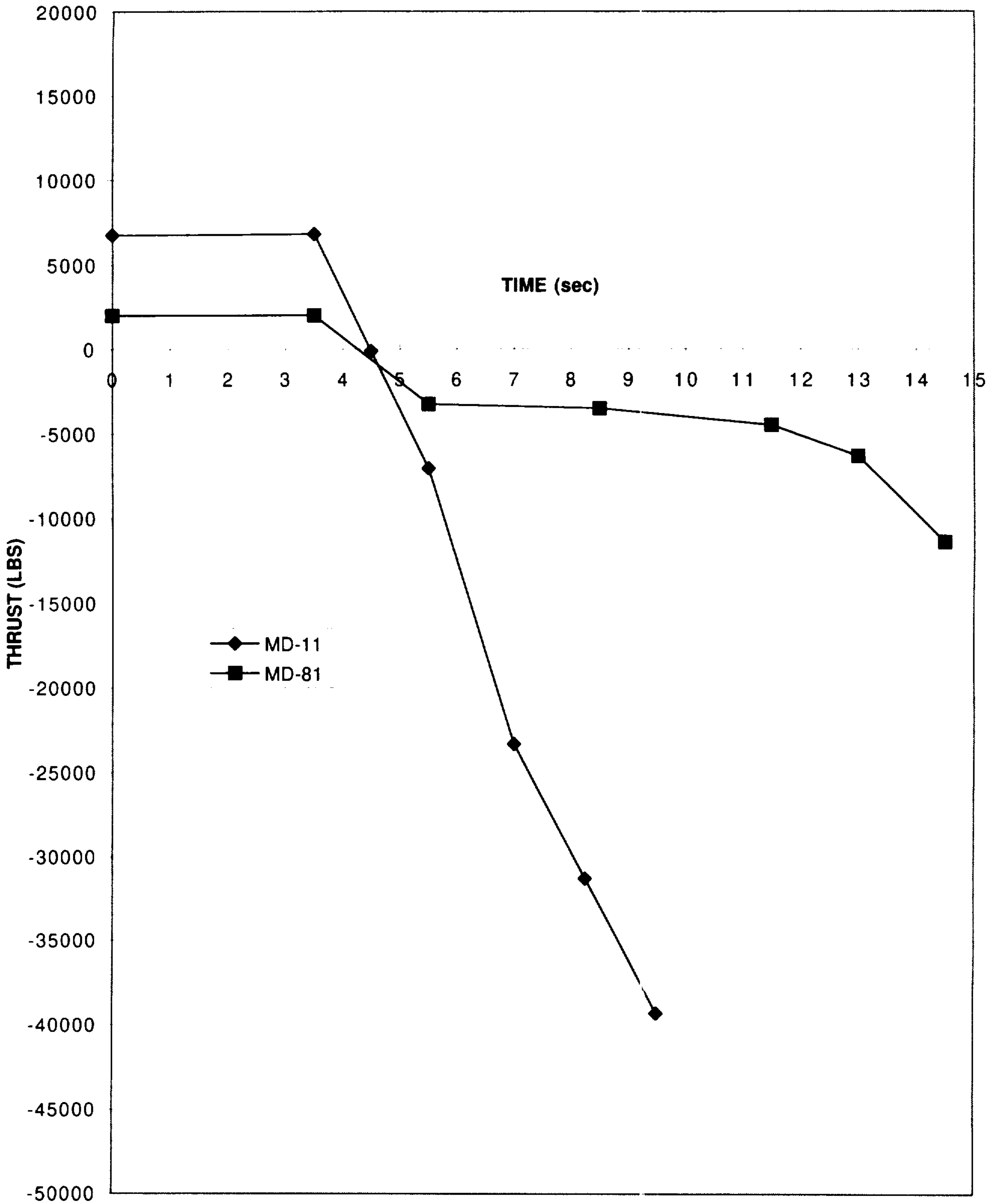


Figure 3.8

Reverse Thrust Maximum vs Airspeed

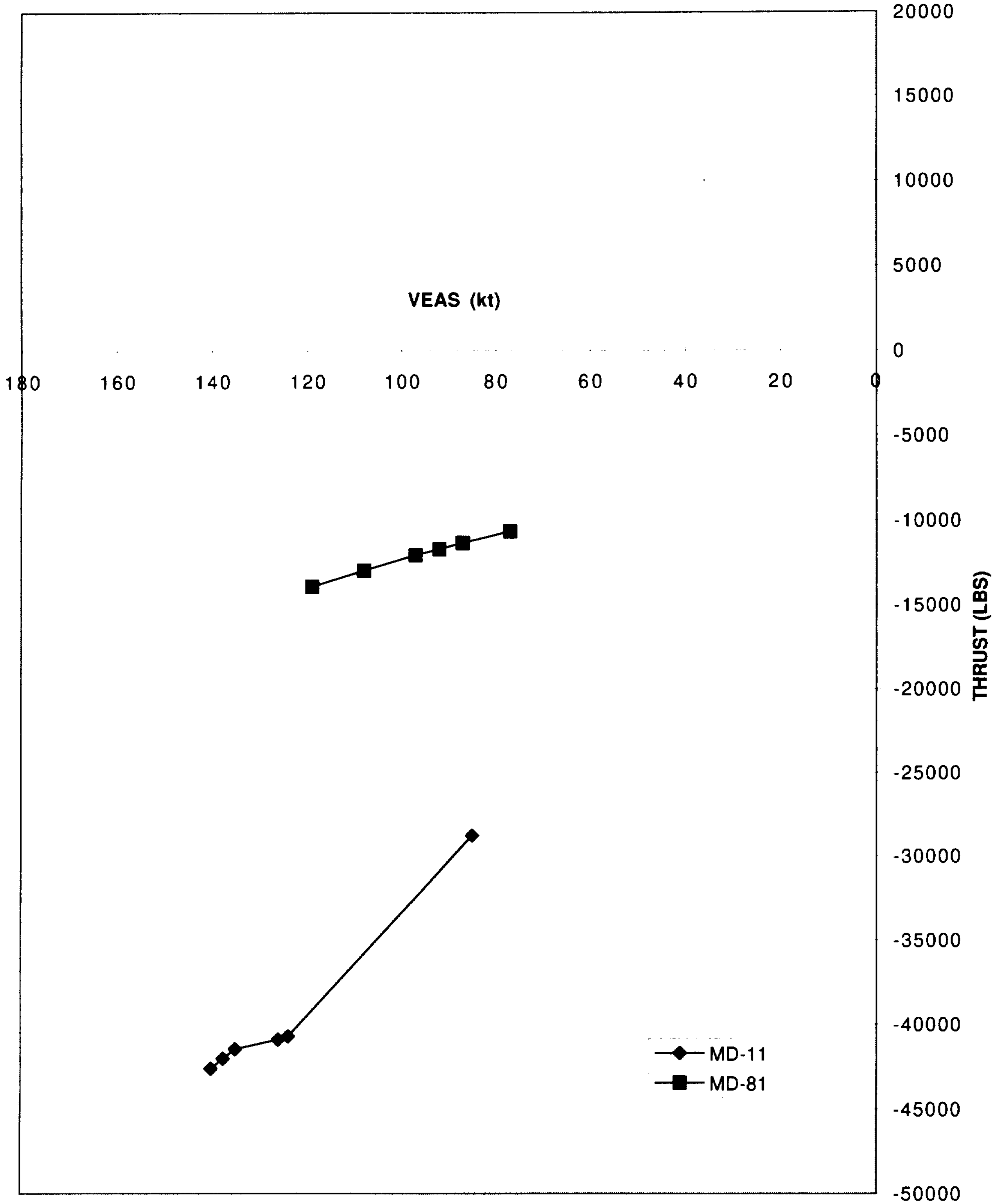
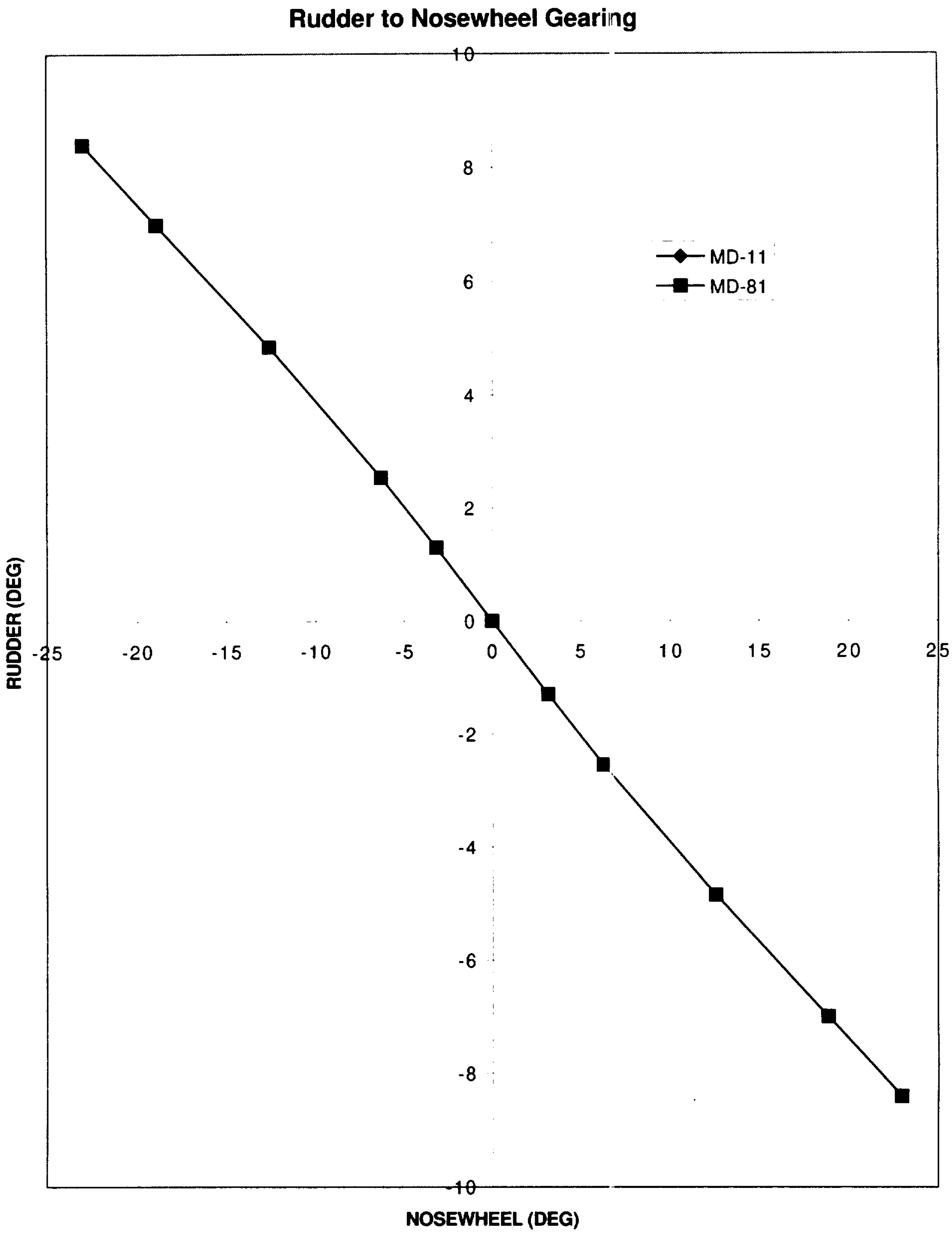
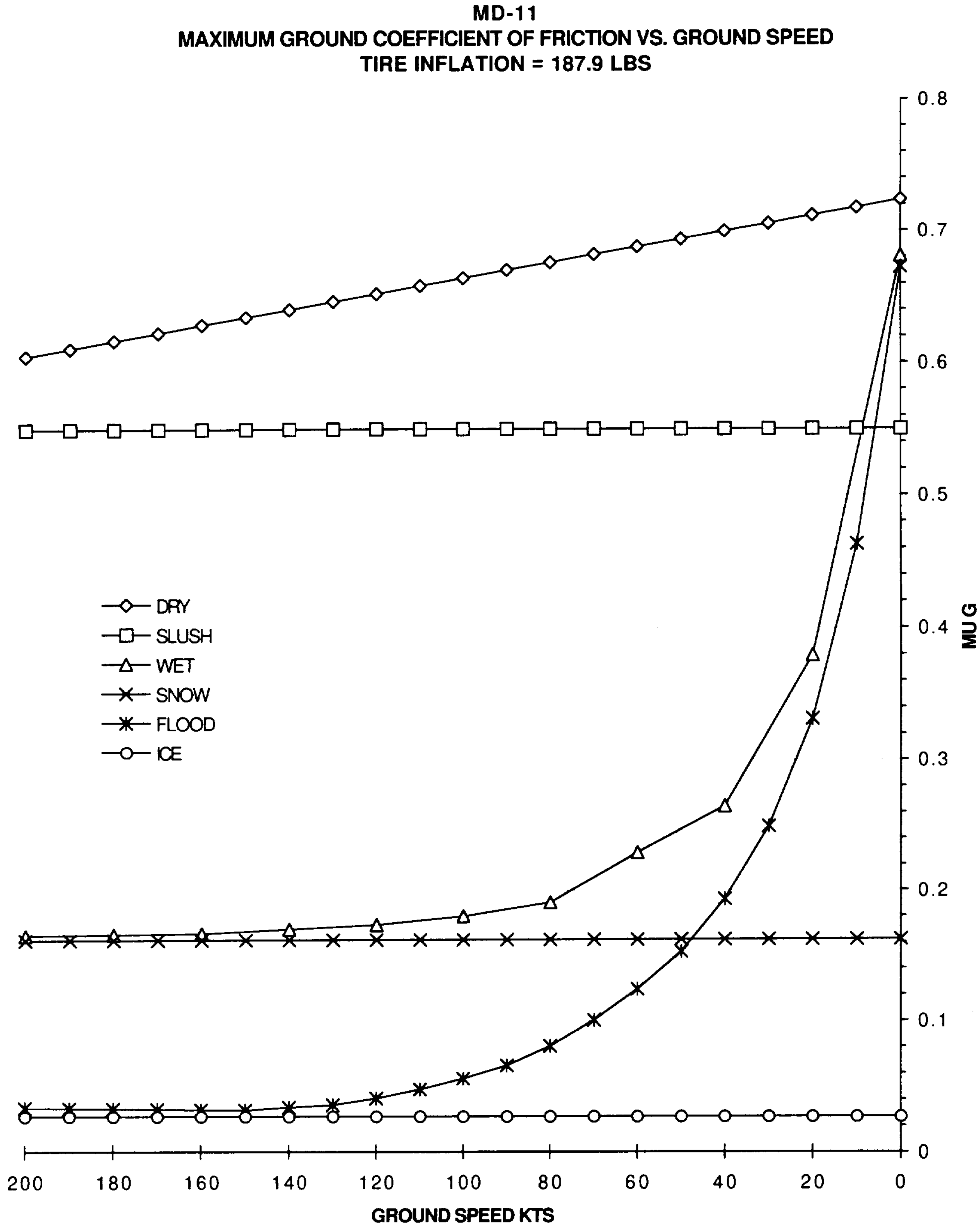


Figure 3.9



Rudder to Nosewheel Gearing
10
8
6
4
2
0
-2
-4
-6
-8
-10
-25
-20
-15
-10
-5
0
5
10
15
20
25
MD-11
MD-81
RUDDER (DEG)
NOSEWHEEL (DEG)

Figure 3.10



MD-11
MAXIMUM GROUND COEFFICIENT OF FRICTION VS. GROUND SPEED
TIRE INFLATION = 187.9 LBS
DRY
SLUSH
WET
SNOW
FLOOD
ICE
MU G
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
200
180
160
140
120
100
80
60
40
20
0
GROUND SPEED KTS

Figure 3.11

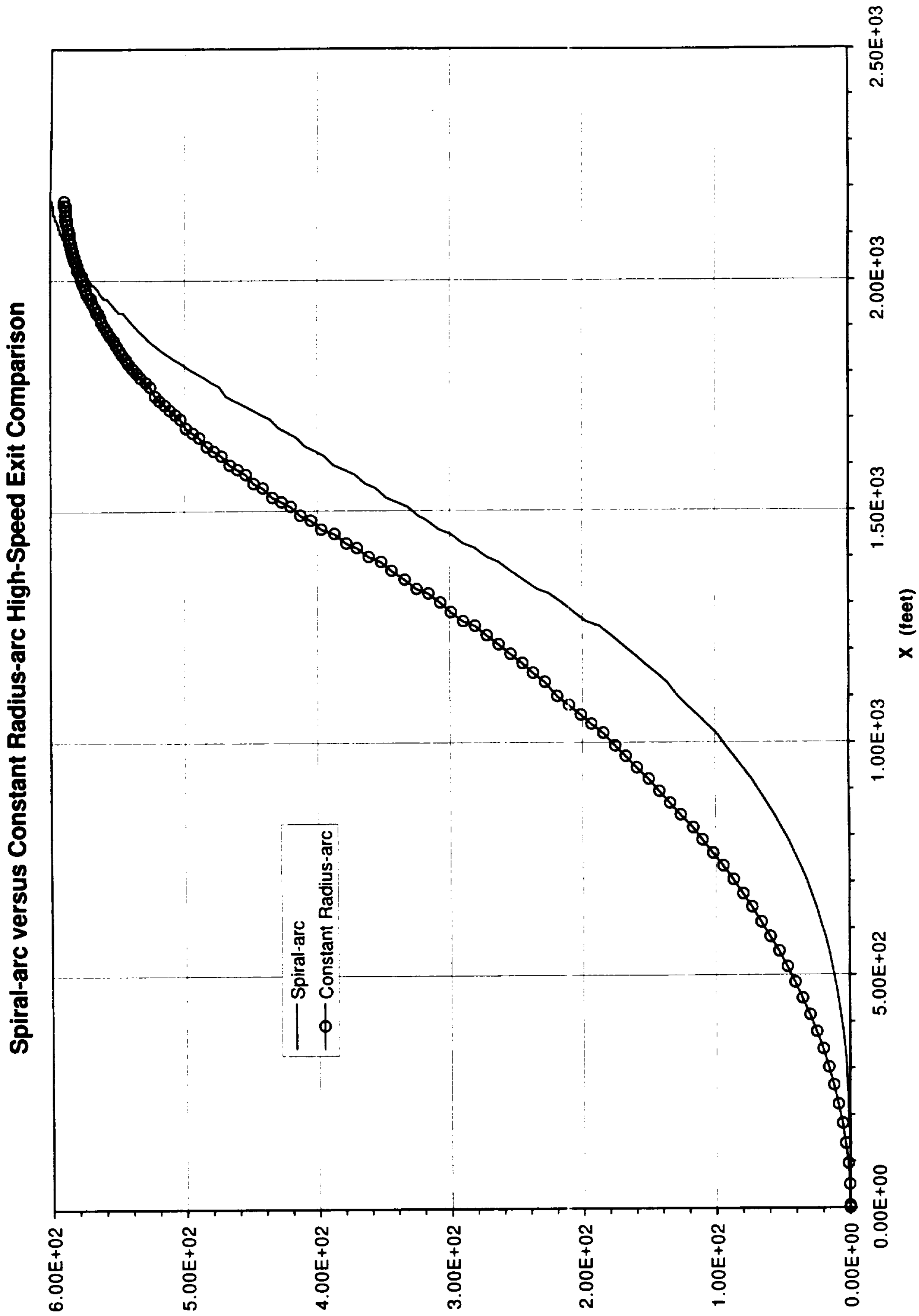
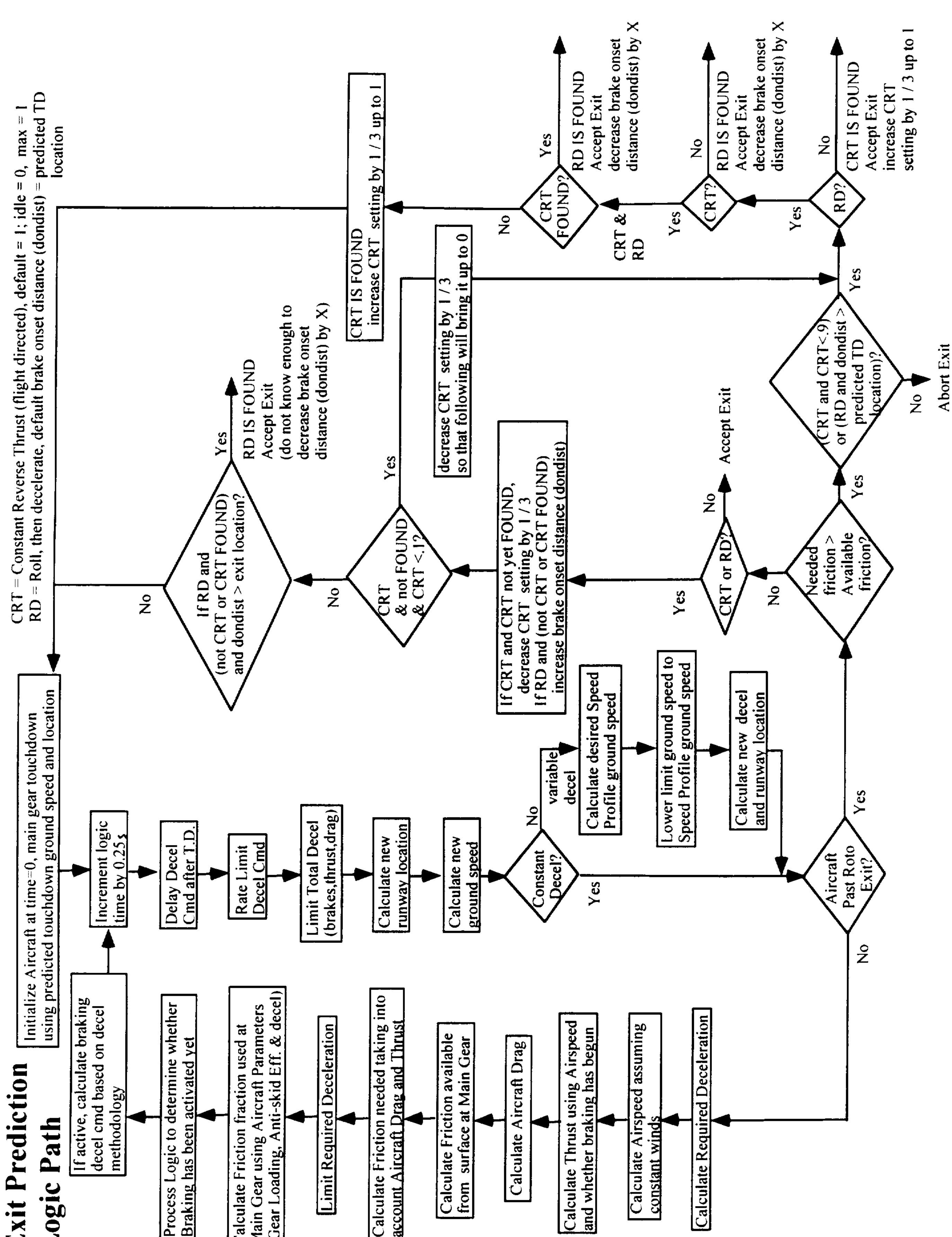

Spiral-arc versus Constant Radius-arc High-Speed Exit Comparison
Spiral-arc
Constant Radius-arc
X (feet)
Y (feet)
0.00E+00
5.00E+02
1.00E+03
1.50E+03
2.00E+03
2.50E+03
0.00E+00
1.00E+02
2.00E+02
3.00E+02
4.00E+02
5.00E+02
6.00E+02

Figure 3.12



Exit Prediction Logic Path
CRT = Constant Reverse Thrust (flight directed), default = 1; idle = 0, max = 1
RD = Roll, then decelerate, default brake onset distance (dondist) = predicted TD location
Initialize Aircraft at time=0, main gear touchdown using predicted touchdown ground speed and location
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
Constant Decel?
Yes
No
variable decel
Calculate desired Speed Profile ground speed
Lower limit ground speed to Speed Profile ground speed
Calculate new decel and runway location
Aircraft Past Roto Exit?
Yes
No
Calculate Required Deceleration
Calculate Airspeed assuming constant winds
Calculate Thrust using Airspeed and whether braking has begun
Calculate Aircraft Drag
Calculate Friction available from surface at Main Gear
Calculate Friction needed taking into account Aircraft Drag and Thrust
Limit Required Deceleration
Calculate Friction fraction used at Main Gear using Aircraft Parameters (Gear Loading, Anti-skid Eff. & decel)
Process Logic to determine whether Braking has been activated yet
If active, calculate braking decel cmd based on decel methodology
Needed friction > Available friction?
Yes
No
CRT or RD?
Yes
No
Accept Exit
If CRT and CRT not yet FOUND, decrease CRT setting by 1 / 3
If RD and (not CRT or CRT FOUND) increase brake onset distance (dondist)
CRT & not FOUND & CRT <.1?
Yes
No
decrease CRT setting by 1 / 3 so that following will bring it up to 0
If RD and (not CRT or CRT FOUND) and dondist > exit location?
Yes
No
RD IS FOUND
Accept Exit
(do not know enough to decrease brake onset distance (dondist) by X)
(CRT and CRT<.9) or (RD and dondist > predicted TD location)?
Yes
No
Abort Exit
RD?
Yes
No
CRT IS FOUND
Accept Exit
increase CRT setting by 1 / 3 up to 1
CRT?
Yes
No
RD IS FOUND
Accept Exit
decrease brake onset distance (dondist) by X
CRT & RD
CRT FOUND?
Yes
No
RD IS FOUND
Accept Exit
decrease brake onset distance (dondist) by X
CRT IS FOUND
increase CRT setting by 1 / 3 up to 1

Figure 4.1

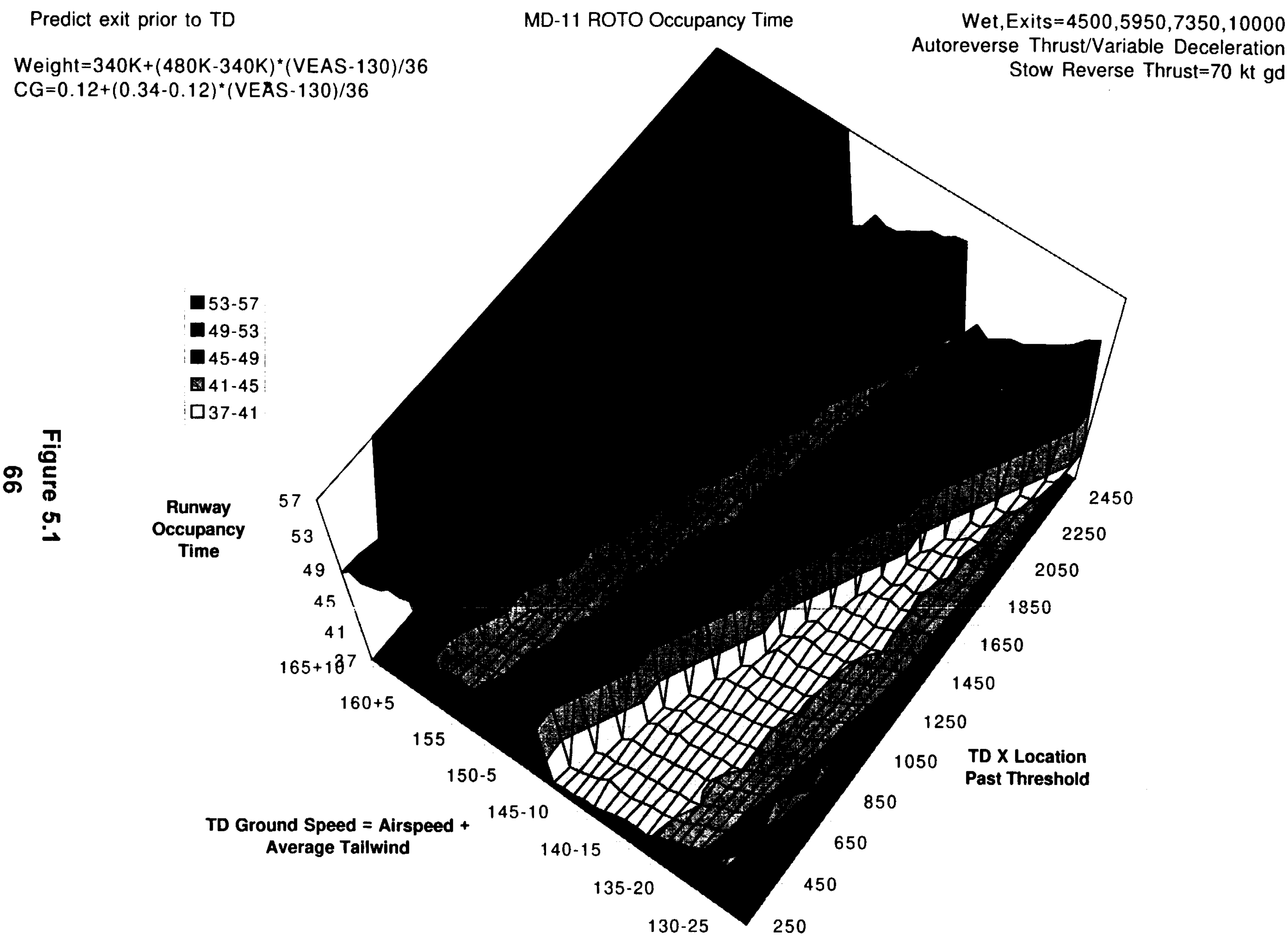

Predict exit prior to TD
MD-11 ROTO Occupancy Time
Wet,Exits=4500,5950,7350,10000
Autoreverse Thrust/Variable Deceleration
Stow Reverse Thrust=70 kt gd
Weight=340K+(480K-340K)*(VEAS-130)/36
CG=0.12+(0.34-0.12)*(VEAS-130)/36
53-57
49-53
45-49
41-45
37-41
Runway Occupancy Time
57
53
49
45
41
37
165+10
160+5
155
150-5
145-10
140-15
135-20
130-25
TD Ground Speed = Airspeed + Average Tailwind
250
450
650
850
1050
1250
1450
1650
1850
2050
2250
2450
TD X Location Past Threshold

Figure 5.1

MD-11 ROTO ROT Probability Distribution
Wet, Auto reverse thrust/variable decel
Mean=47.2, STDEV=4.16

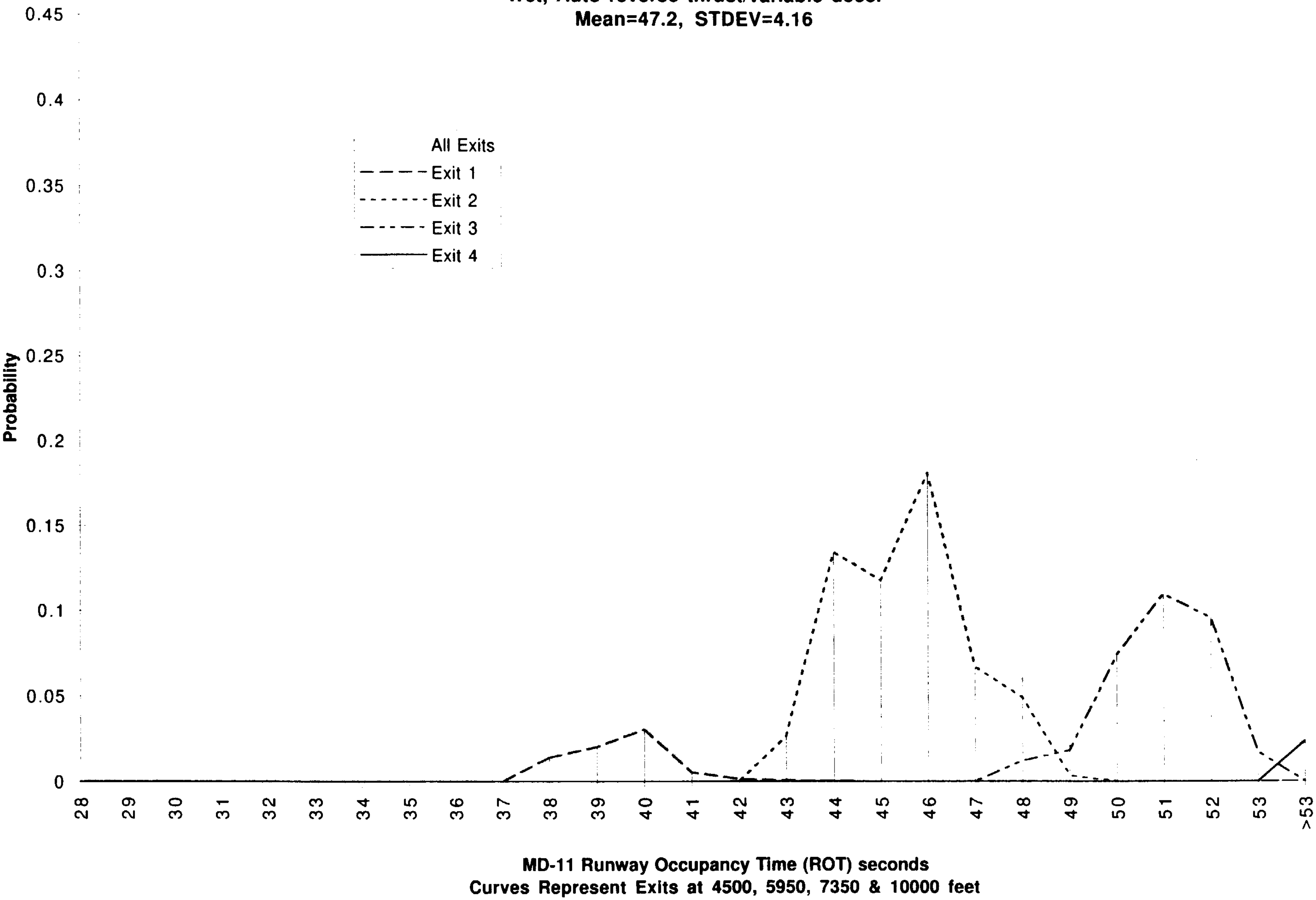
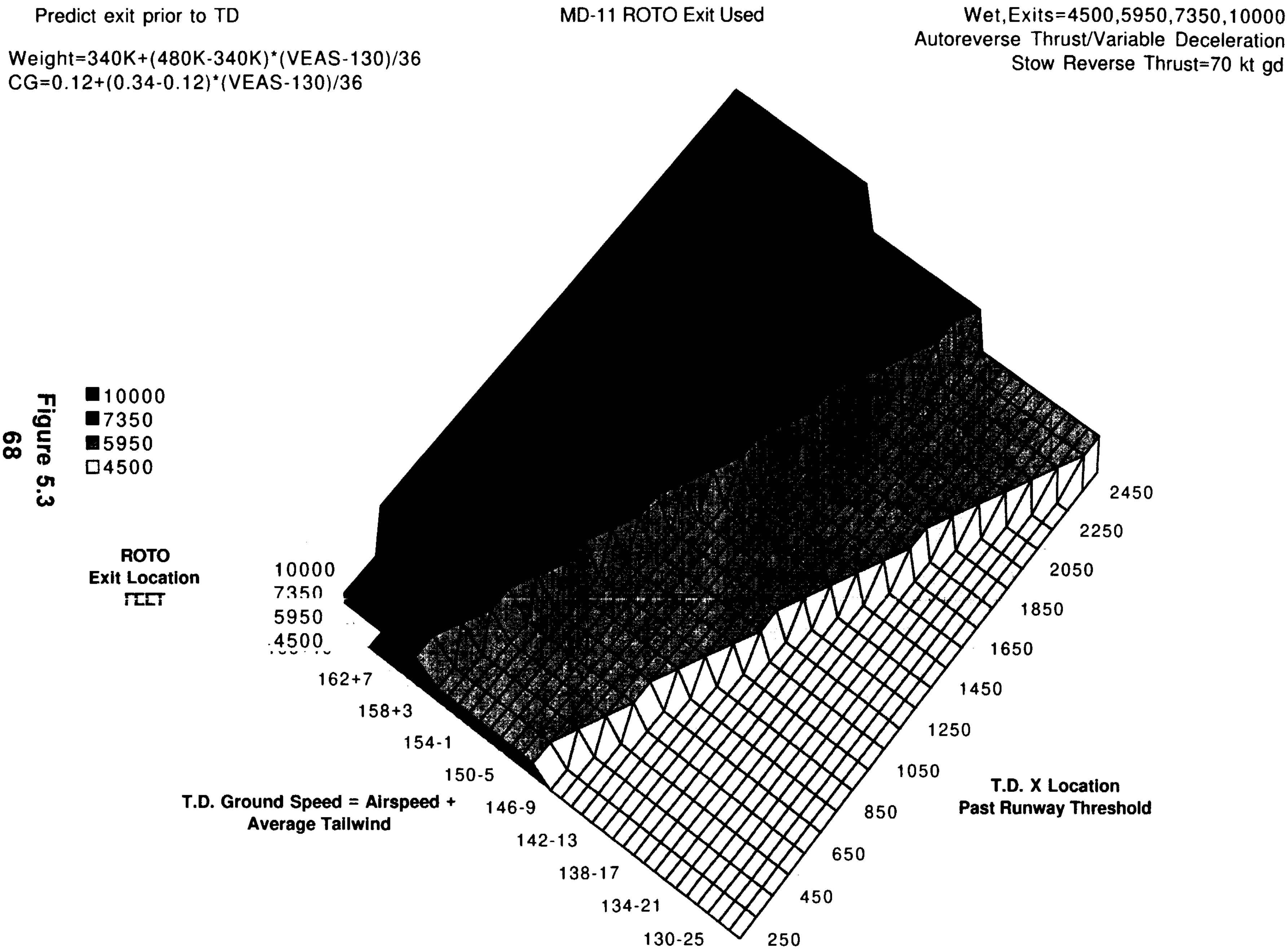


Figure 5.2



Predict exit prior to TD
MD-11 ROTO Exit Used
Wet,Exits=4500,5950,7350,10000
Autoreverse Thrust/Variable Deceleration
Stow Reverse Thrust=70 kt gd
Weight=340K+(480K-340K)*(VEAS-130)/36
CG=0.12+(0.34-0.12)*(VEAS-130)/36
10000
7350
5950
4500
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
T.D. Ground Speed = Airspeed +
Average Tailwind
250
450
650
850
1050
1250
1450
1650
1850
2050
2250
2450
T.D. X Location
Past Runway Threshold

Figure 5.3

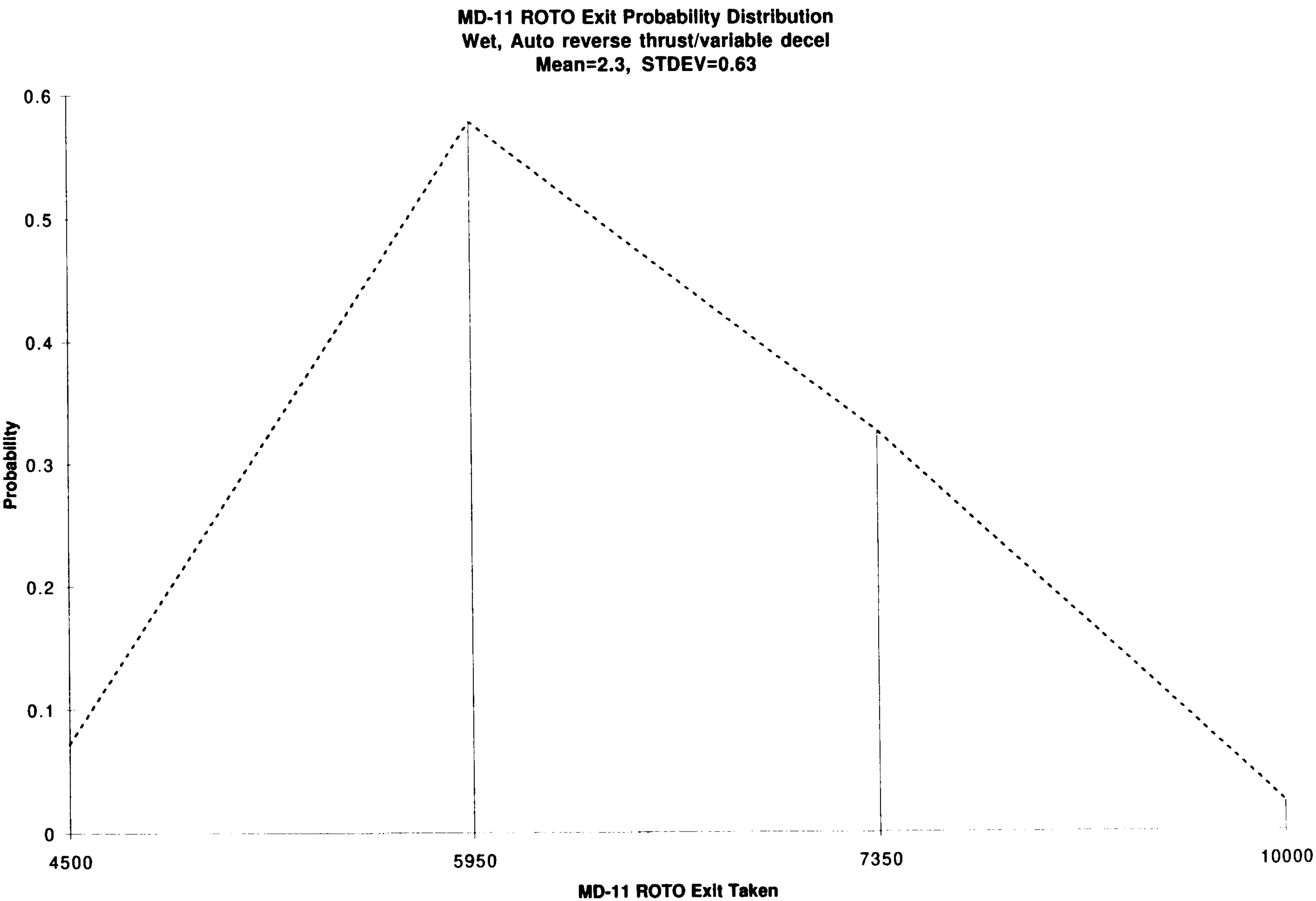
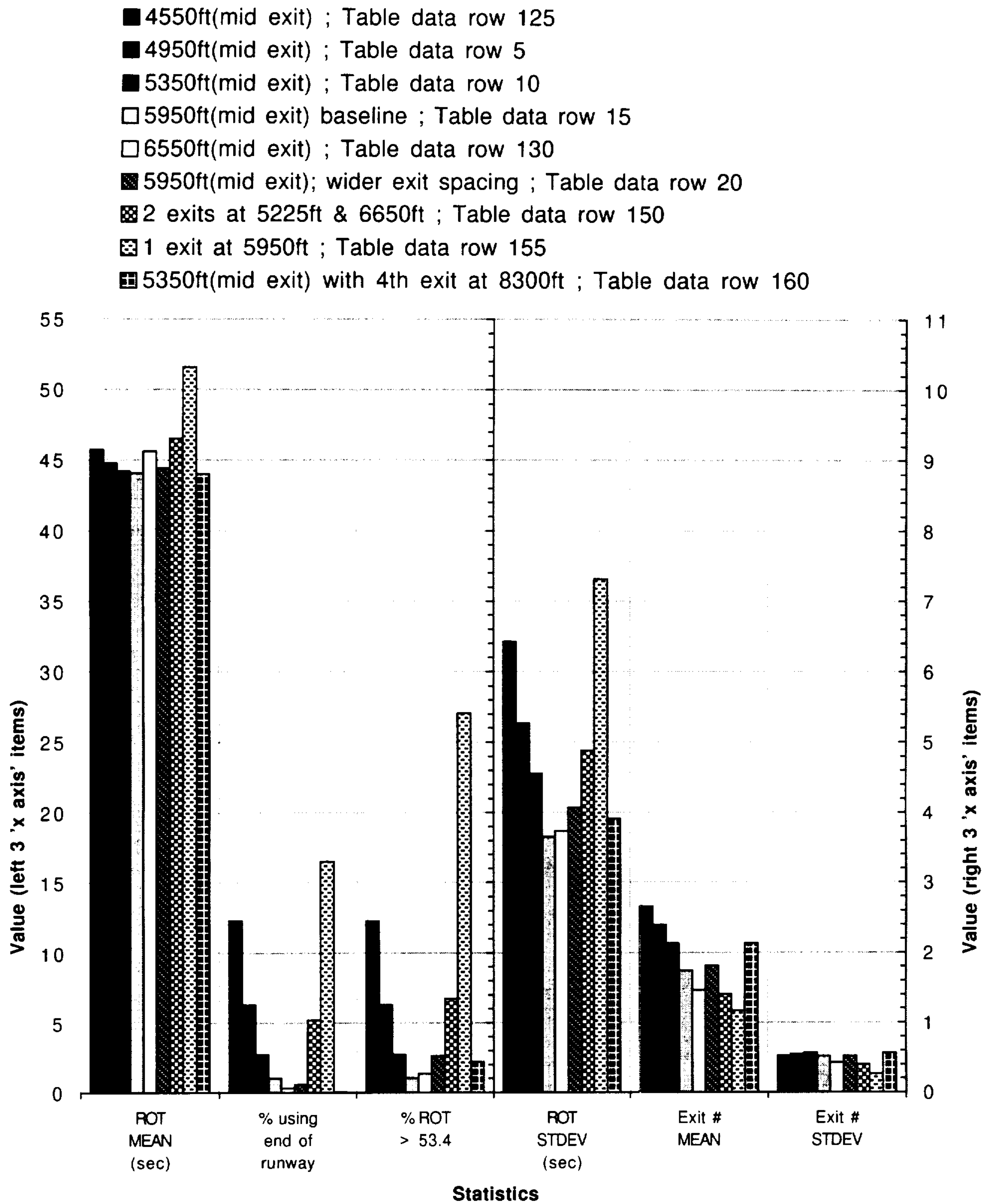
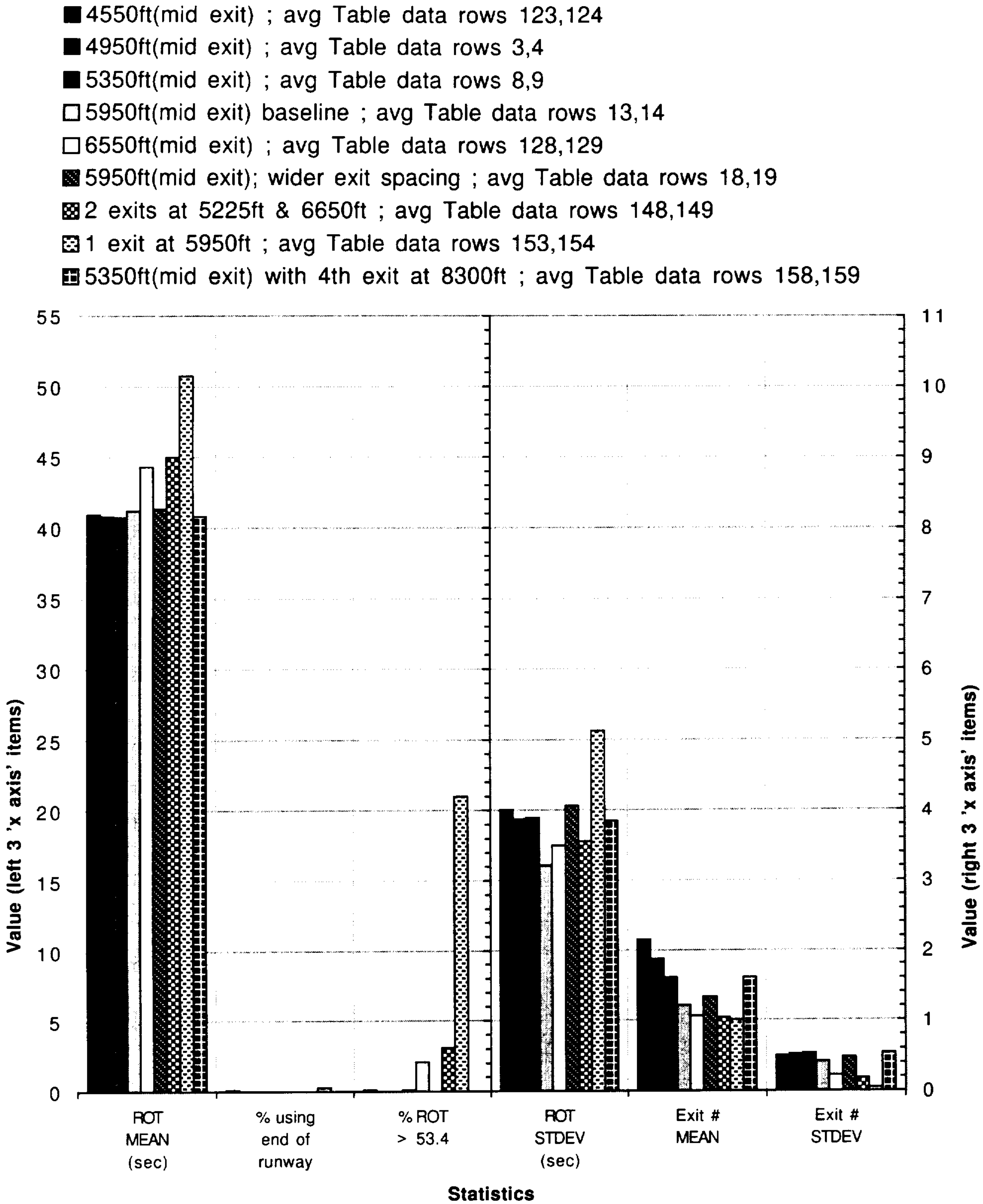

MD-11 ROTO Exit Probability Distribution
Wet, Auto reverse thrust/variable decel
Mean=2.3, STDEV=0.63
Probability
0.6
0.5
0.4
0.3
0.2
0.1
0
4500
5950
7350
10000
MD-11 ROTO Exit Taken

Figure 5.4



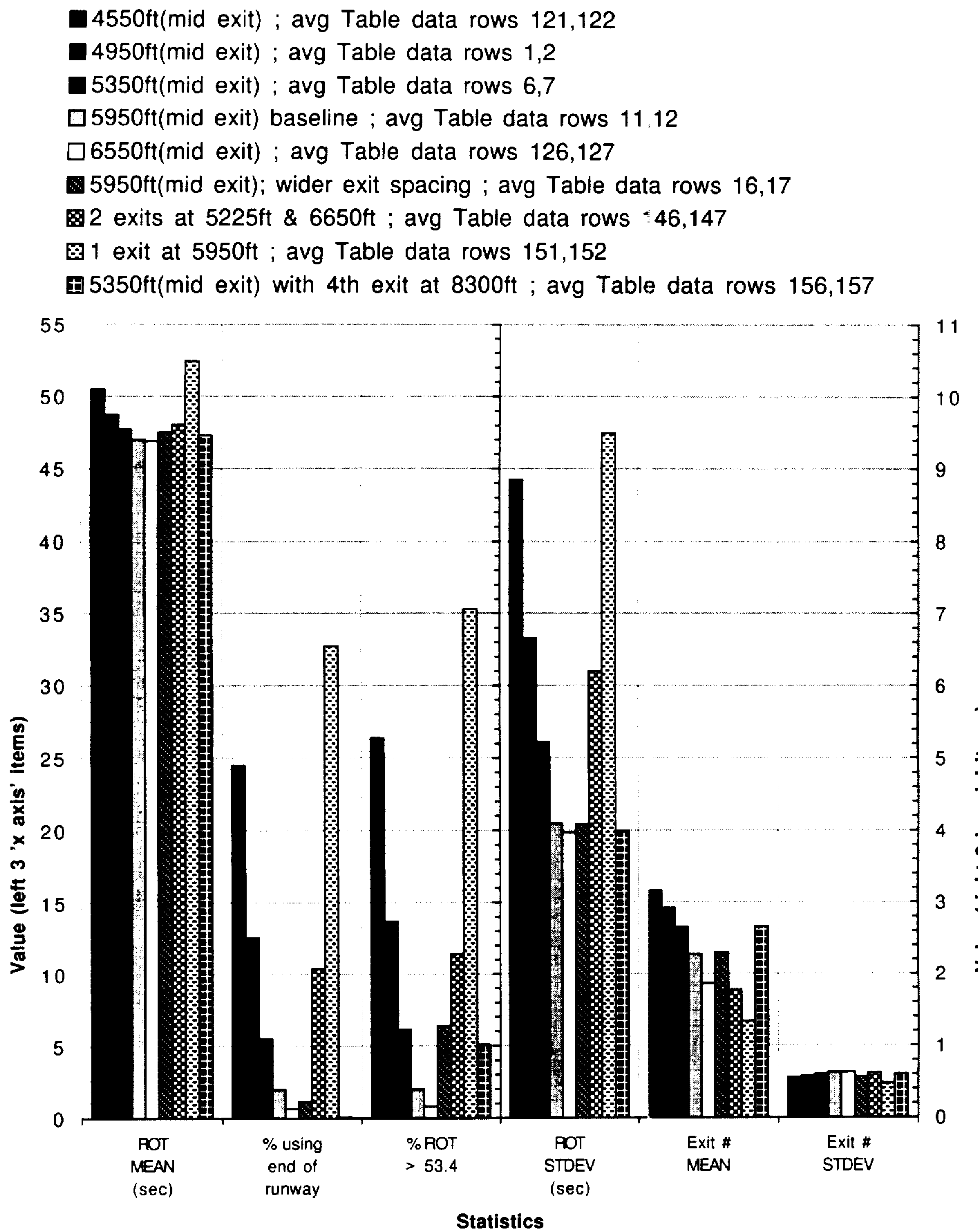
ROT sensitivity to exit location, spacing & number of exits
Autoreverse thrust/variable braking
Statistics average wet/dry/MD-11/MD-81 dispersions

Figure 6.1a



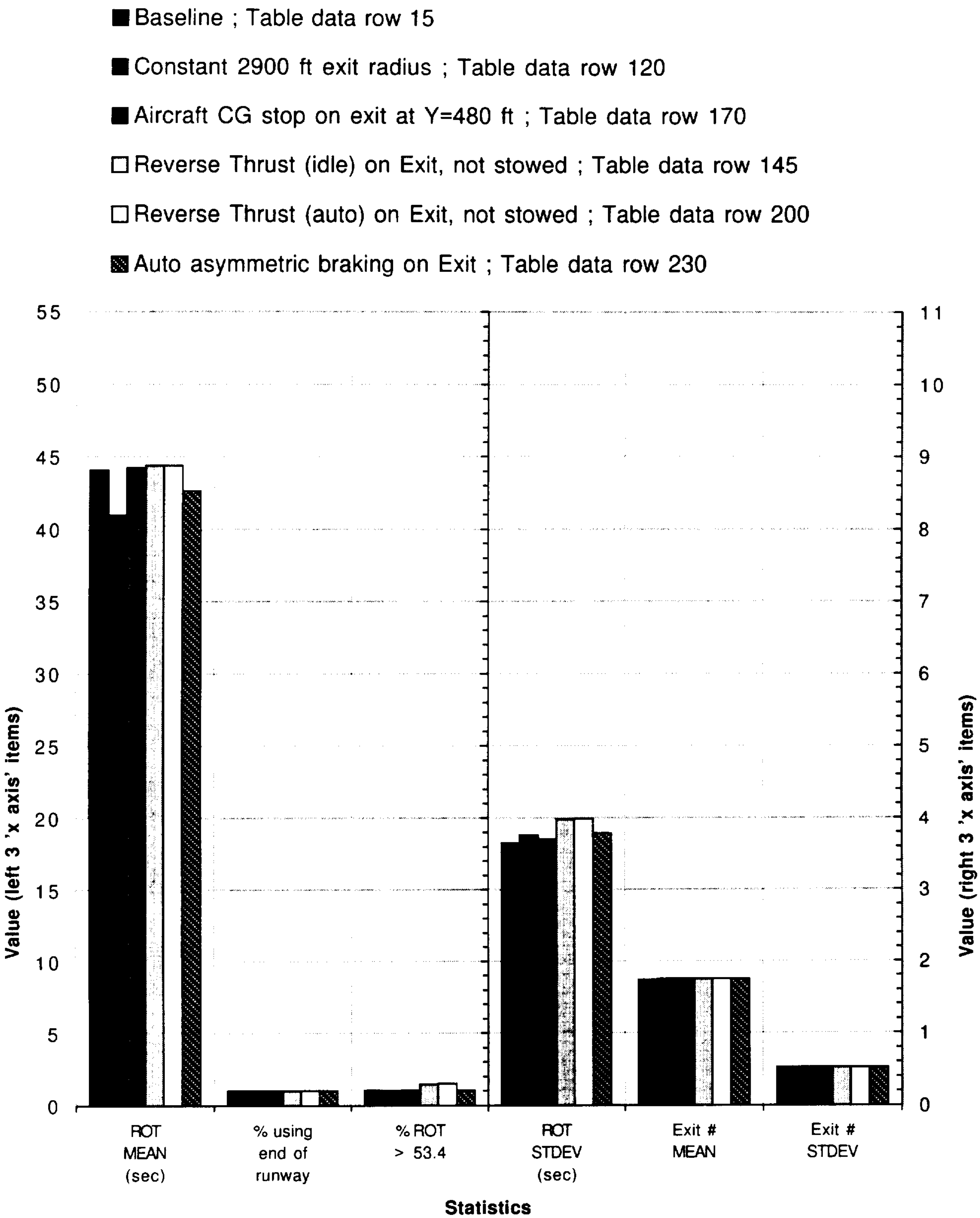
ROT sensitivity to exit location, spacing & number of exits (MD-81 only)
Autoreverse thrust/variable braking
Statistics average wet/dry/MD-81 dispersions

Figure 6.1b



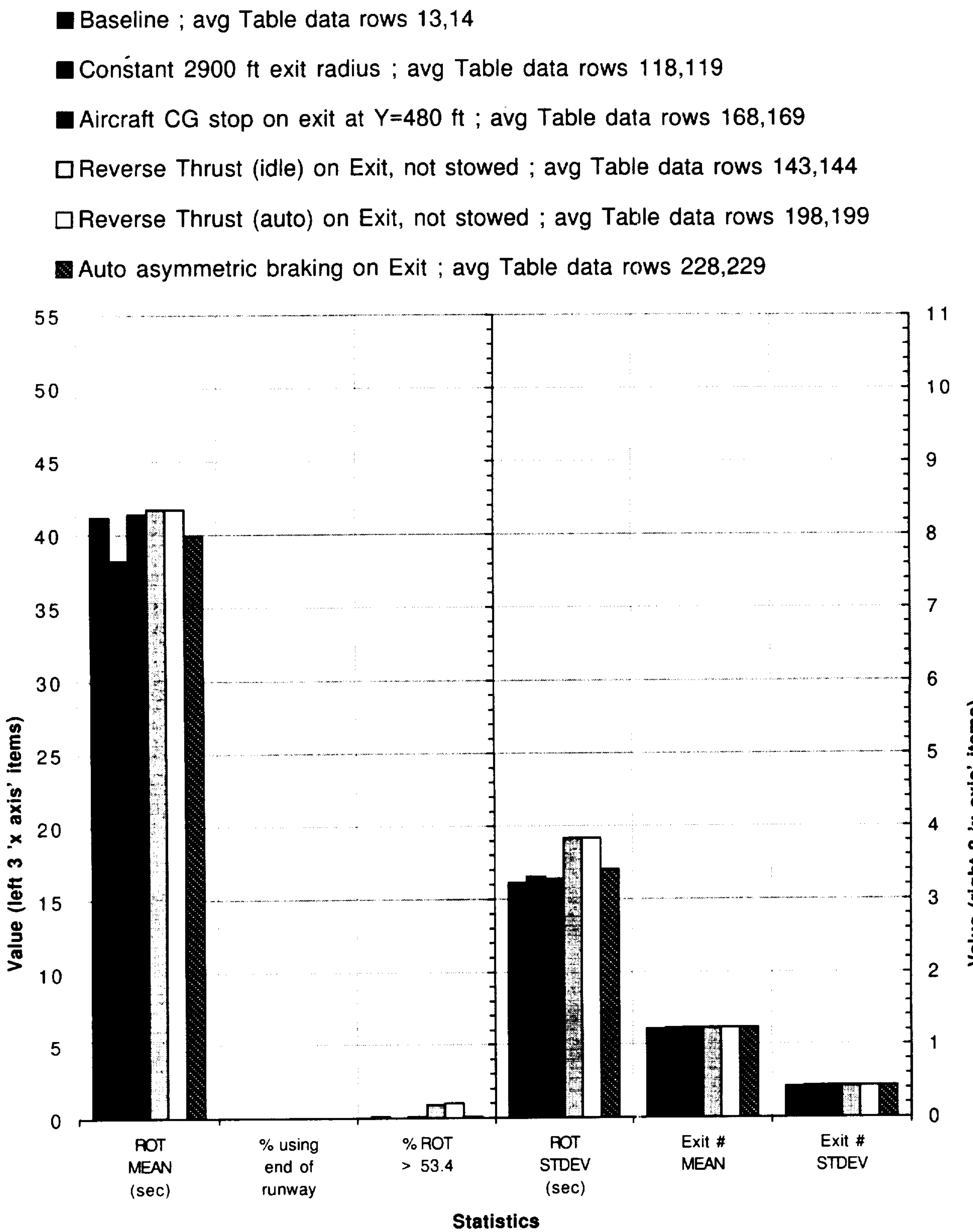
ROT sensitivity to exit location, spacing & number of exits (MD-11 only)
Autoreverse thrust/variable braking
Statistics average wet/dry/MD-11 dispersions

Figure 6.1c



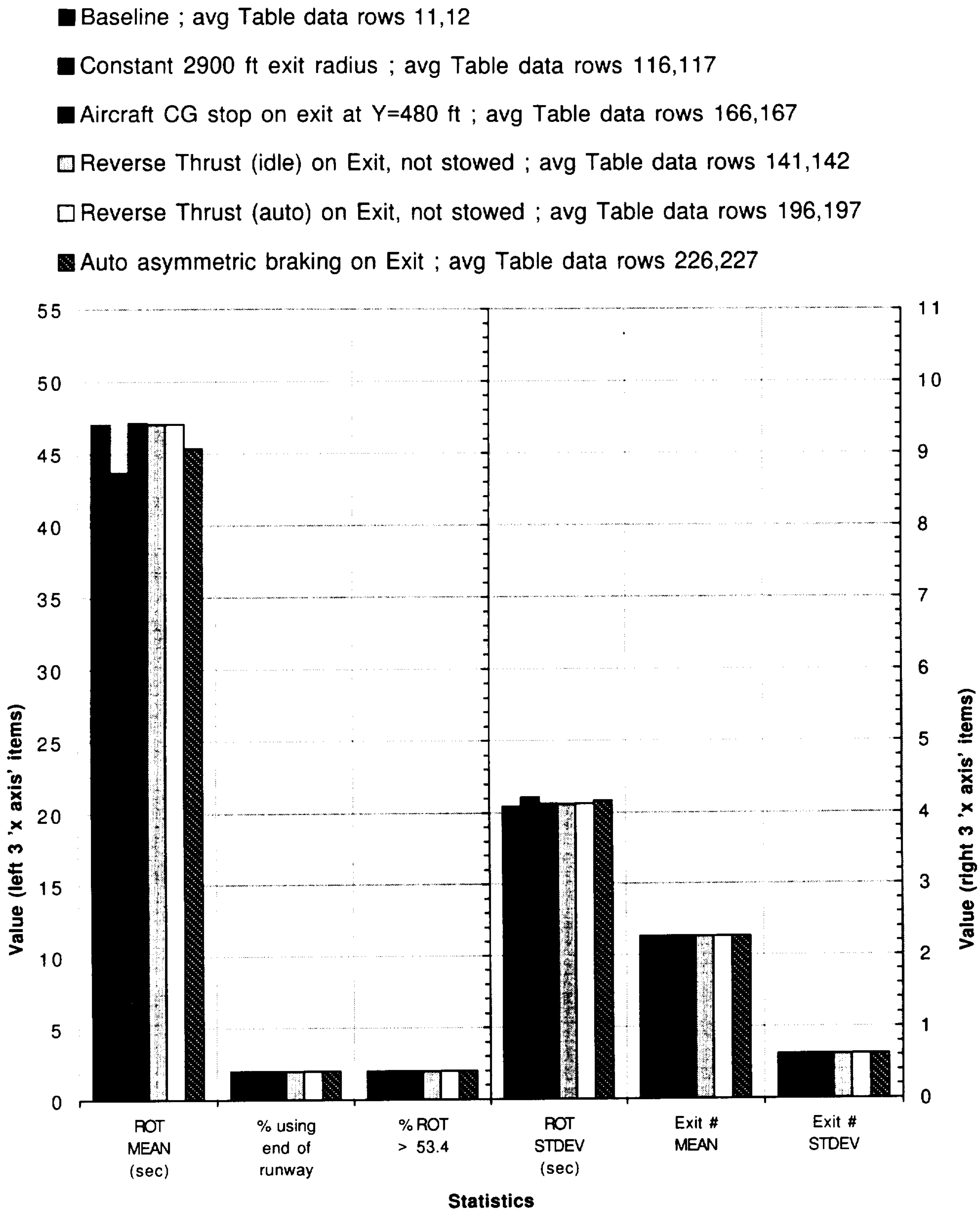
ROT sensitivity to 'on exit' Operational Factors
Autoreverse thrust/variable braking
Mid exit location 5950
Statistics average wet/dry/MD-11/MD-81 dispersions

Figure 6.2a



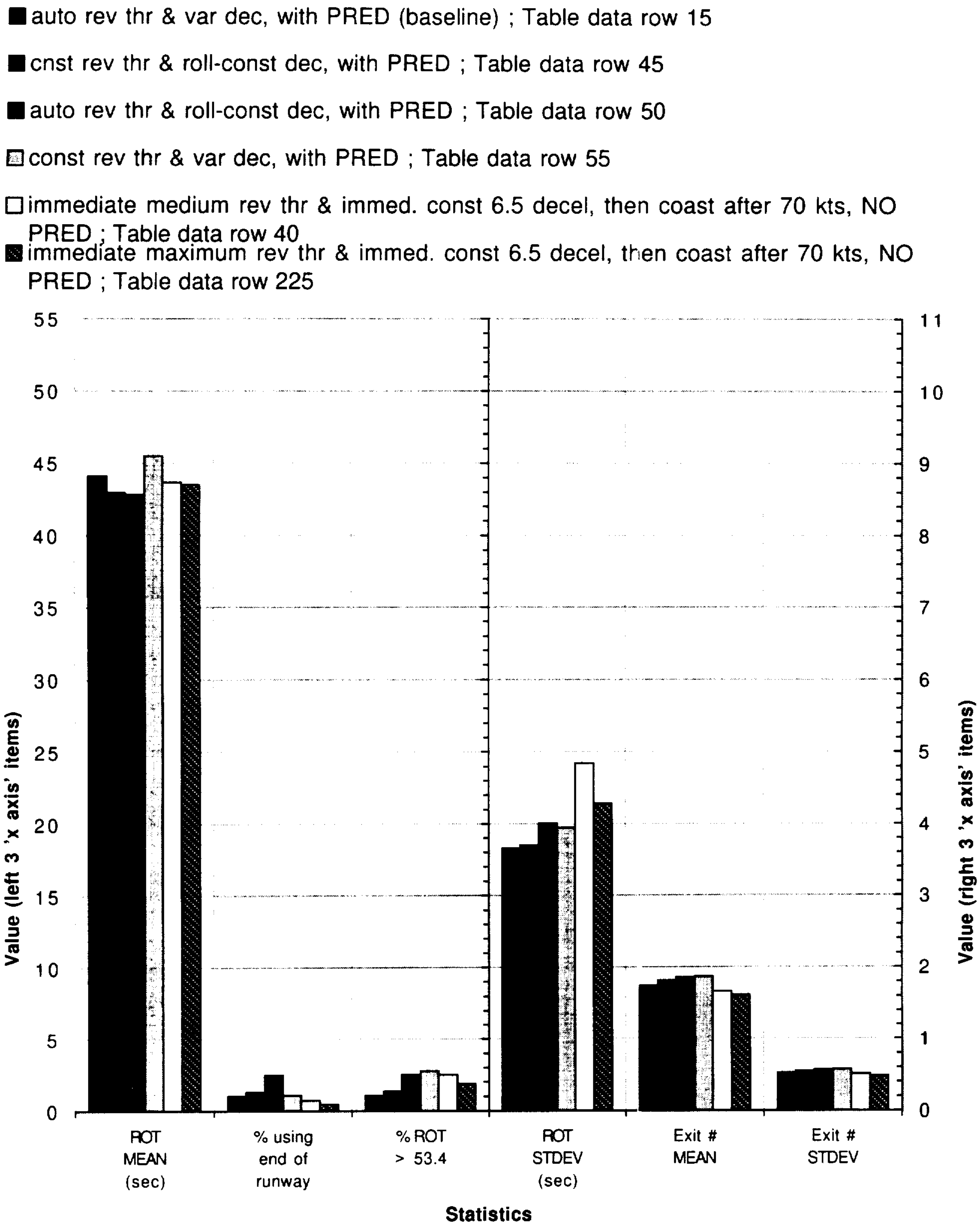
ROT sensitivity to 'on exit' Operational Factors (MD-81 only)
Autoreverse thrust/variable braking
Mid exit location 5950
Statistics average wet/dry/MD-81 dispersions

Figure 6.2b



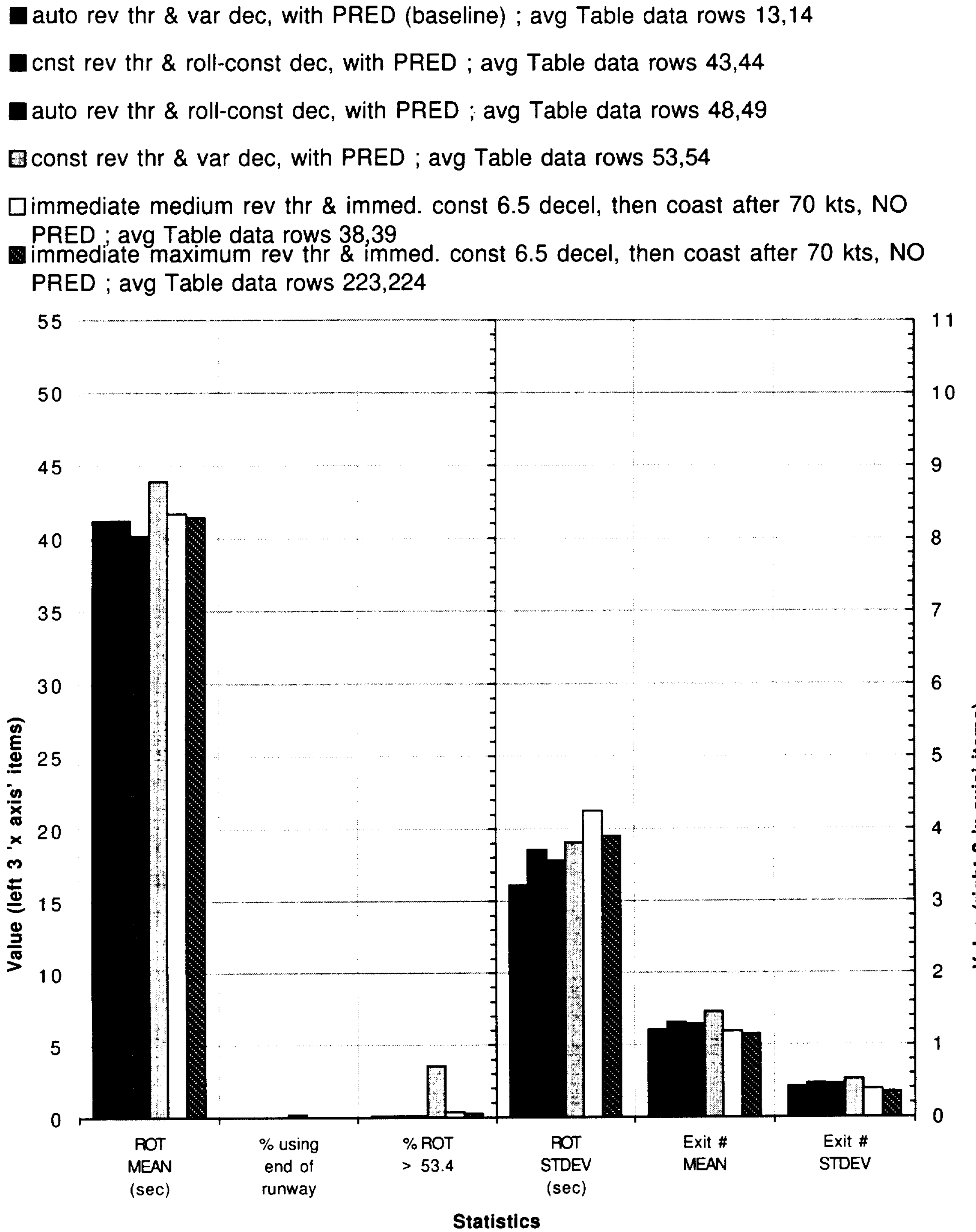
ROT sensitivity to 'on exit' Operational Factors (MD-11 only)
Autoreverse thrust/variable braking
Mid exit location 5950
Statistics average wet/dry/MD-11 dispersions

Figure 6.2c



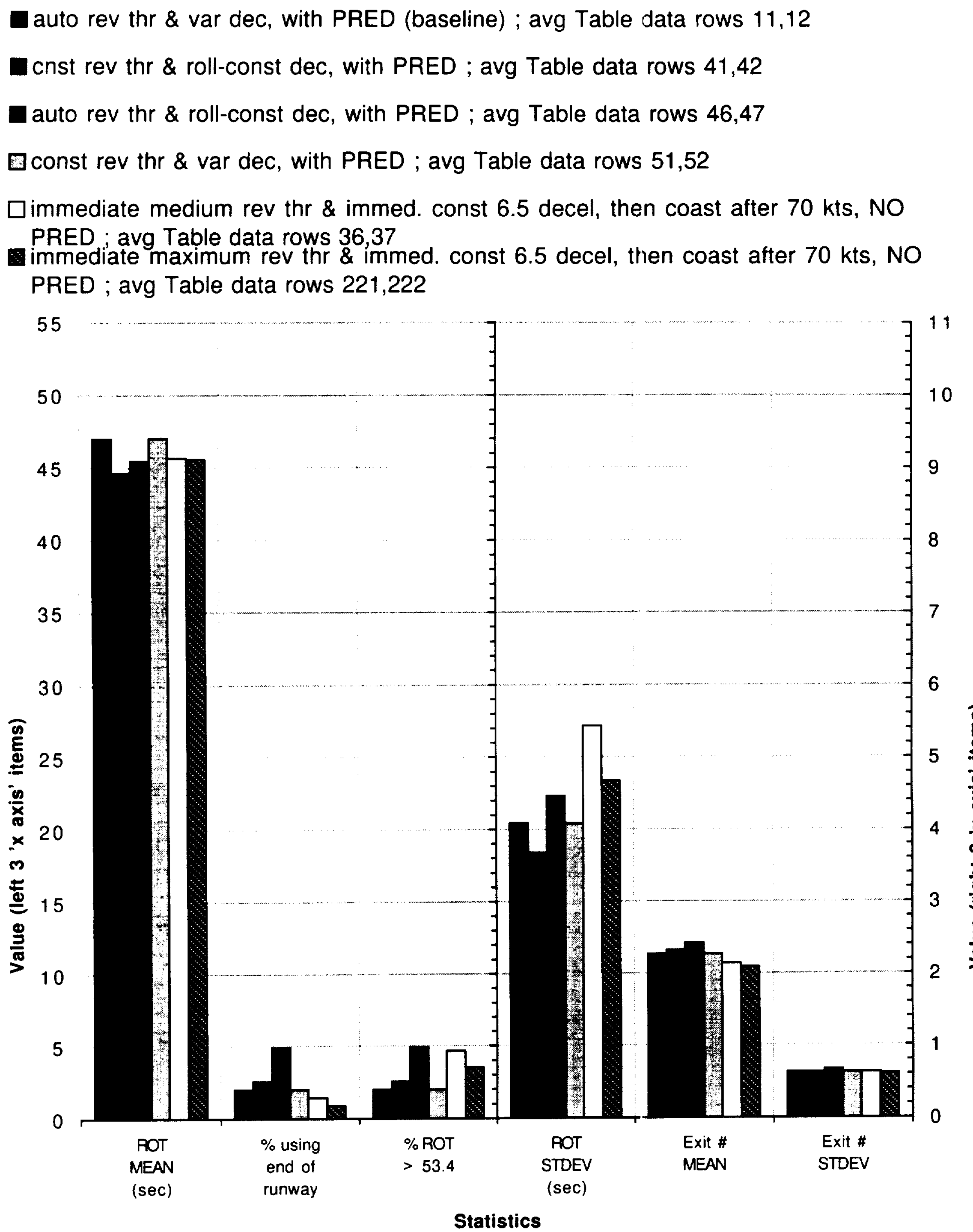
ROT sensitivity to reverse thrust and braking deceleration methods
Mid exit location at 5950
Statistics average wet/dry/MD-11/MD-81 dispersions

Figure 6.3a



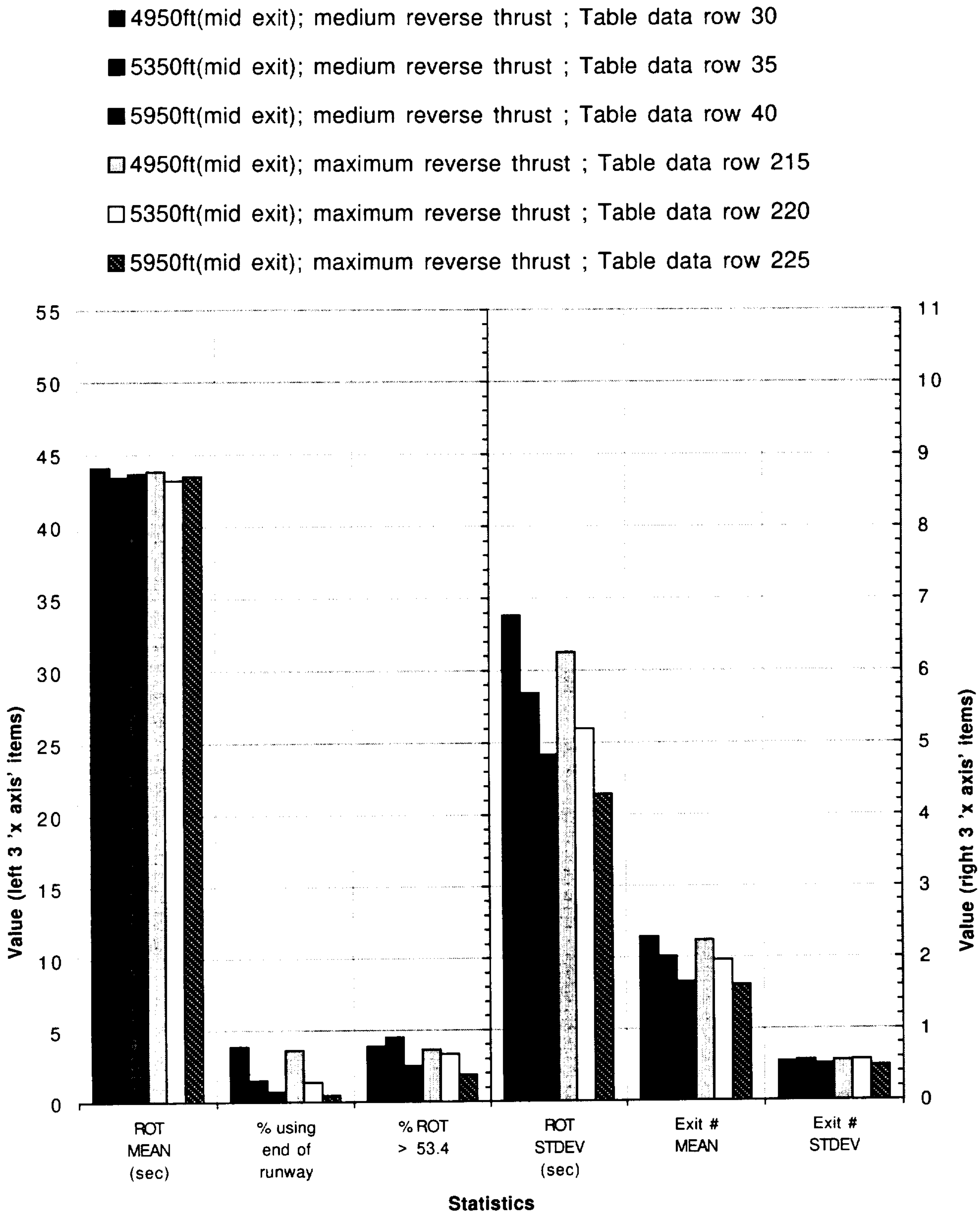
ROT sensitivity to thrust and braking deceleration methods (MD-81 only)
Mid exit location at 5950
Statistics average wet/dry/MD-81 dispersions

Figure 6.3b



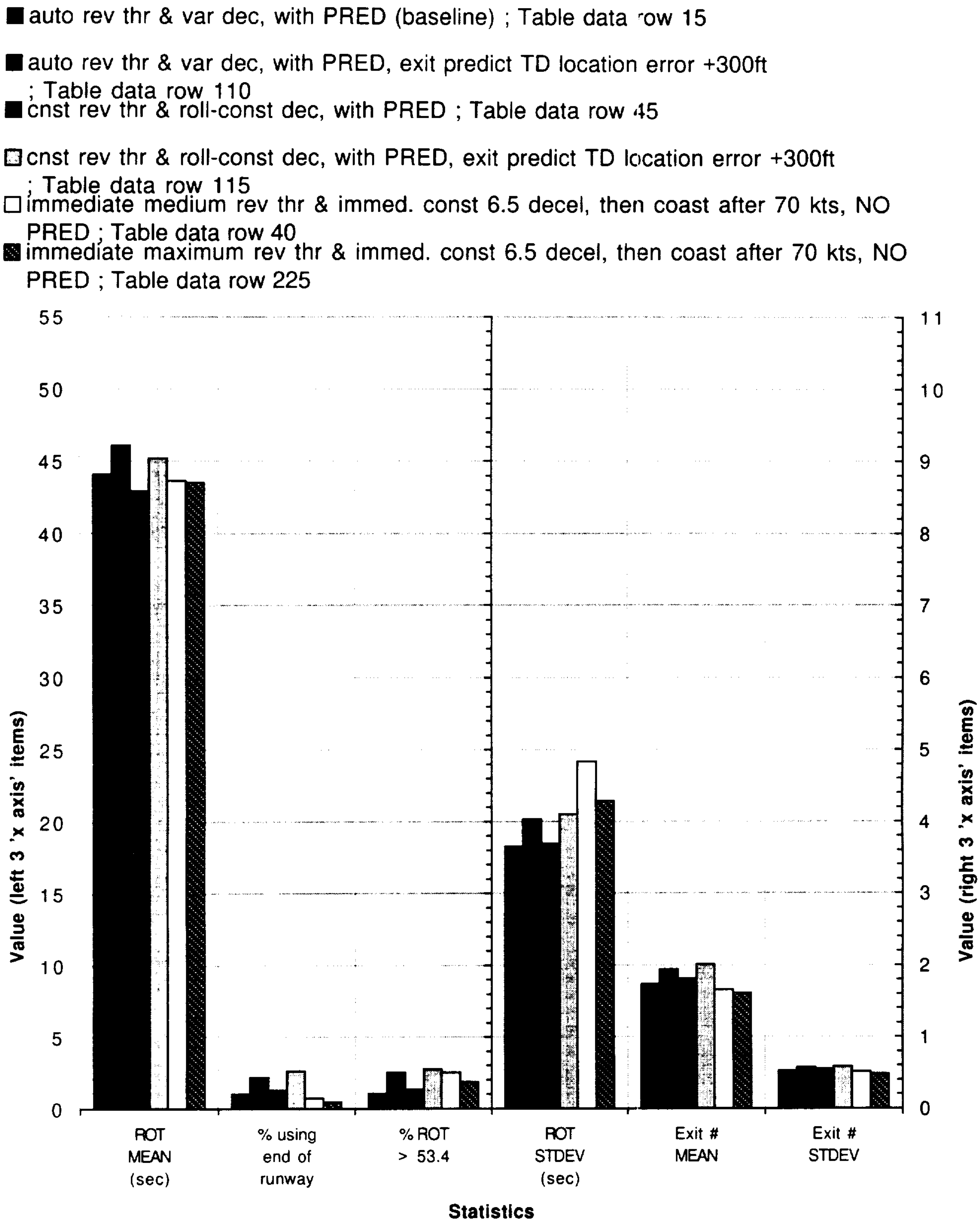
ROT sensitivity to thrust and braking deceleration methods (MD-11 only)
Mid exit location at 5950
Statistics average wet/dry/MD-11 dispersions

Figure 6.3c



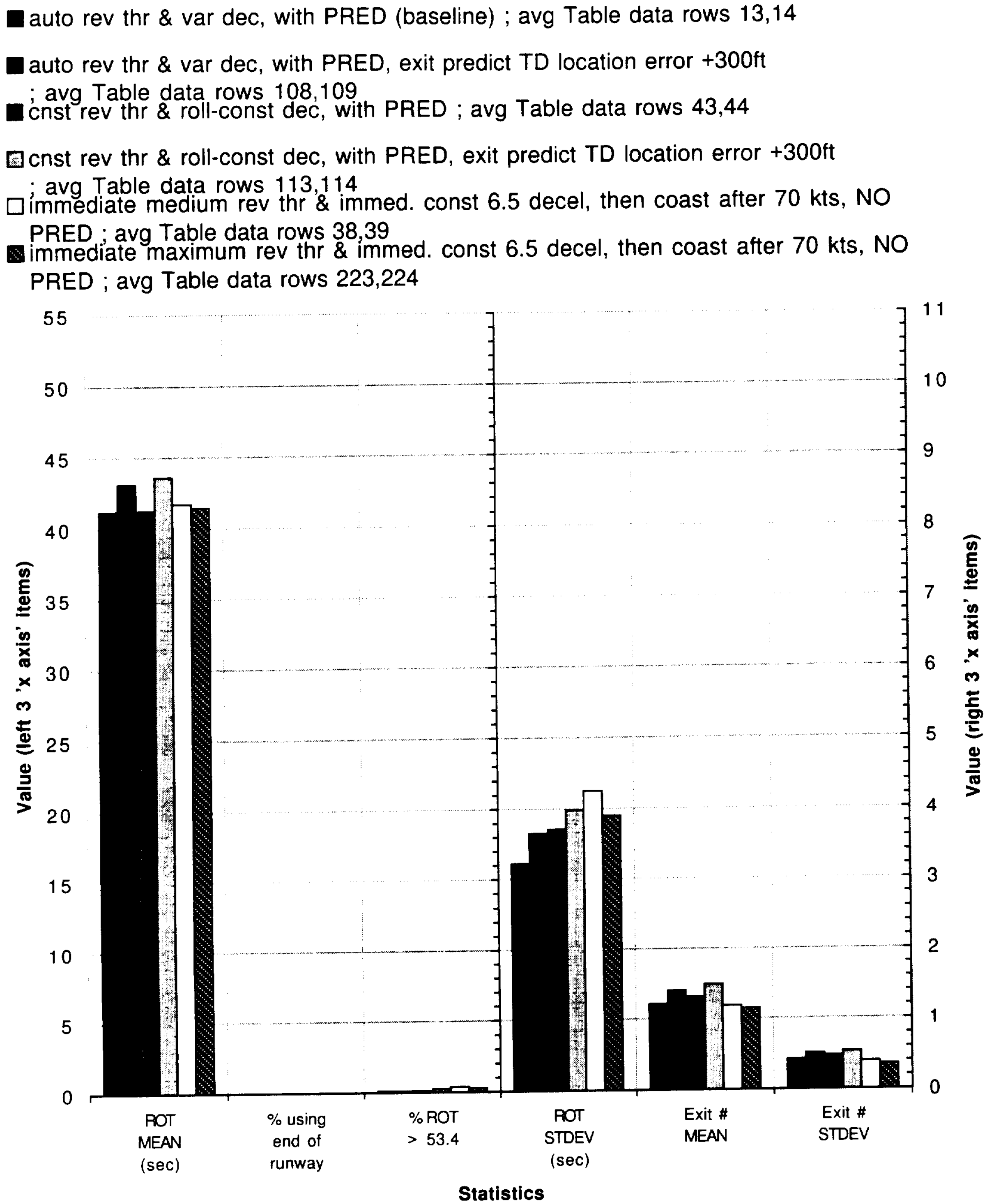
ROT sensitivity to exit location for NON-ROTO/NO Exit Prediction
Immediate reverse thrust & immediate 6.5 constant deceleration
Statistics average wet/dry/MD-11/MD-81 dispersions

Figure 6.4



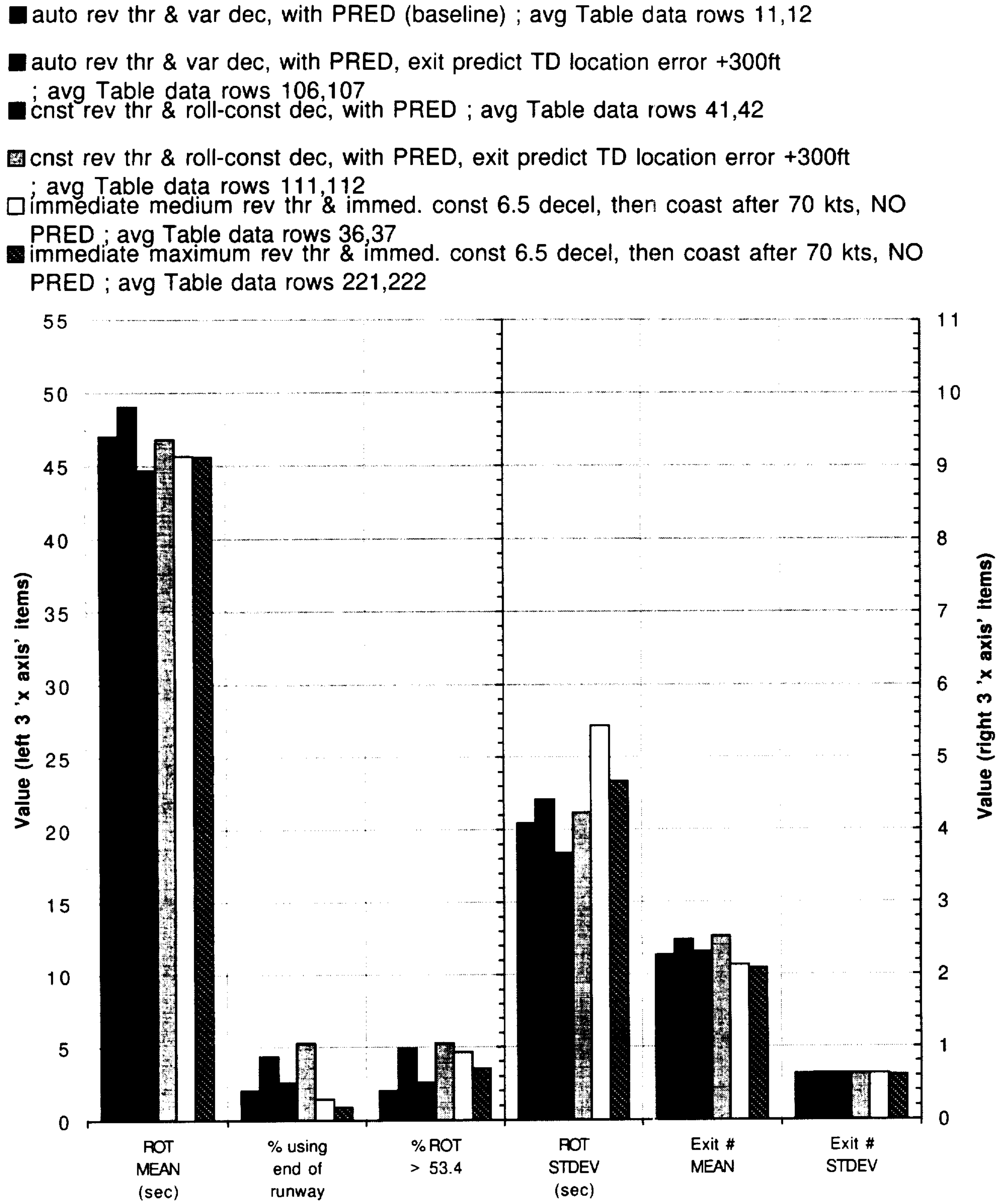
ROT sensitivity to ROTO/Exit Prediction Capability
Mid exit location at 5950
Statistics average wet/dry/MD-11/MD-81 dispersions

Figure 6.5a



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

Figure 6.5b



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

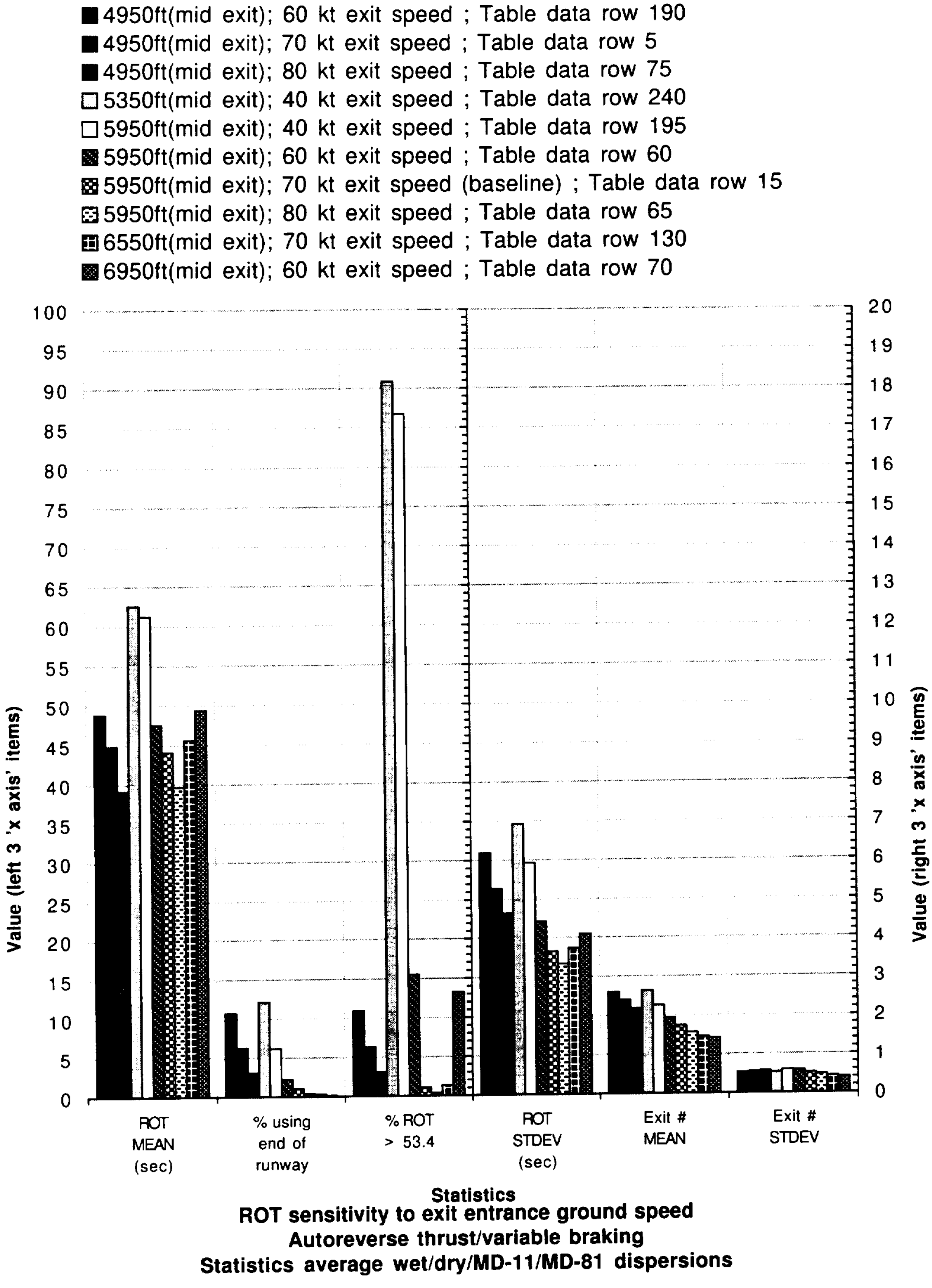
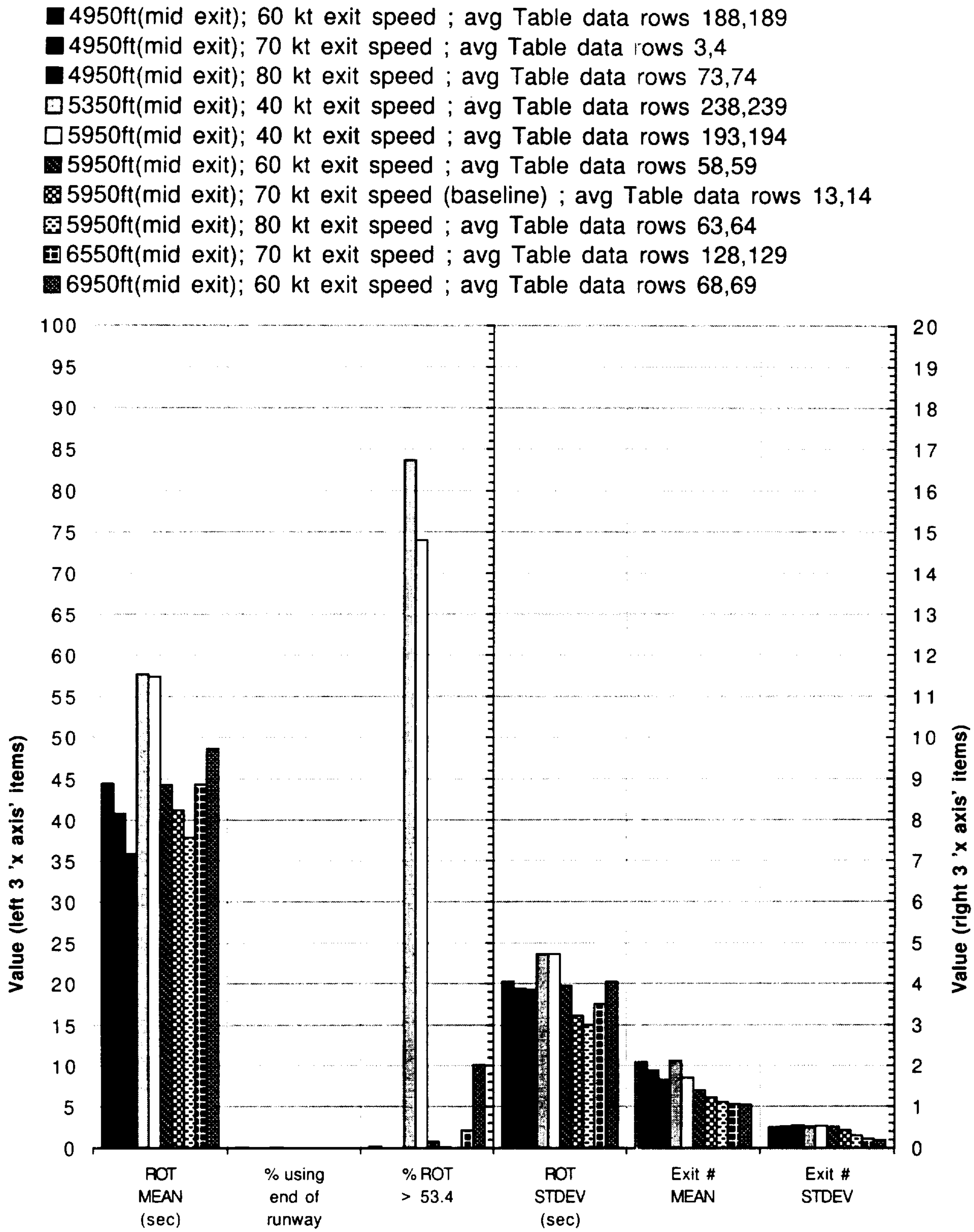
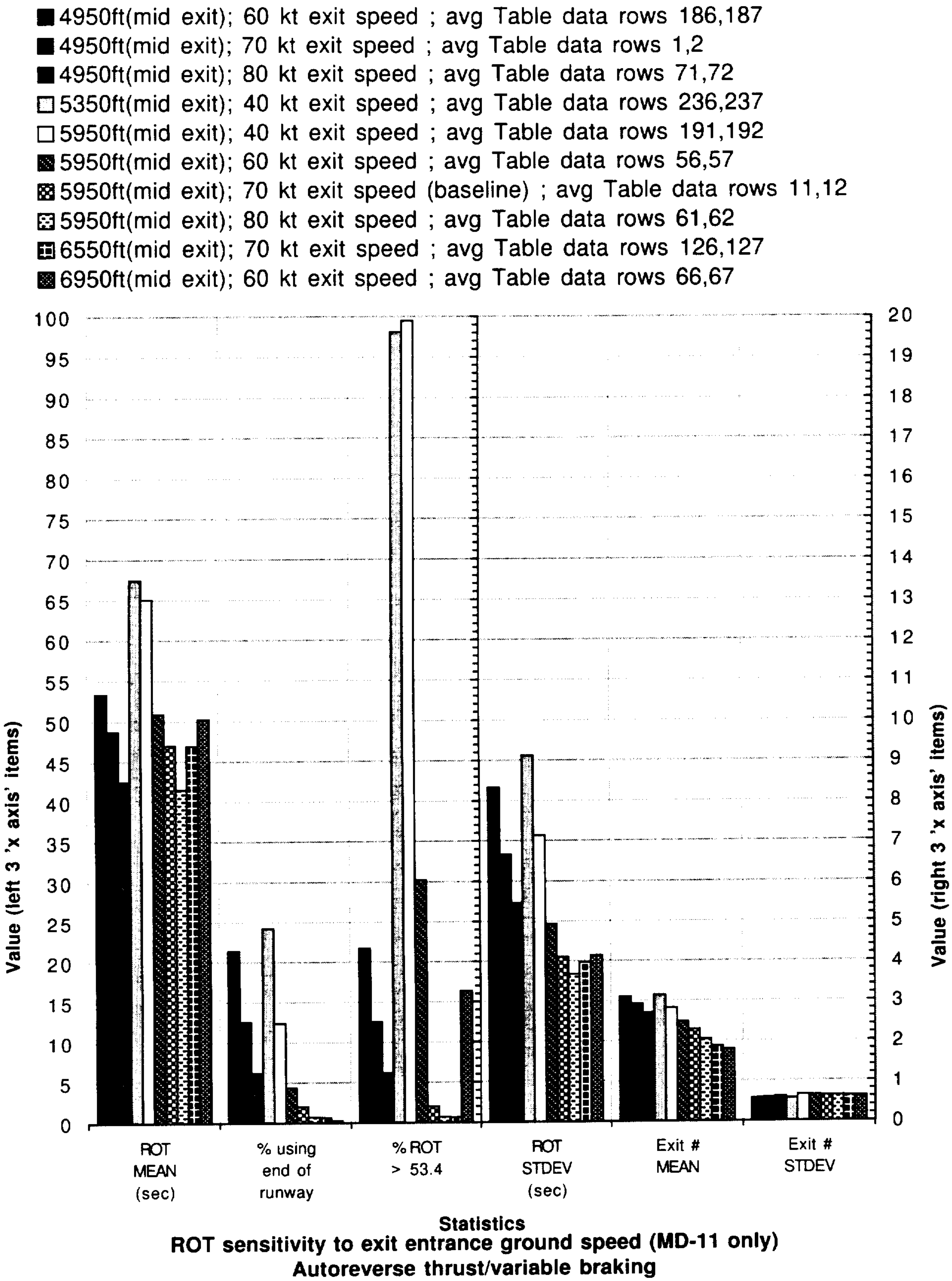

4950ft(mid exit); 60 kt exit speed ; Table data row 190
4950ft(mid exit); 70 kt exit speed ; Table data row 5
4950ft(mid exit); 80 kt exit speed ; Table data row 75
5350ft(mid exit); 40 kt exit speed ; Table data row 240
5950ft(mid exit); 40 kt exit speed ; Table data row 195
5950ft(mid exit); 60 kt exit speed ; Table data row 60
5950ft(mid exit); 70 kt exit speed (baseline) ; Table data row 15
5950ft(mid exit); 80 kt exit speed ; Table data row 65
6550ft(mid exit); 70 kt exit speed ; Table data row 130
6950ft(mid exit); 60 kt exit speed ; Table data row 70
Value (left 3 'x axis' items)
Value (right 3 'x axis' items)
ROT MEAN (sec)
% using end of runway
% ROT > 53.4
ROT STDEV (sec)
Exit # MEAN
Exit # STDEV
Statistics
ROT sensitivity to exit entrance ground speed
Autoreverse thrust/variable braking
Statistics average wet/dry/MD-11/MD-81 dispersions

Figure 6.6a



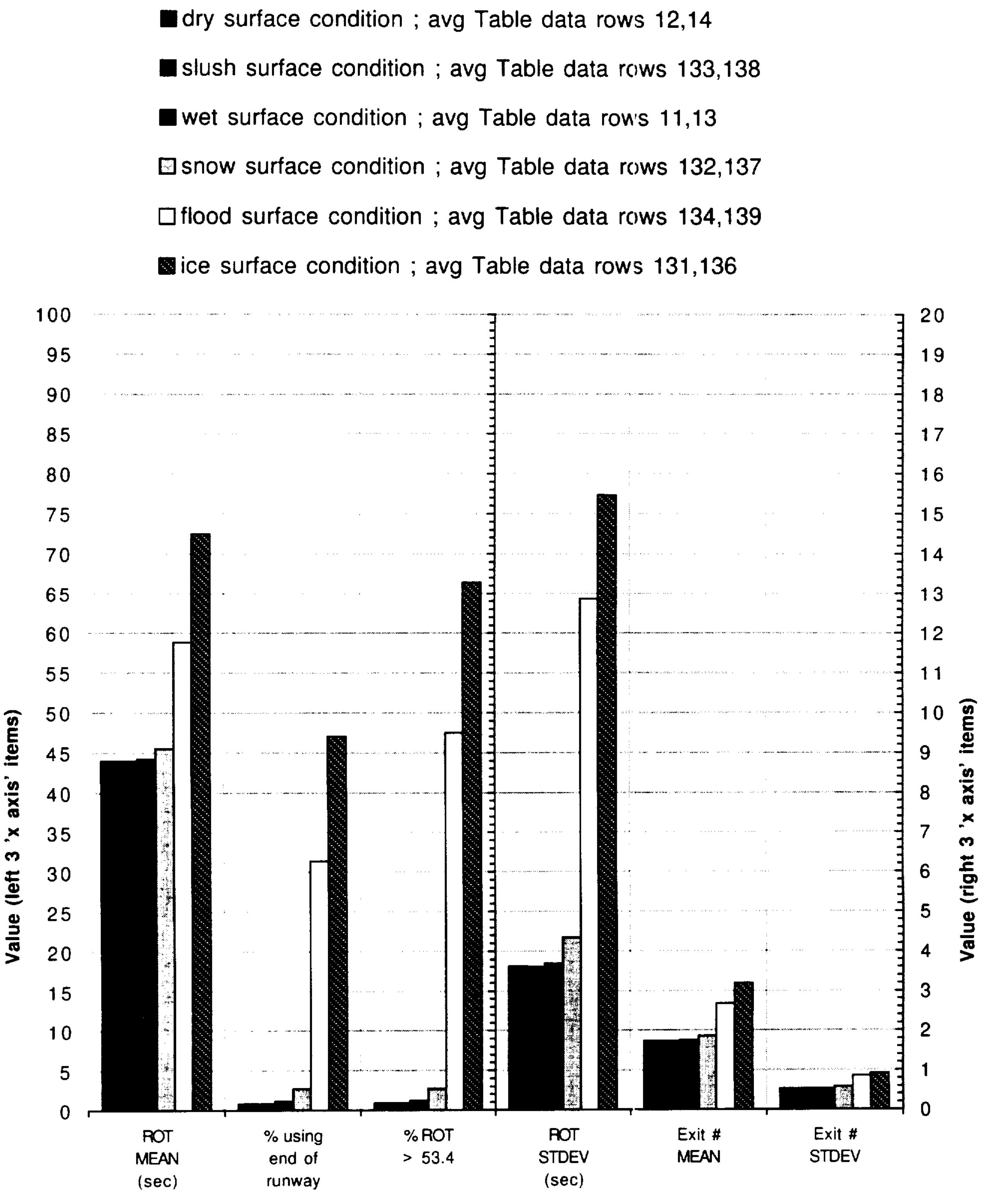
ROT sensitivity to exit entrance ground speed (MD-81 only)
Autoreverse thrust/variable braking
Statistics average wet/dry/MD-81 dispersions

Figure 6.6b



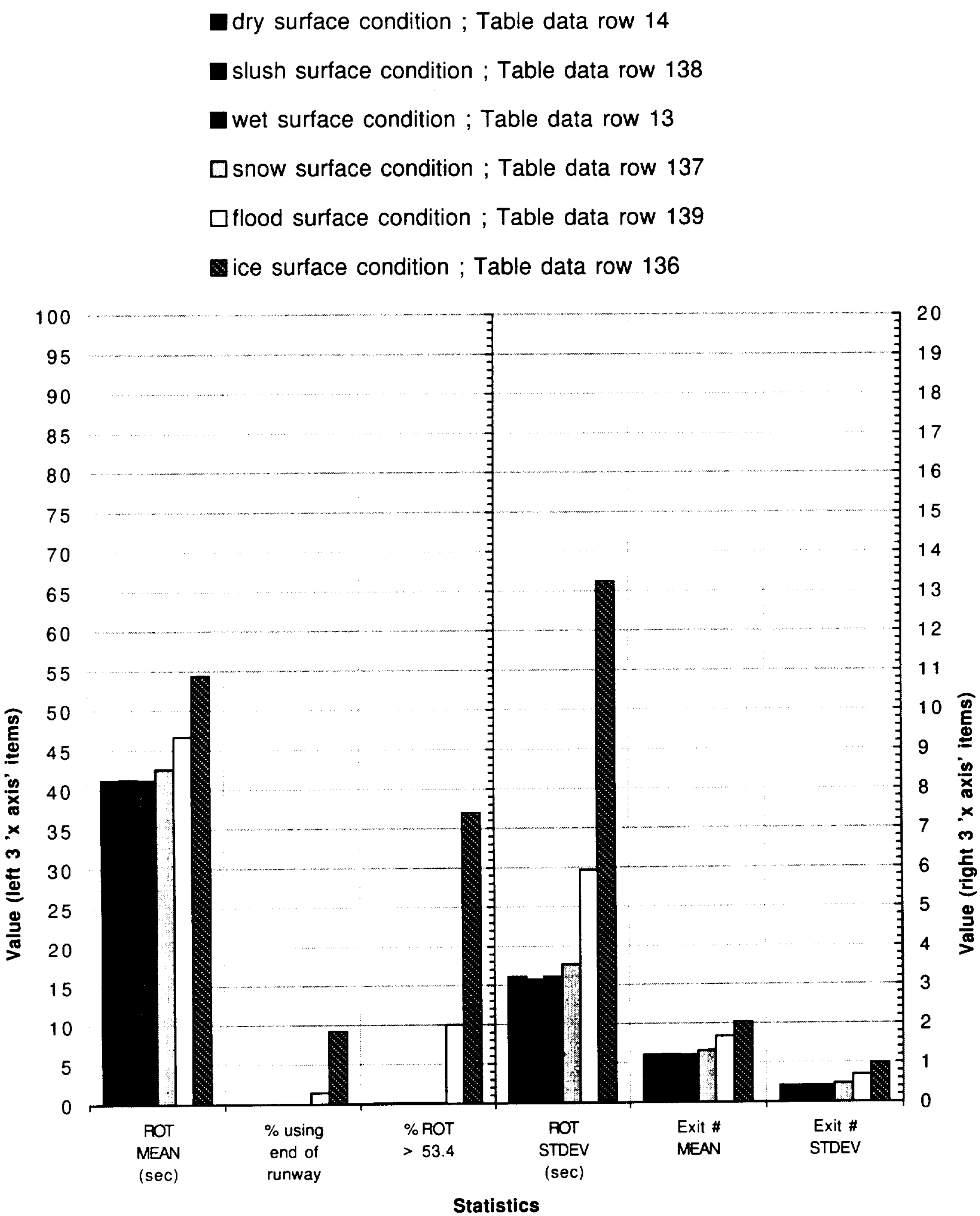
ROT sensitivity to exit entrance ground speed (MD-11 only)
Autoreverse thrust/variable braking
Statistics average wet/dry/MD-11 dispersions

Figure 6.6c



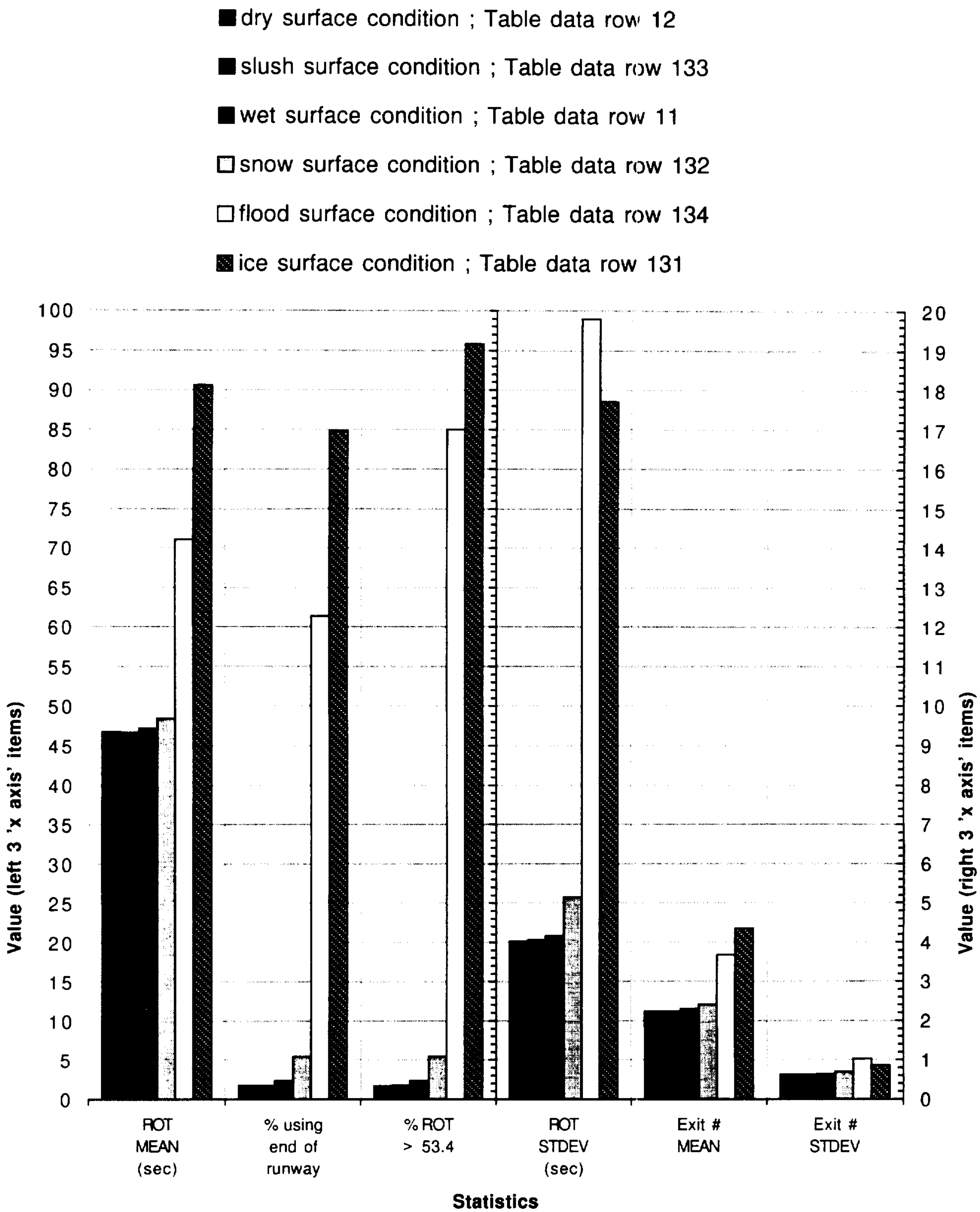
ROT sensitivity to runway surface condition
Autoreverse thrust/variable braking
Mid exit location at 5950
Statistics average MD-11/MD-81 dispersions

Figure 6.7a



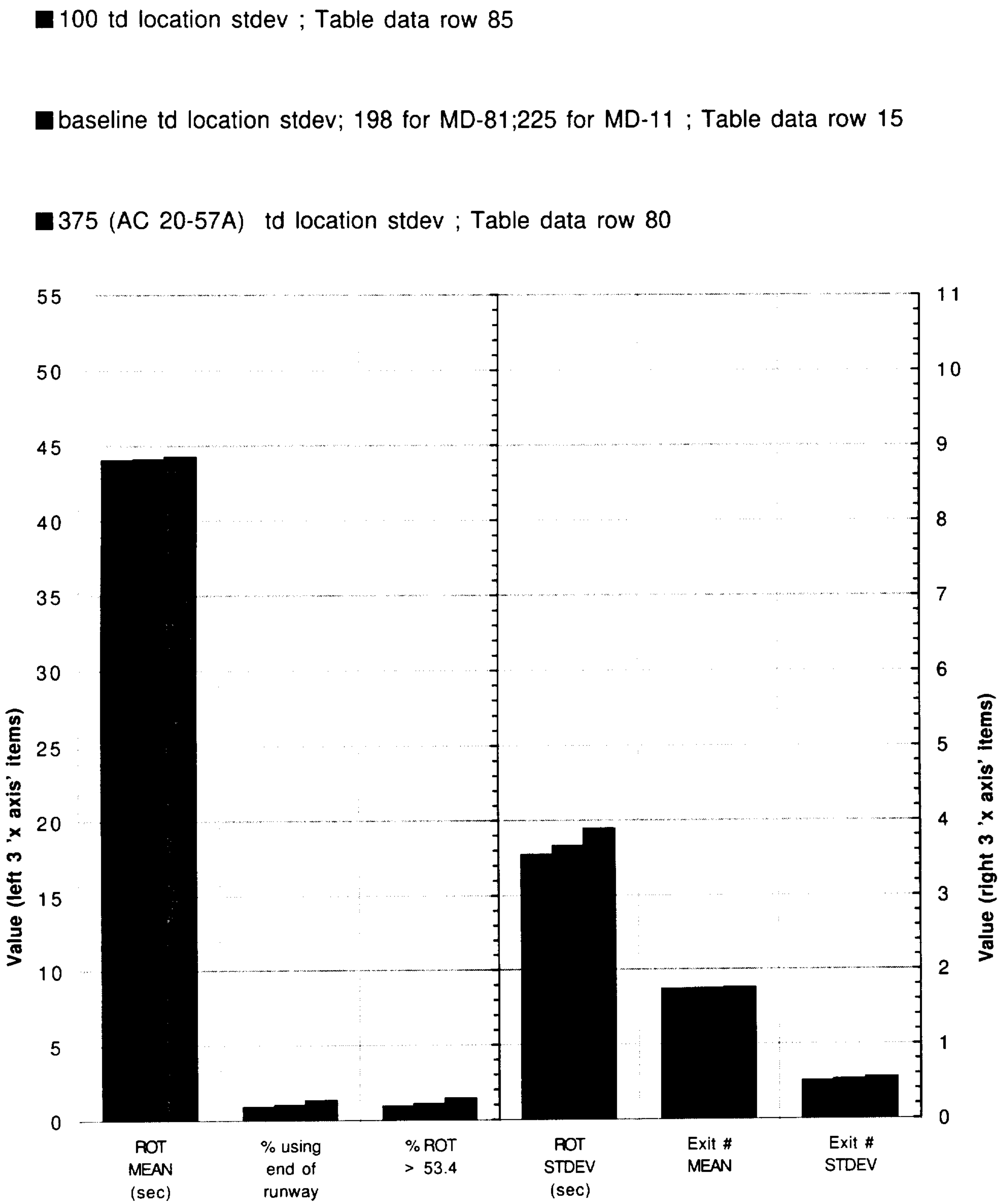
ROT sensitivity to runway surface condition (MD-81 only)
Autoreverse thrust/variable braking
MD-81 dispersions with mid exit location at 5950

Figure 6.7b



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



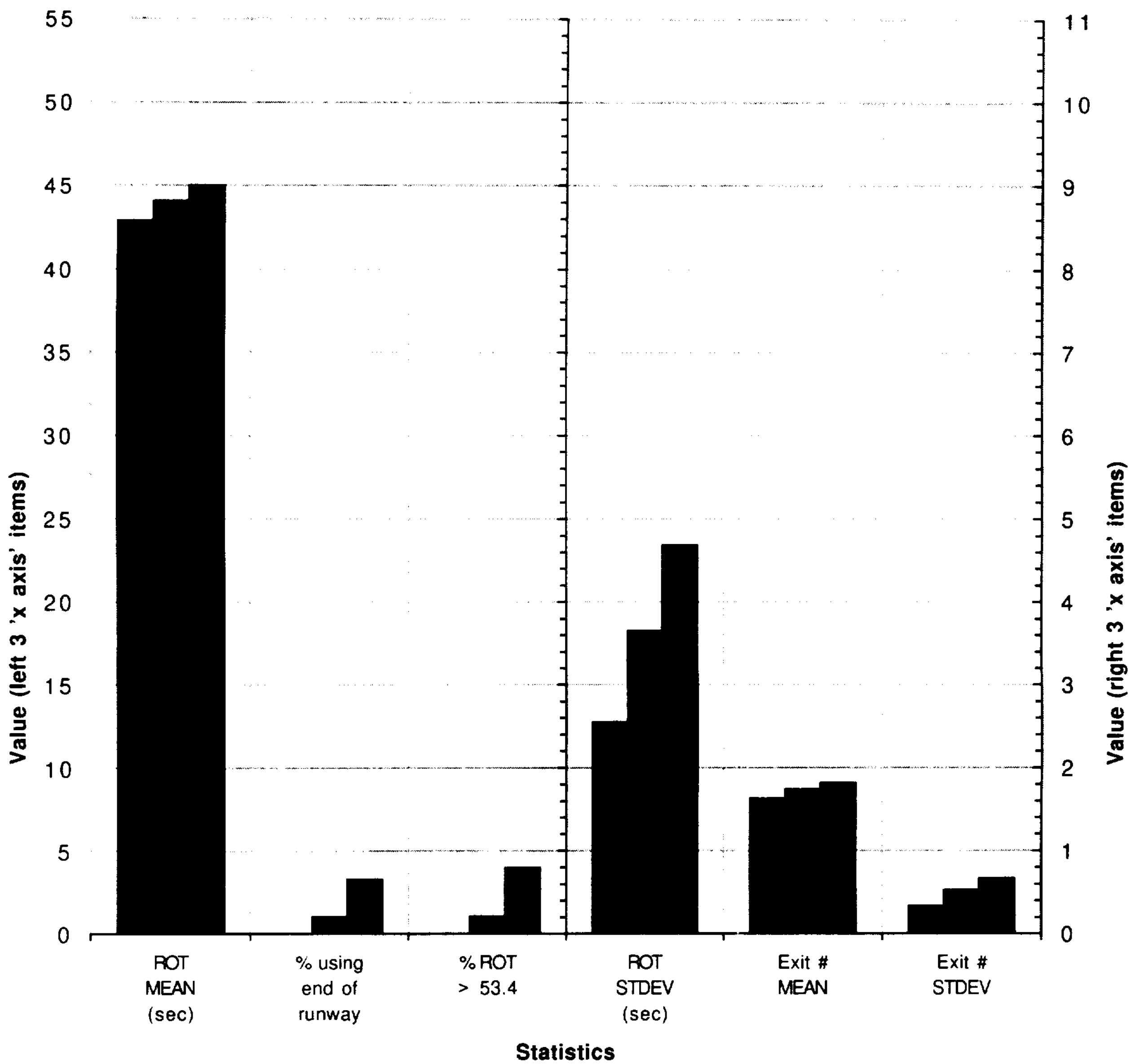
ROT sensitivity to touchdown longitudinal location stdev (ft)
Autoreverse thrust/variable braking
Mid exit location at 5950
Statistics average wet/dry/MD-11/MD-81 dispersions

Figure 6.8

■ 5 kt td gnd speed stdev ; Table data row 95

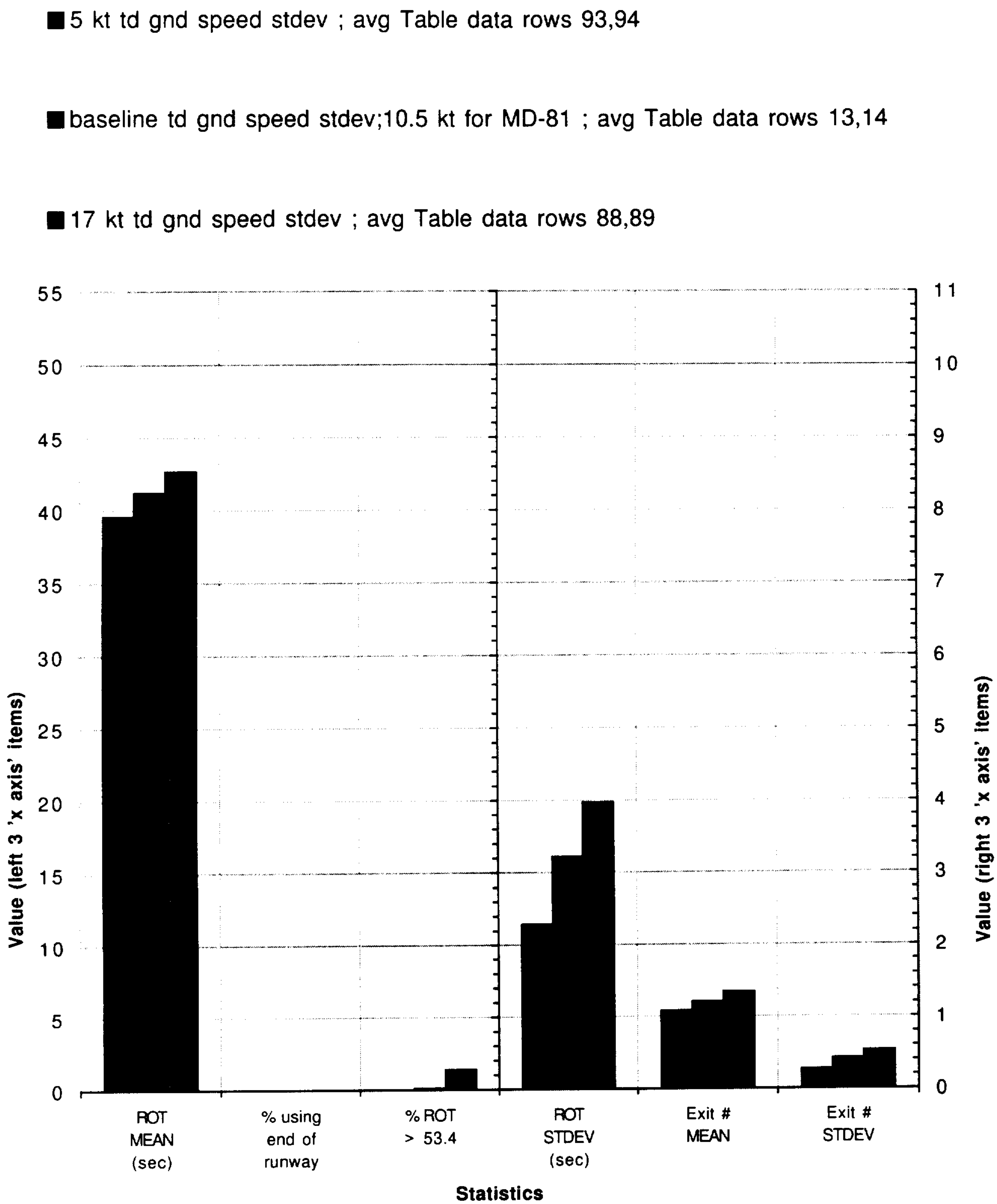
■ baseline td gnd speed stdev;10.5 kt for MD-81;11.5 kt fcr MD-11 ; Table data row 15

■ 17 kt td gnd speed stdev ; Table data row 90



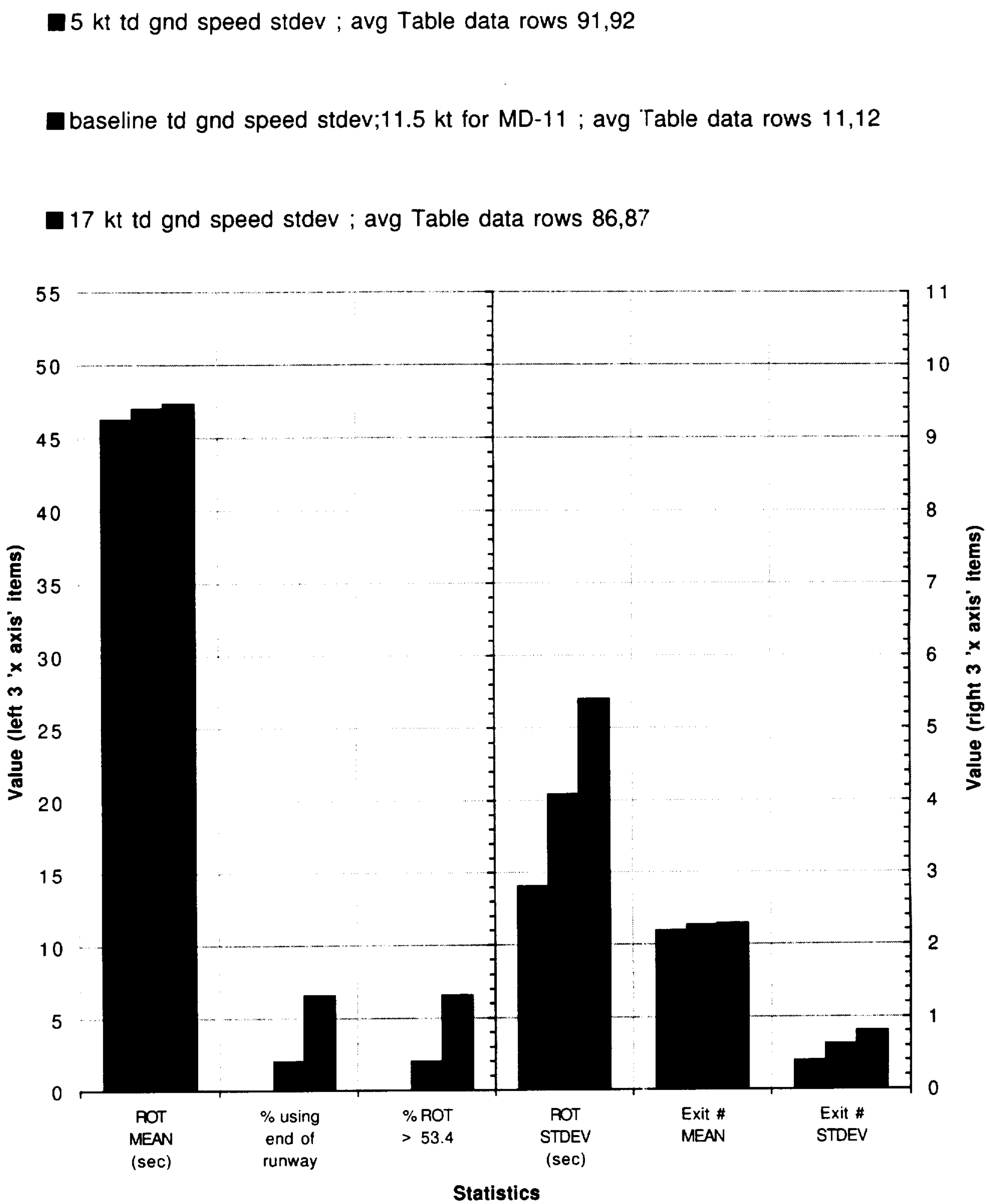
ROT sensitivity to touchdown ground speed stdev (kts)
Autoreverse thrust/variable braking
Mid exit location at 5950
Statistics average wet/dry/MD-11/MD-81 dispersions

Figure 6.9a



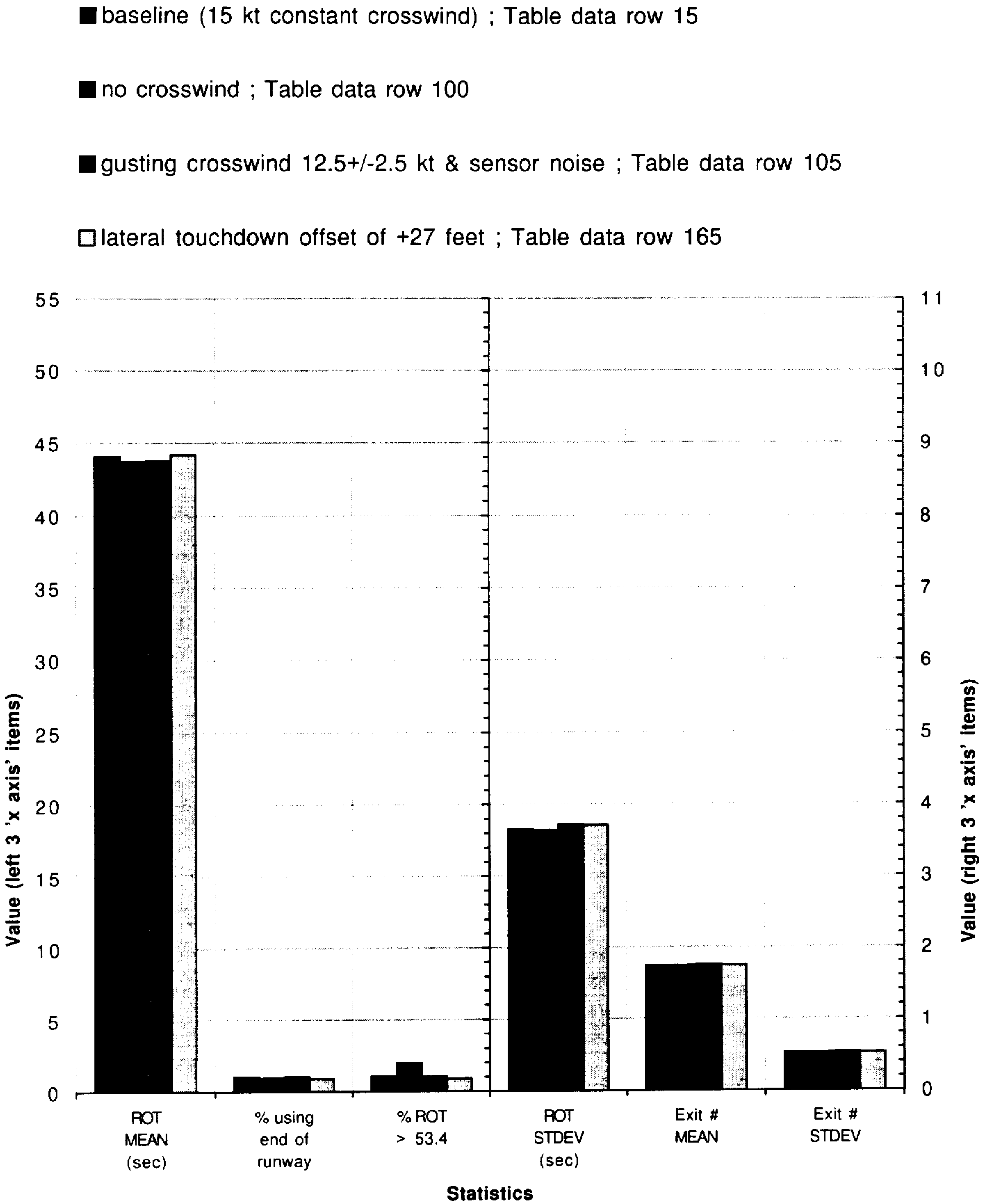
ROT sensitivity to touchdown ground speed stdev (kts) (MD-81 only)
Autoreverse thrust/variable braking
Mid exit location at 5950
Statistics average wet/dry/MD-81 dispersions

Figure 6.9b



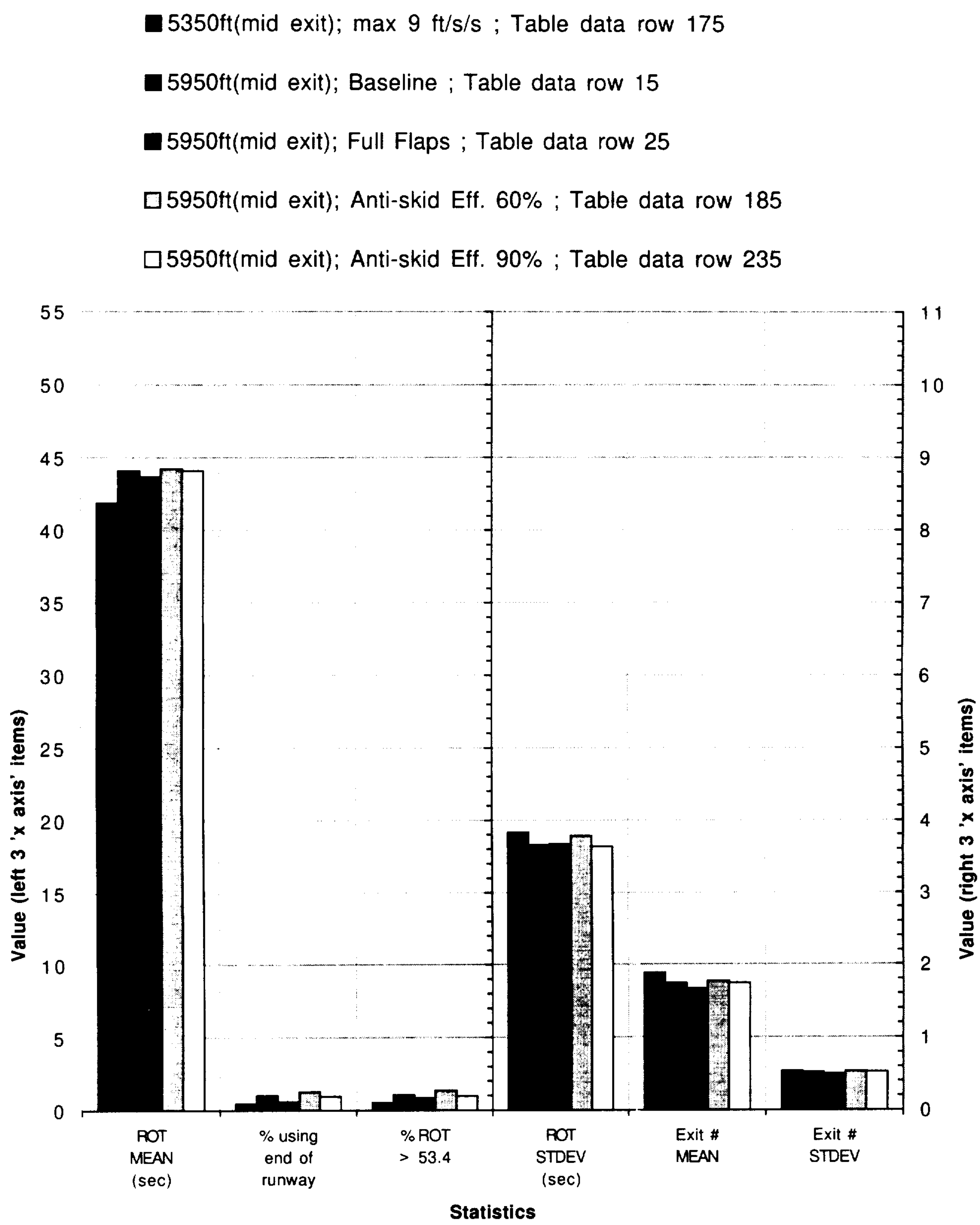
ROT sensitivity to touchdown ground speed stdev (kts) (MD-11 only)
Autoreverse thrust/variable braking
Mid exit location at 5950
Statistics average wet/dry/MD-11 dispersions

Figure 6.9c



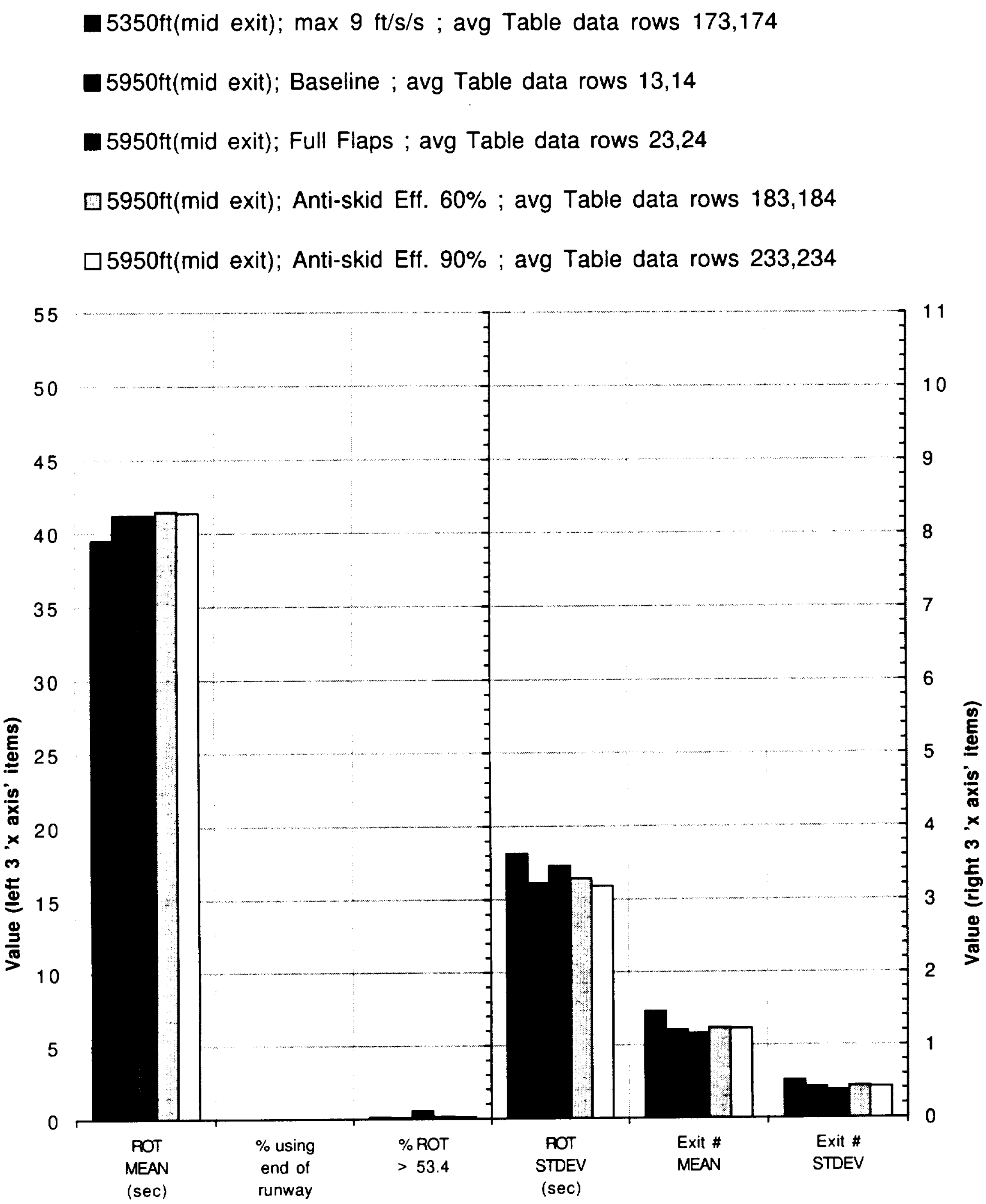
ROT sensitivity to crosswind conditions and lateral touchdown offset
Autoreverse thrust/variable braking
Mid exit location at 5950
Statistics average wet/dry/MD-11/MD-81 dispersions

Figure 6.10



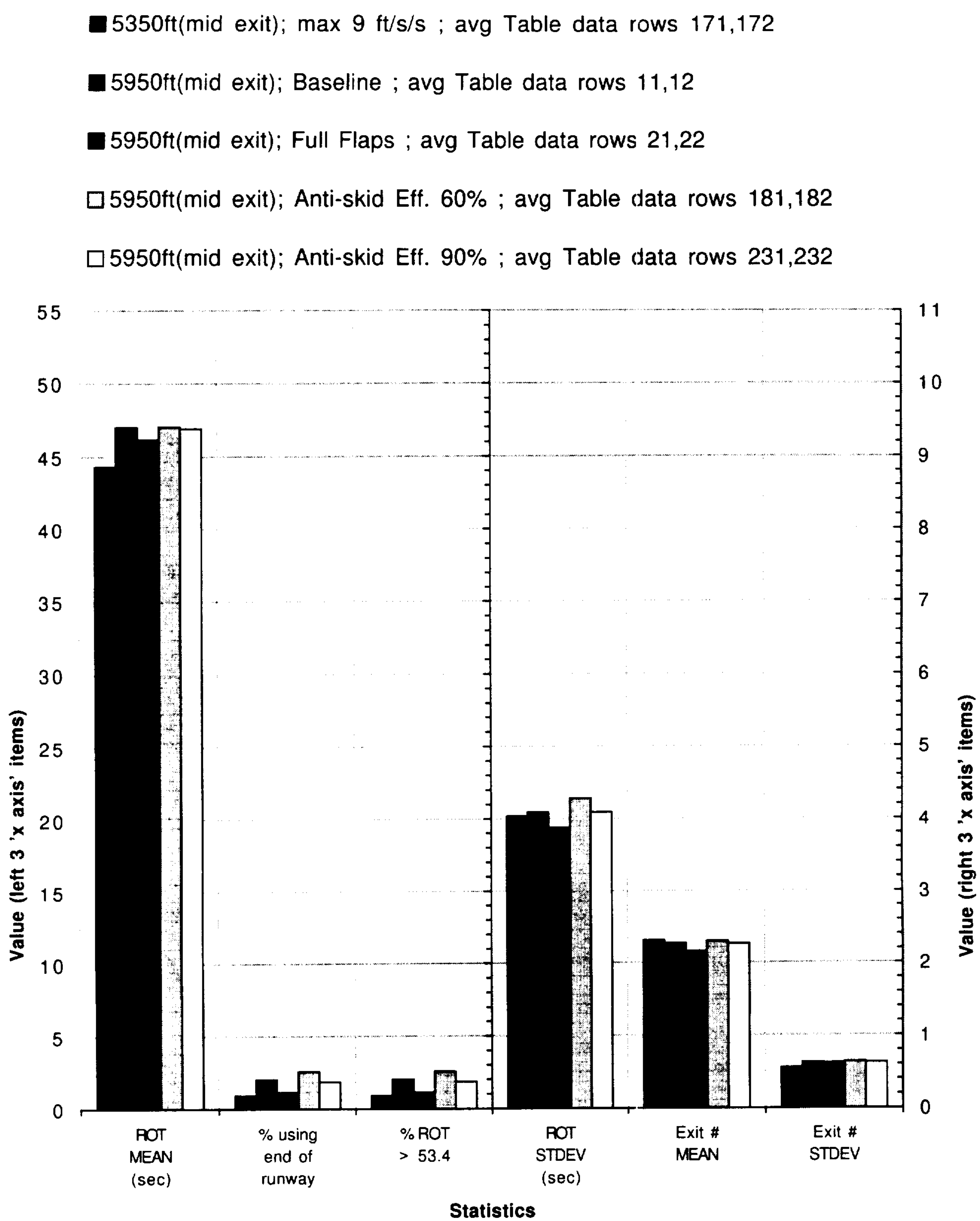
ROT sensitivity to full flaps, anti-skid eff. & max 9ft/s/s decel
Autoreverse thrust/variable braking
Statistics average wet/dry/MD-11/MD-81 dispersions

Figure 6.11a



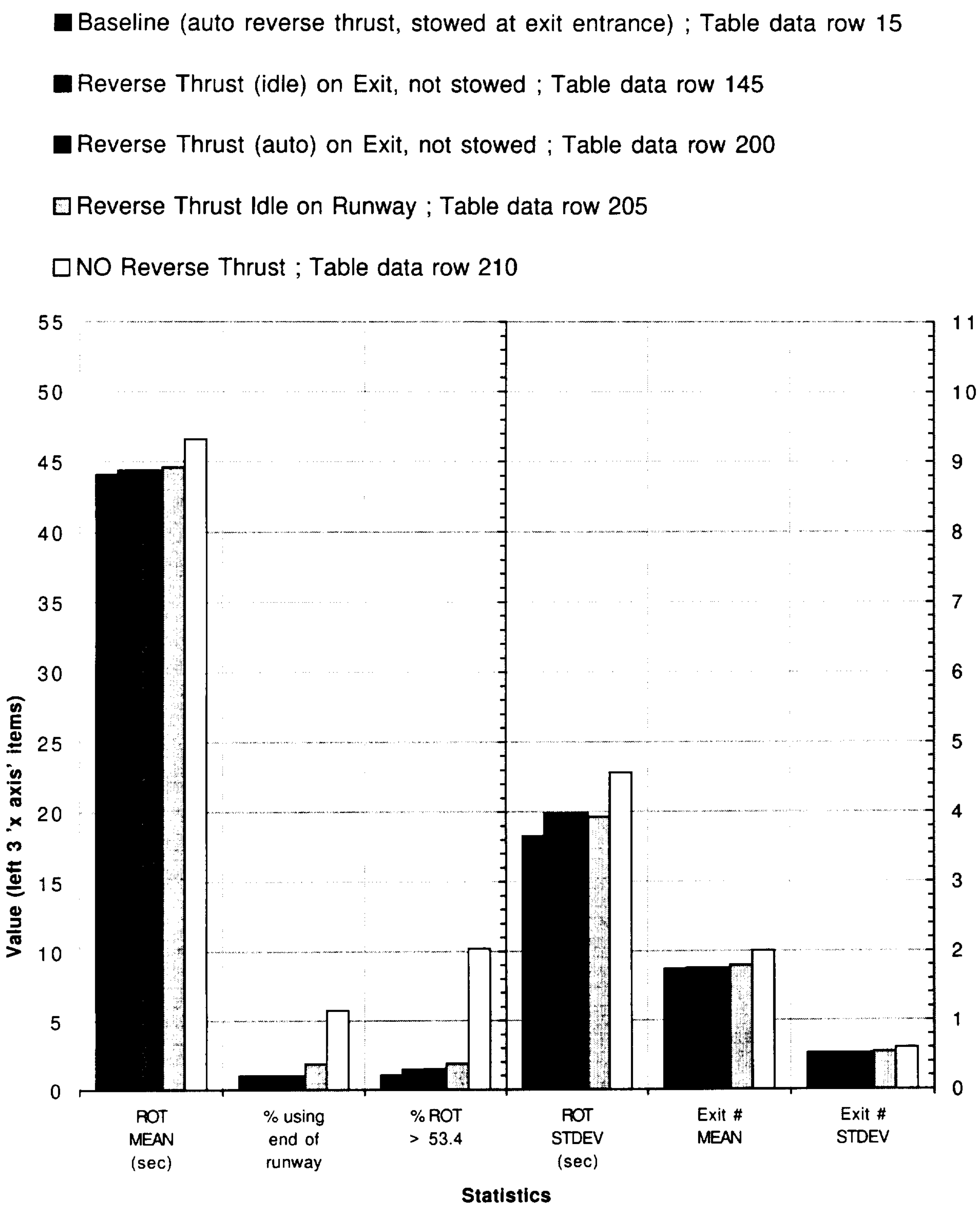
ROT sensitivity to full flaps, anti-skid eff. & max 9ft/s/s decel (MD-81 only)
Autoreverse thrust/variable braking
Statistics average wet/dry/MD-81 dispersions

Figure 6.11b



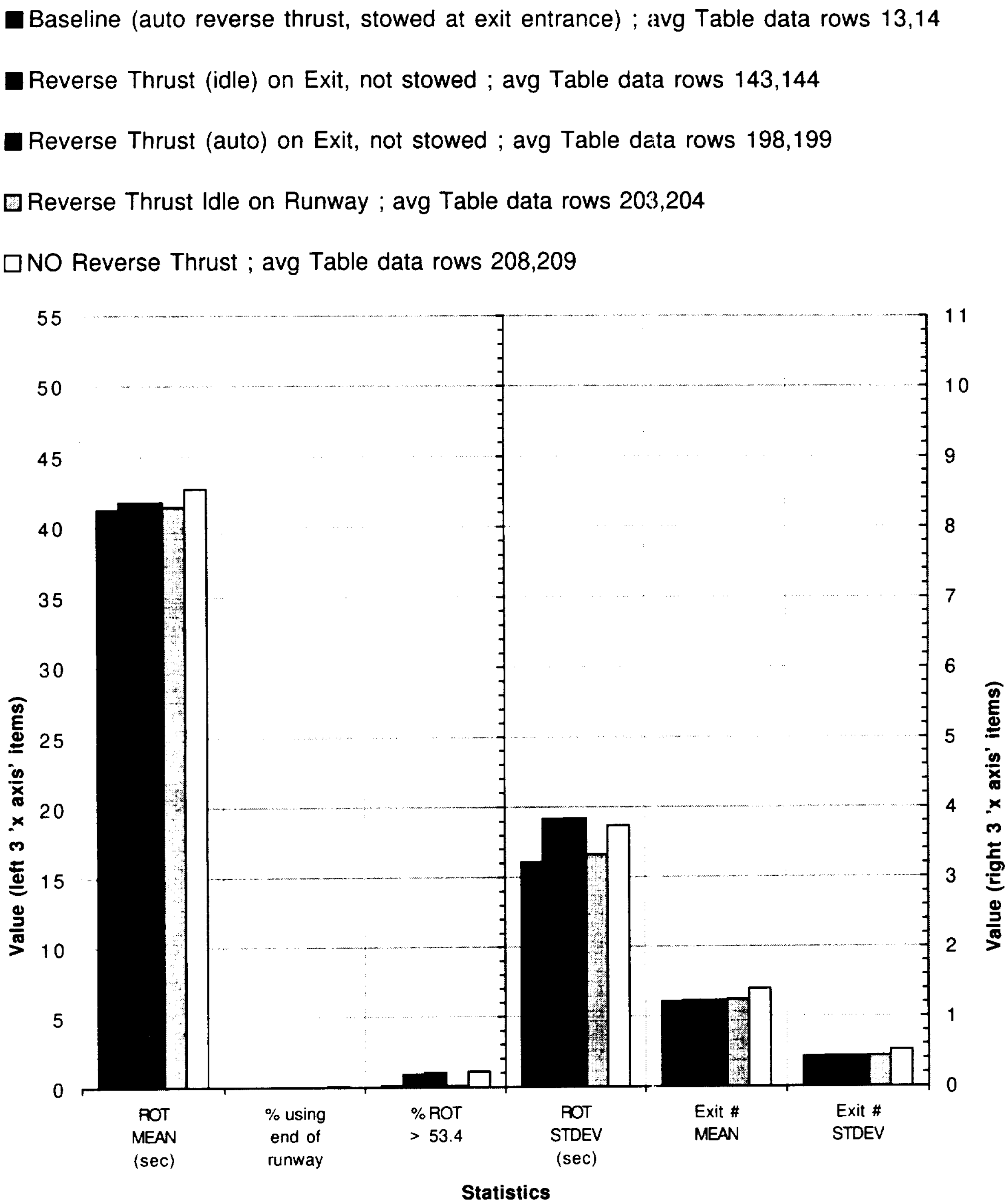
ROT sensitivity to full flaps, anti-skid eff. & max 9ft/s/s decel (MD-11 only)
Autoreverse thrust/variable braking
Statistics average wet/dry/MD-11 dispersions

Figure 6.11c



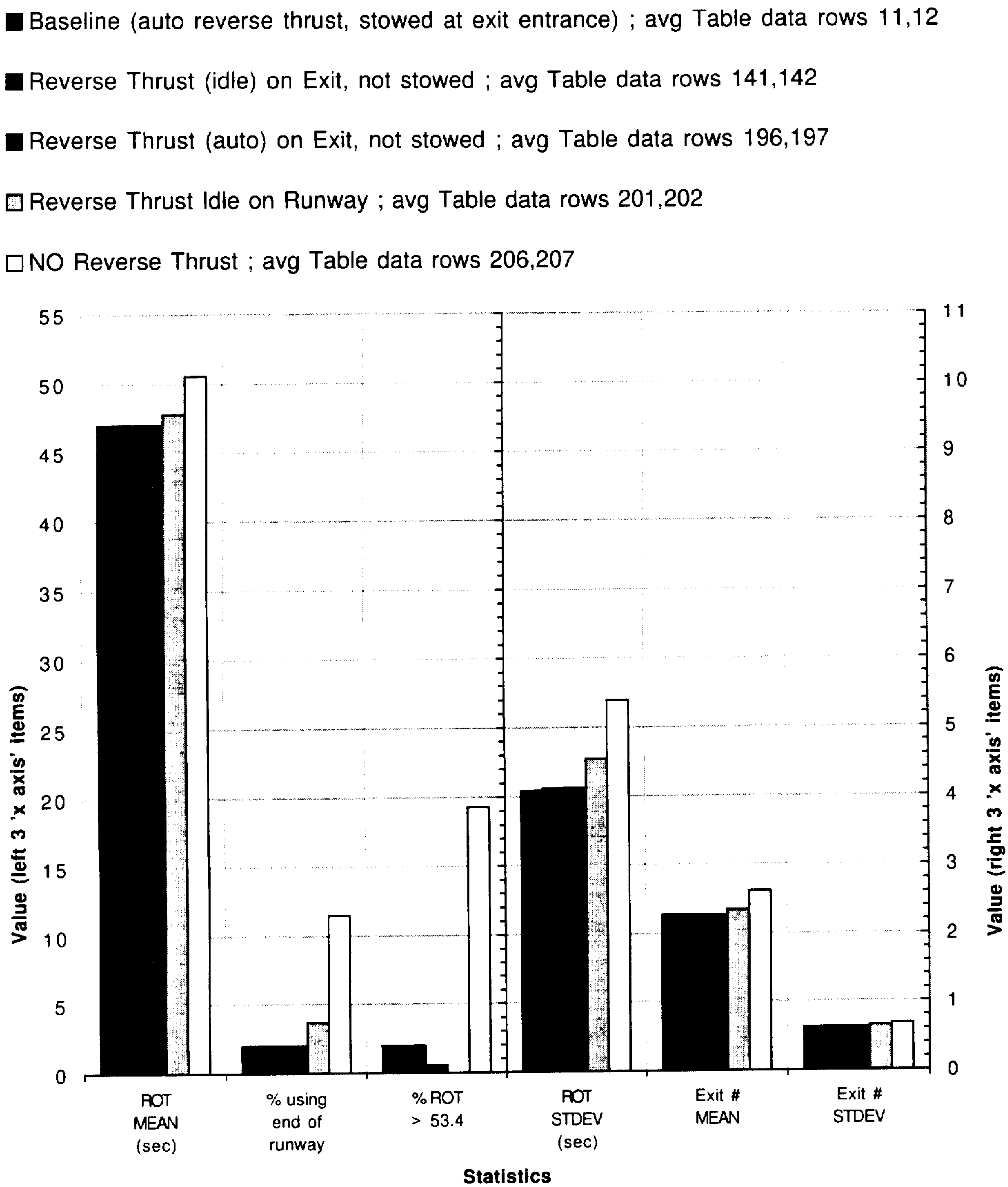
ROT sensitivity to variations of reverse thrust usage on runway and exit
Autoreverse thrust/variable braking
Mid exit location 5950
Statistics average wet/dry/MD-11/MD-81 dispersions

Figure 6.12a



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



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

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

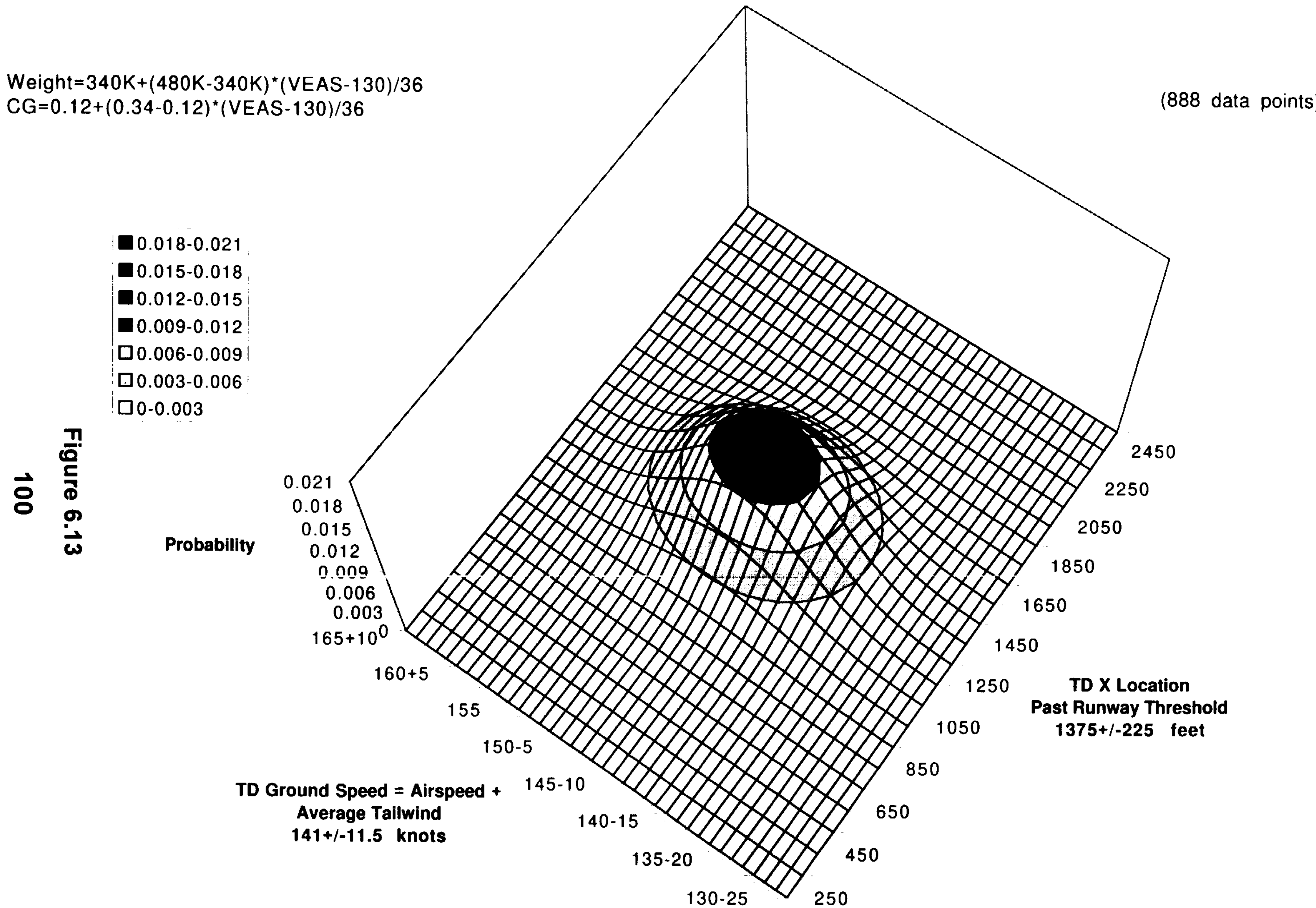


Figure 6.13

MD-81 Joint Probability Distribution based on 2 touchdown independent, normal, random input variables

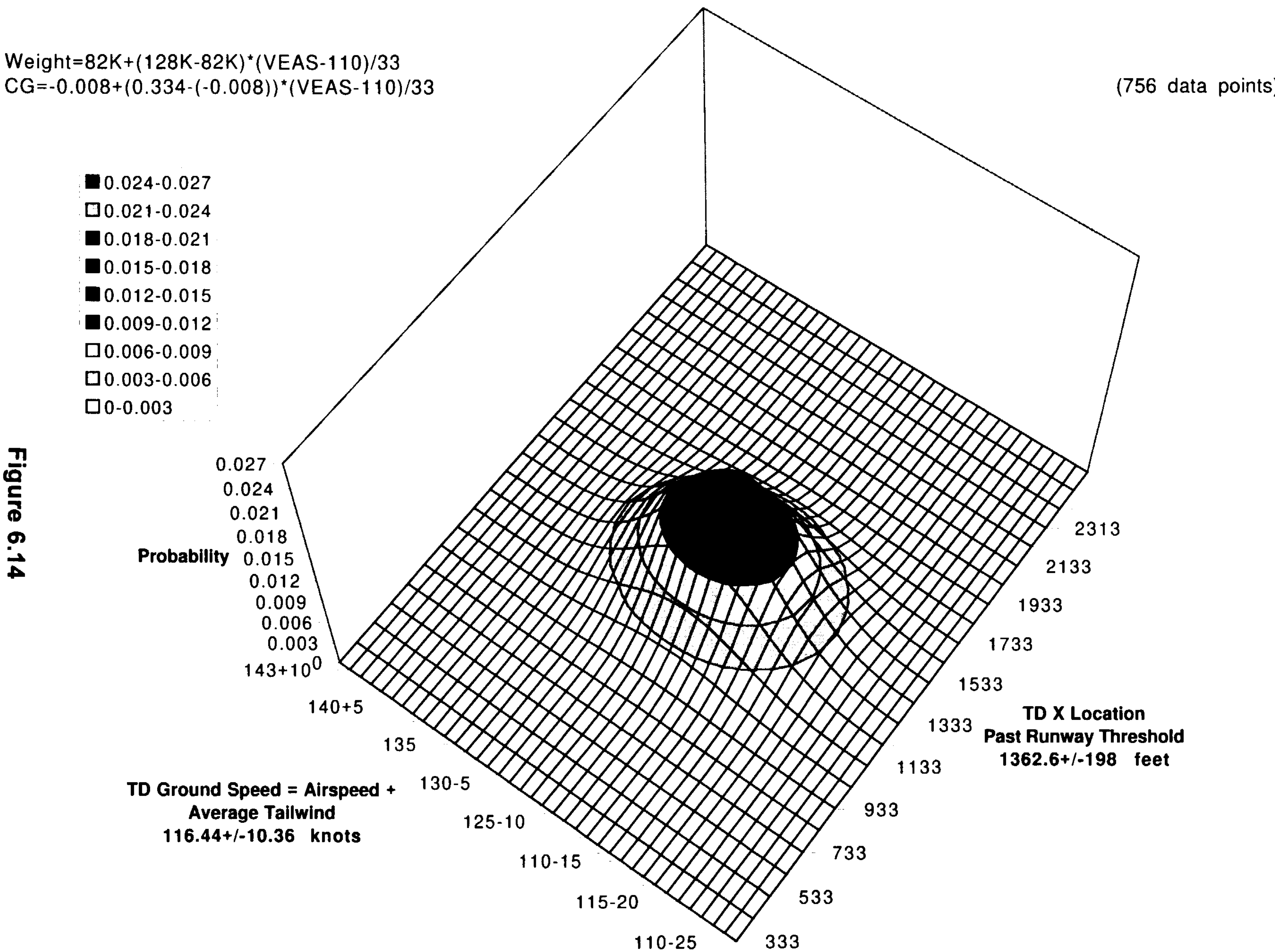


Figure 6.14

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

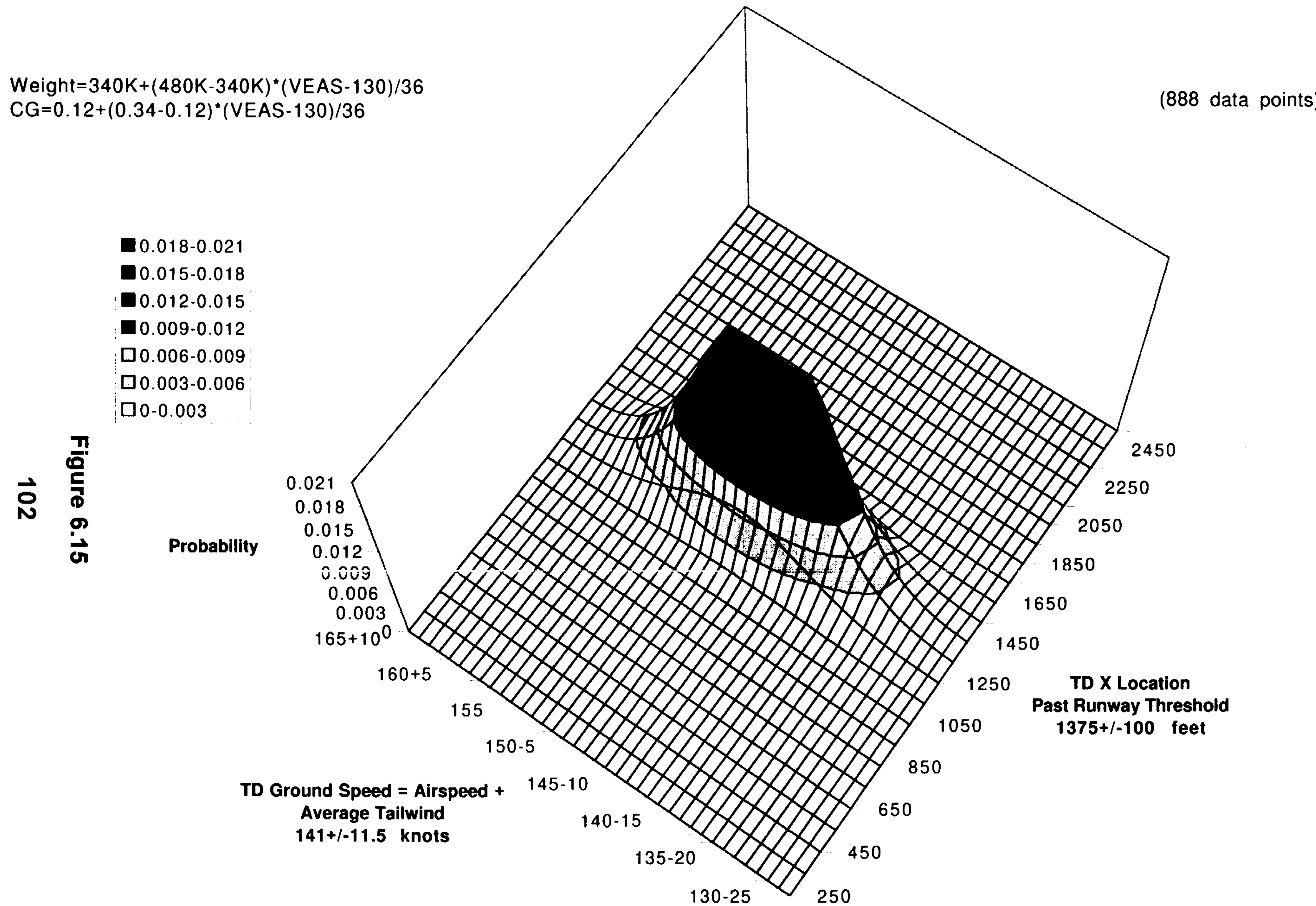


Figure 6.15

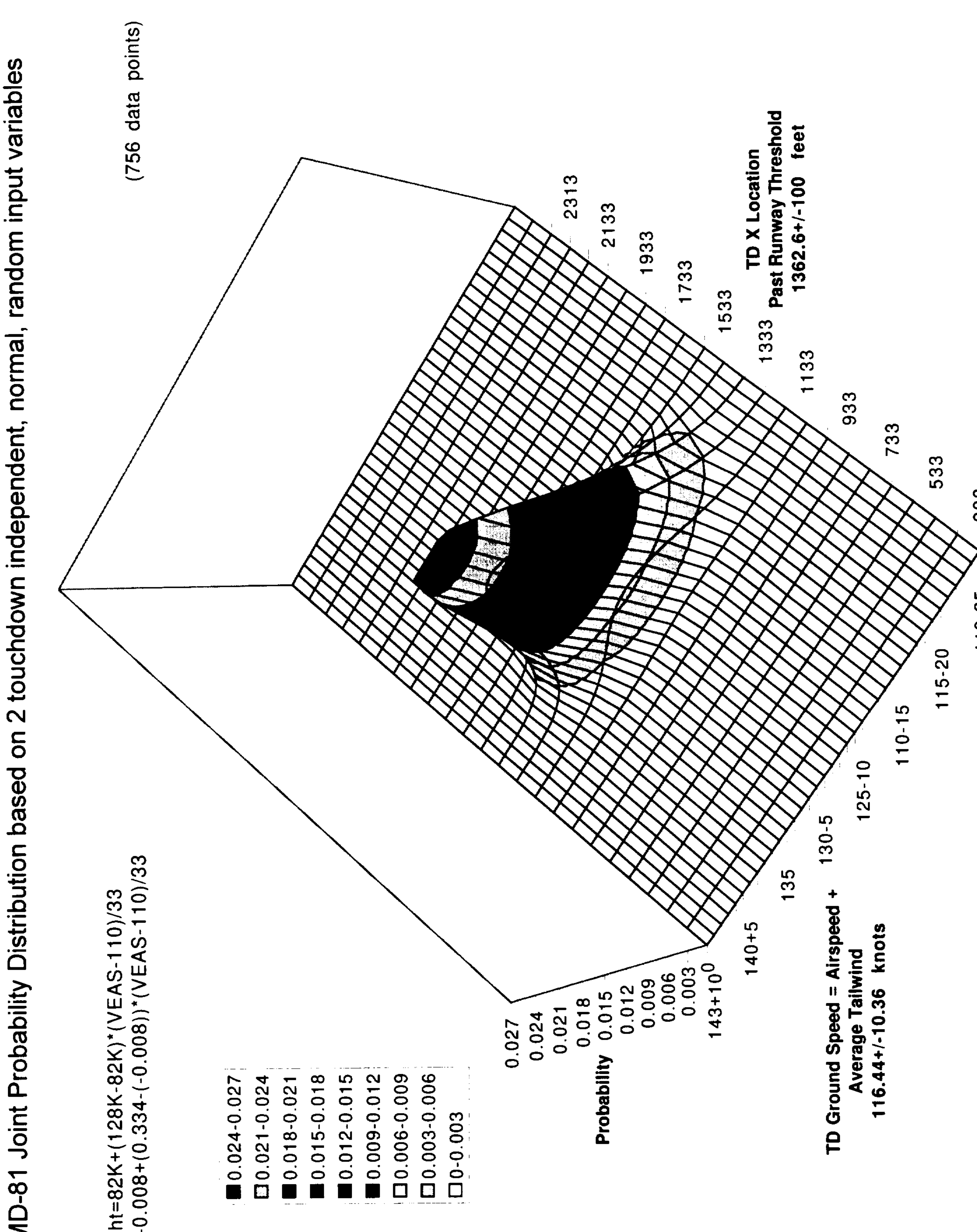

MD-81 Joint Probability Distribution based on 2 touchdown independent, normal, random input variables
(756 data points)
Weight=82K+(128K-82K)*(VEAS-110)/33
CG=-0.008+(0.334-(-0.008))*(VEAS-110)/33
0.024-0.027
0.021-0.024
0.018-0.021
0.015-0.018
0.012-0.015
0.009-0.012
0.006-0.009
0.003-0.006
0-0.003
Probability
0.027
0.024
0.021
0.018
0.015
0.012
0.009
0.006
0.003
0
143+10
140+5
135
130-5
125-10
110-15
115-20
110-25
333
533
733
933
1133
1333
1533
1733
1933
2133
2313
TD Ground Speed = Airspeed + Average Tailwind
116.44+/-10.36 knots
TD X Location Past Runway Threshold
1362.6+/-100 feet

Figure 6.16

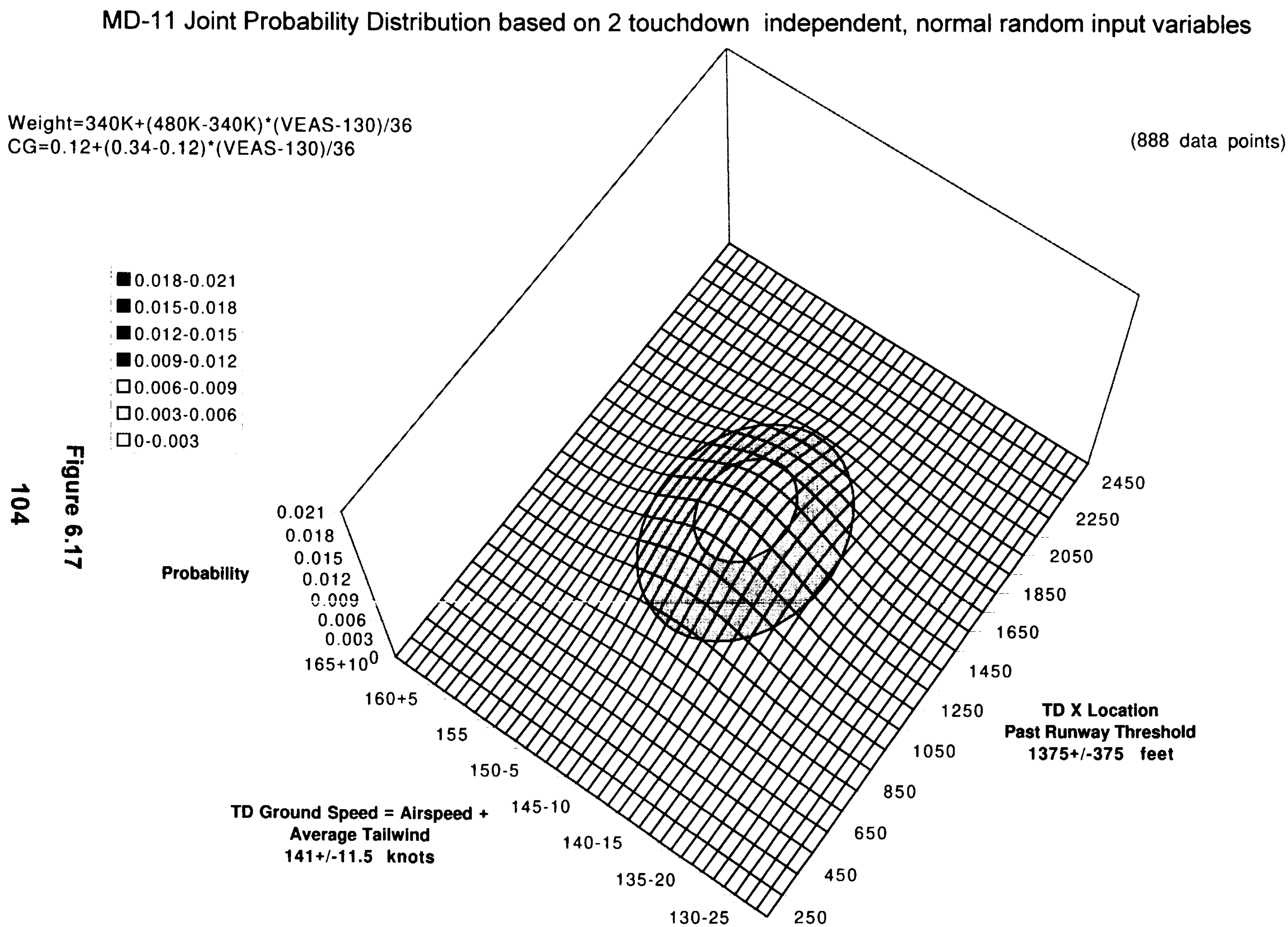
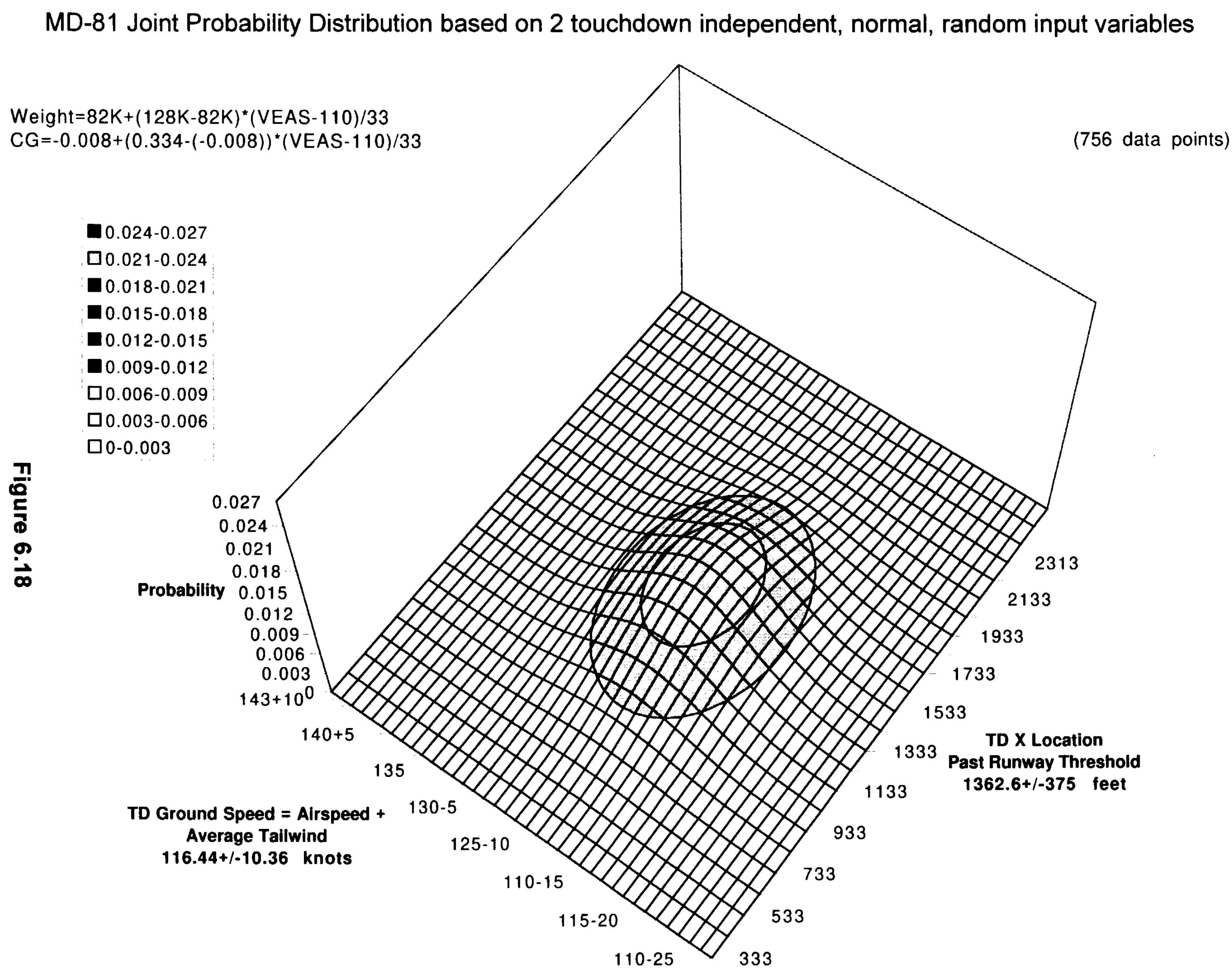

MD-11 Joint Probability Distribution based on 2 touchdown independent, normal random input variables
Weight=340K+(480K-340K)*(VEAS-130)/36
CG=0.12+(0.34-0.12)*(VEAS-130)/36
(888 data points)
0.018-0.021
0.015-0.018
0.012-0.015
0.009-0.012
0.006-0.009
0.003-0.006
0-0.003
Probability
0.021
0.018
0.015
0.012
0.009
0.006
0.003
0
165+10
160+5
155
150-5
145-10
140-15
135-20
130-25
TD Ground Speed = Airspeed + Average Tailwind 141+/-11.5 knots
2450
2250
2050
1850
1650
1450
1250
1050
850
650
450
250
TD X Location Past Runway Threshold 1375+/-375 feet

Figure 6.17



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)
0.024-0.027
0.021-0.024
0.018-0.021
0.015-0.018
0.012-0.015
0.009-0.012
0.006-0.009
0.003-0.006
0-0.003
Probability
0.027
0.024
0.021
0.018
0.015
0.012
0.009
0.006
0.003
0
143+10
140+5
135
130-5
125-10
110-15
115-20
110-25
TD Ground Speed = Airspeed + Average Tailwind
116.44+/-10.36 knots
333
533
733
933
1133
1333
1533
1733
1933
2133
2313
TD X Location Past Runway Threshold
1362.6+/-375 feet

Figure 6.18

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

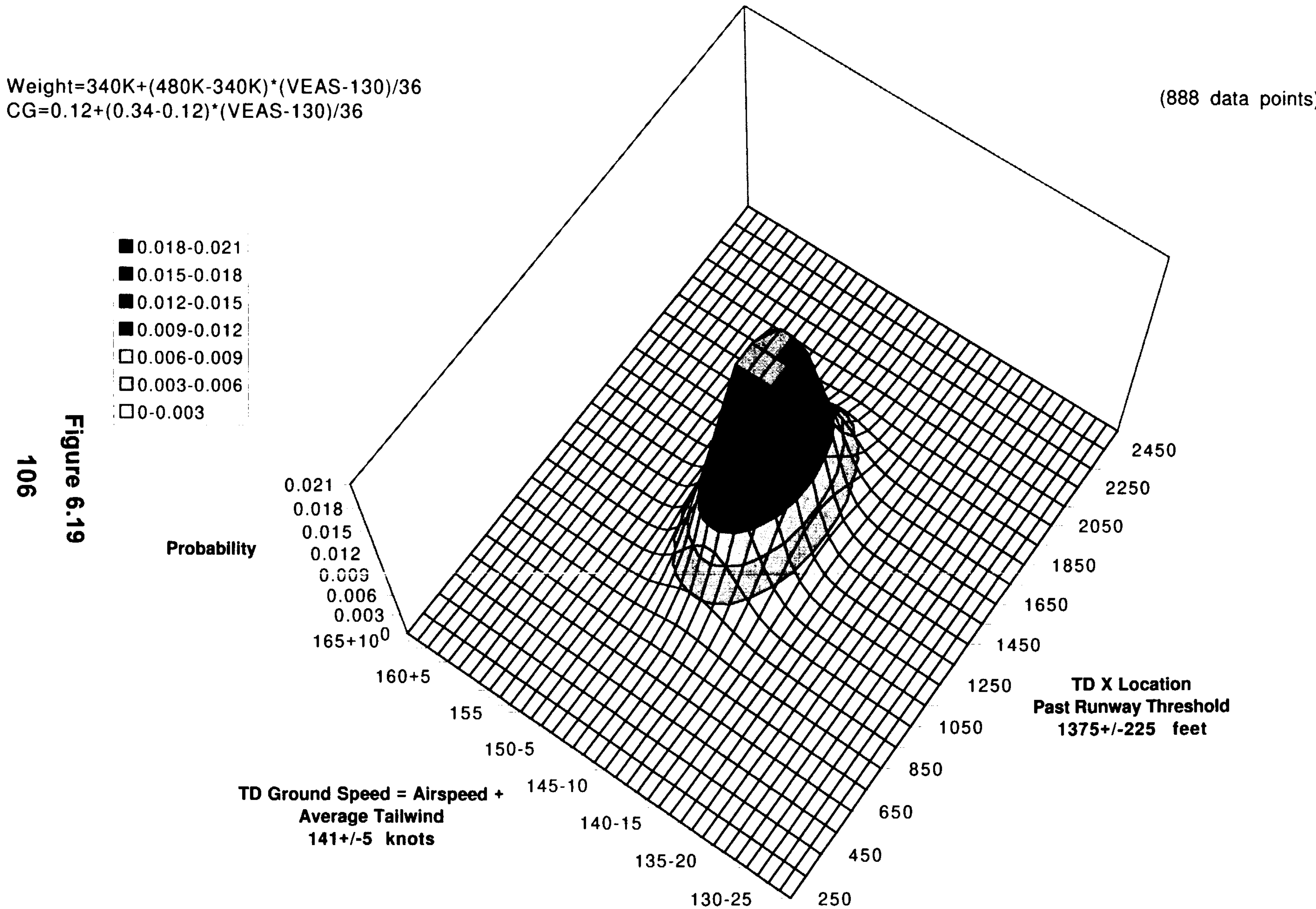


Figure 6.19

MD-81 Joint Probability Distribution based on 2 touchdown independent, normal, random input variables

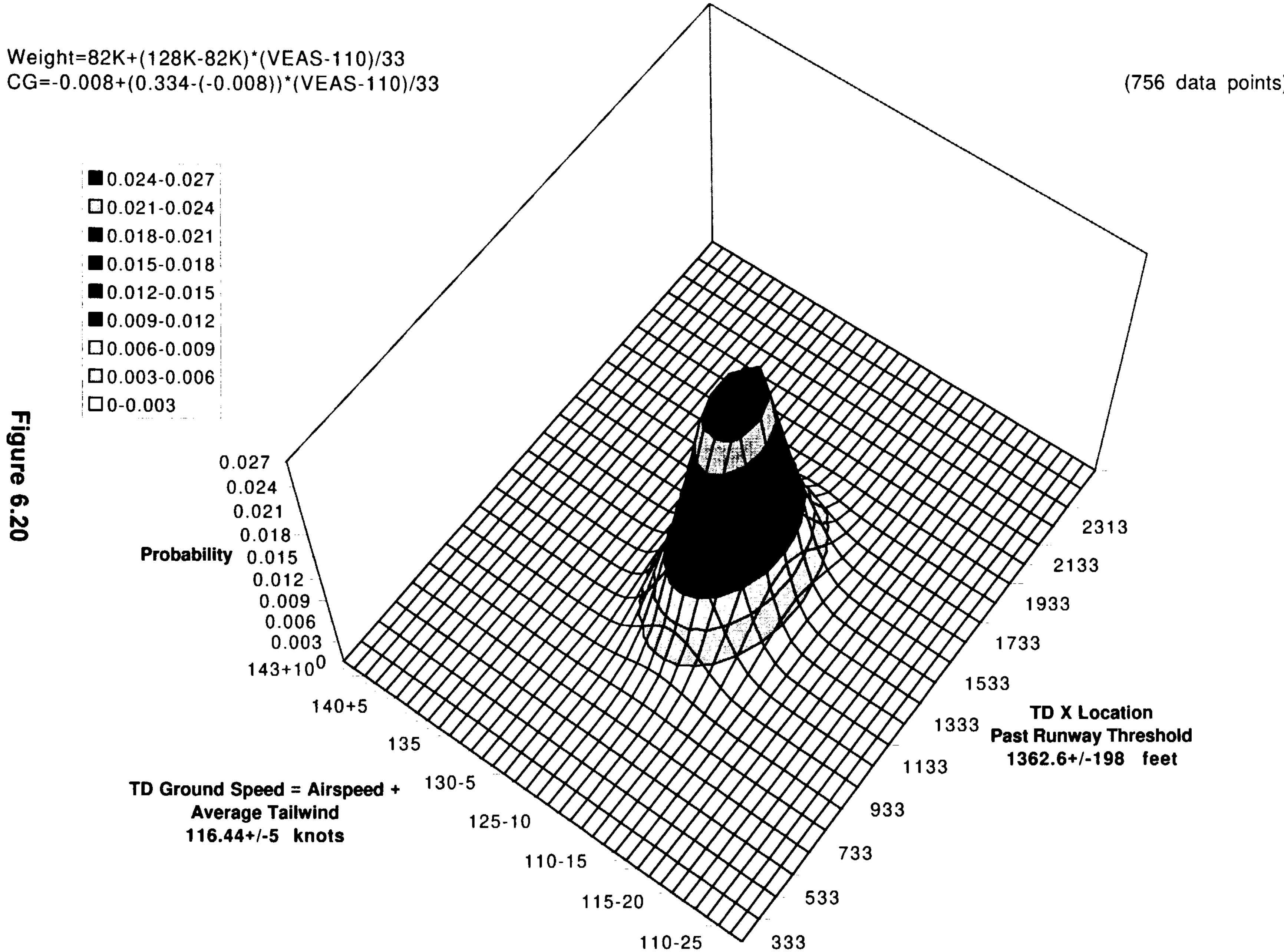


Figure 6.20

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

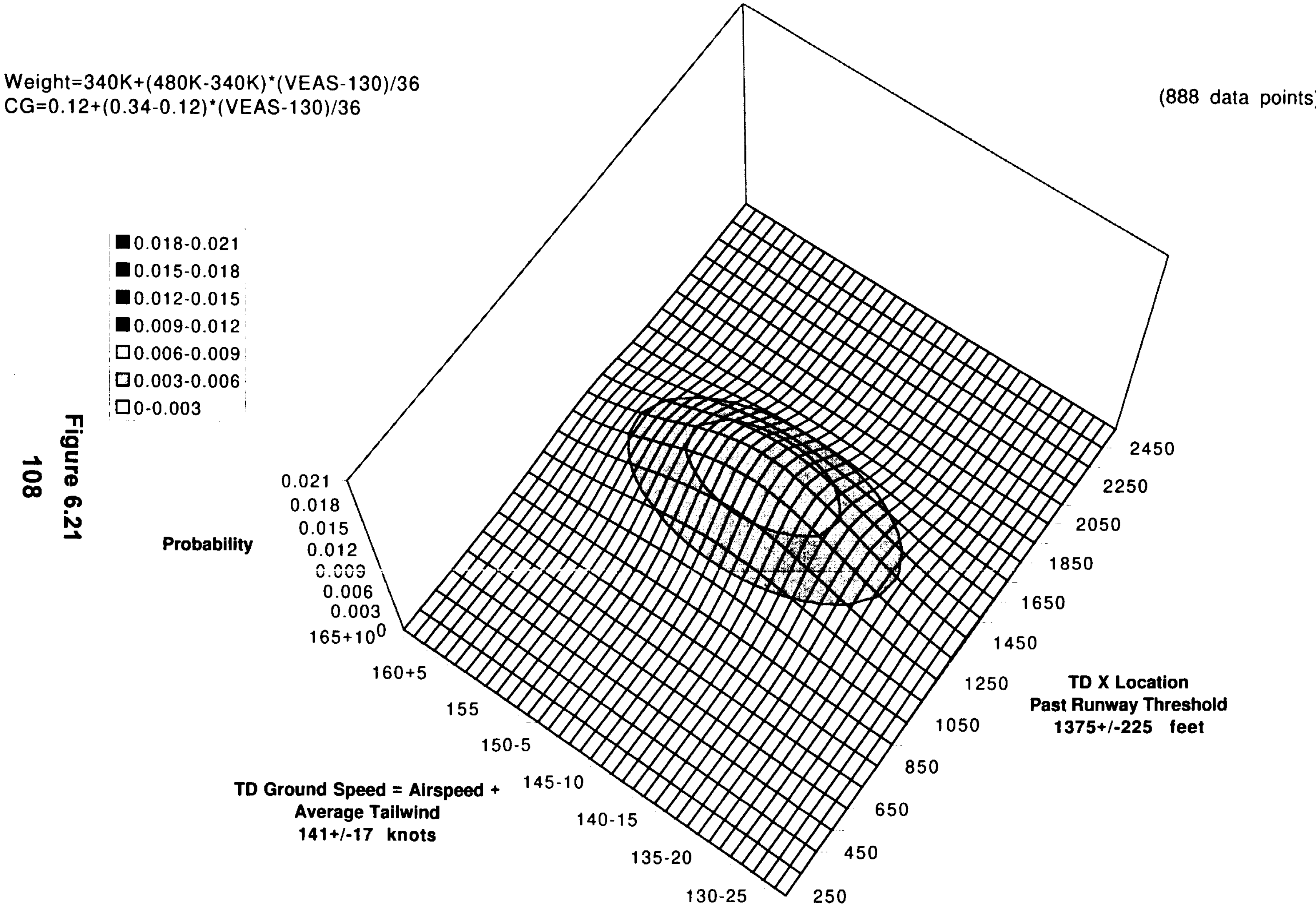


Figure 6.21

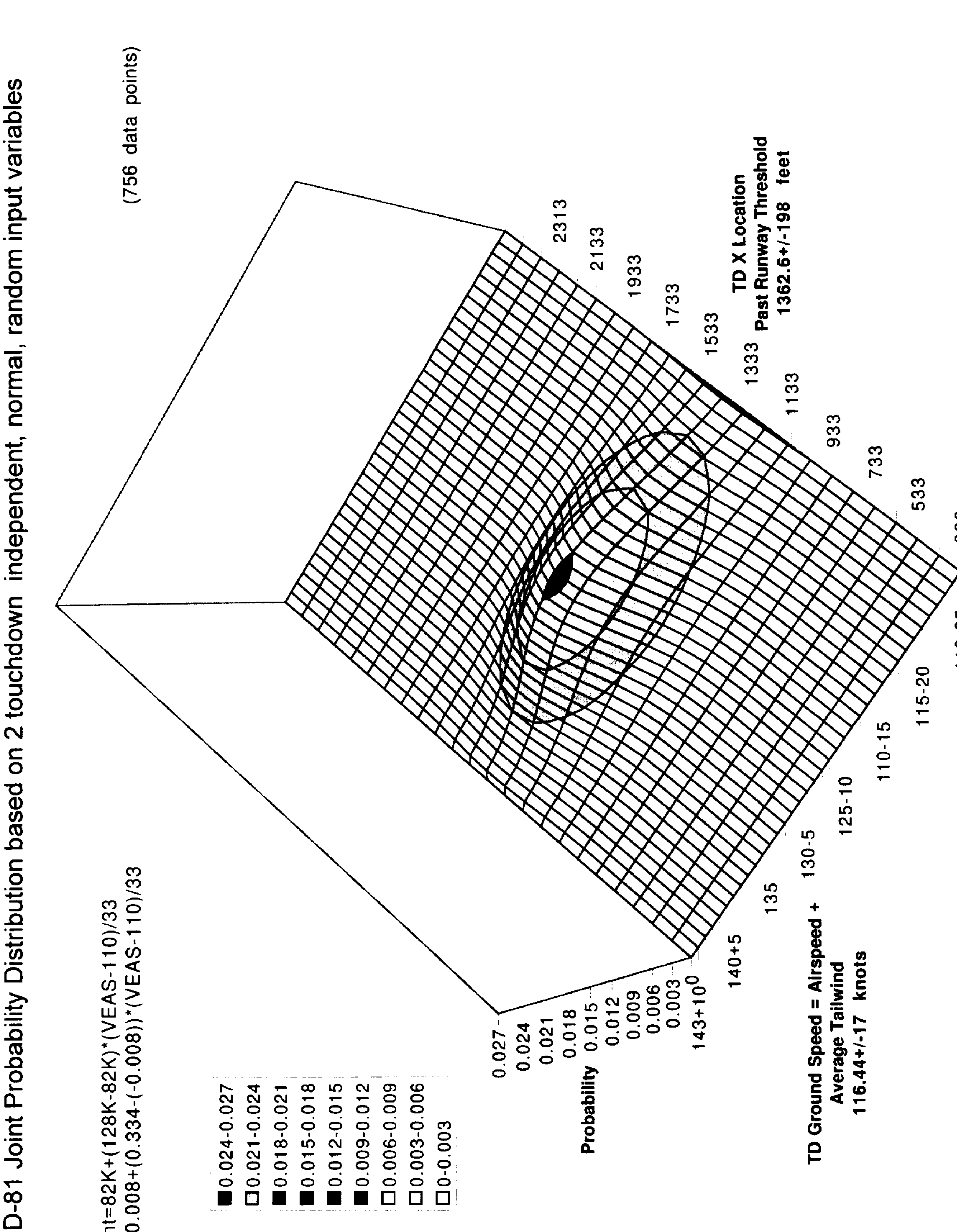

MD-81 Joint Probability Distribution based on 2 touchdown independent, normal, random input variables
(756 data points)
Weight=82K+(128K-82K)*(VEAS-110)/33
CG=-0.008+(0.334-(-0.008))*(VEAS-110)/33
0.024-0.027
0.021-0.024
0.018-0.021
0.015-0.018
0.012-0.015
0.009-0.012
0.006-0.009
0.003-0.006
0-0.003
Probability
0.027
0.024
0.021
0.018
0.015
0.012
0.009
0.006
0.003
0
143+10
140+5
135
130-5
125-10
110-15
115-20
110-25
333
533
733
933
1133
1333
1533
1733
1933
2133
2313
TD Ground Speed = Airspeed + Average Tailwind 116.44+/-17 knots
TD X Location Past Runway Threshold 1362.6+/-198 feet

Figure 6.22

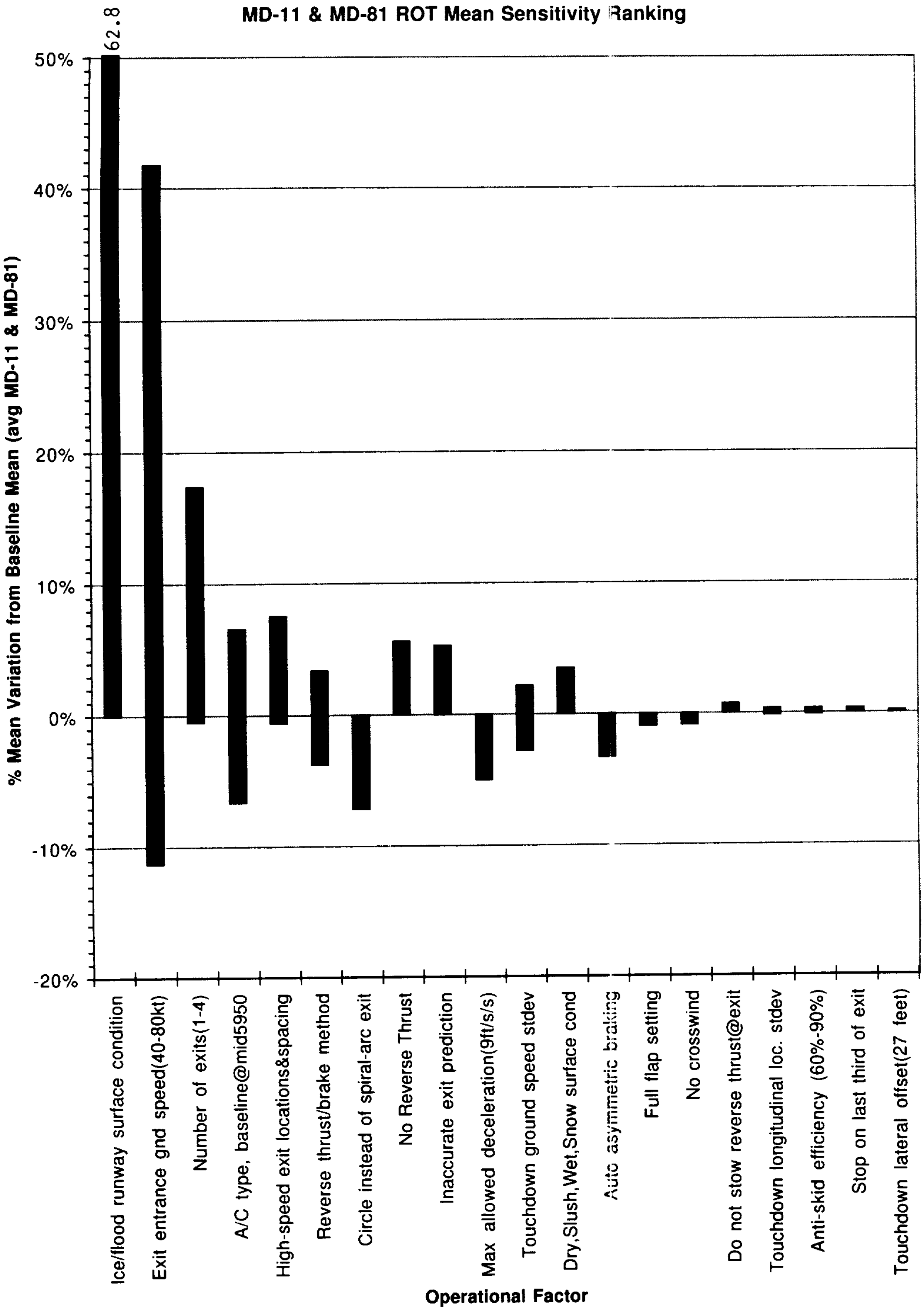

MD-11 & MD-81 ROT Mean Sensitivity Ranking
62.8
50%
40%
30%
20%
10%
0%
-10%
-20%
% Mean Variation from Baseline Mean (avg MD-11 & MD-81)
Ice/flood runway surface condition
Exit entrance gnd speed(40-80kt)
Number of exits(1-4)
A/C type, baseline@mid5950
High-speed exit locations&spacing
Reverse thrust/brake method
Circle instead of spiral-arc exit
No Reverse Thrust
Inaccurate exit prediction
Max allowed deceleration(9ft/s/s)
Touchdown ground speed stdev
Dry,Slush,Wet,Snow surface cond
Auto asymmetric braking
Full flap setting
No crosswind
Do not stow reverse thrust@exit
Touchdown longitudinal loc. stdev
Anti-skid efficiency (60%-90%)
Stop on last third of exit
Touchdown lateral offset(27 feet)
Operational Factor

Figure 7.1a

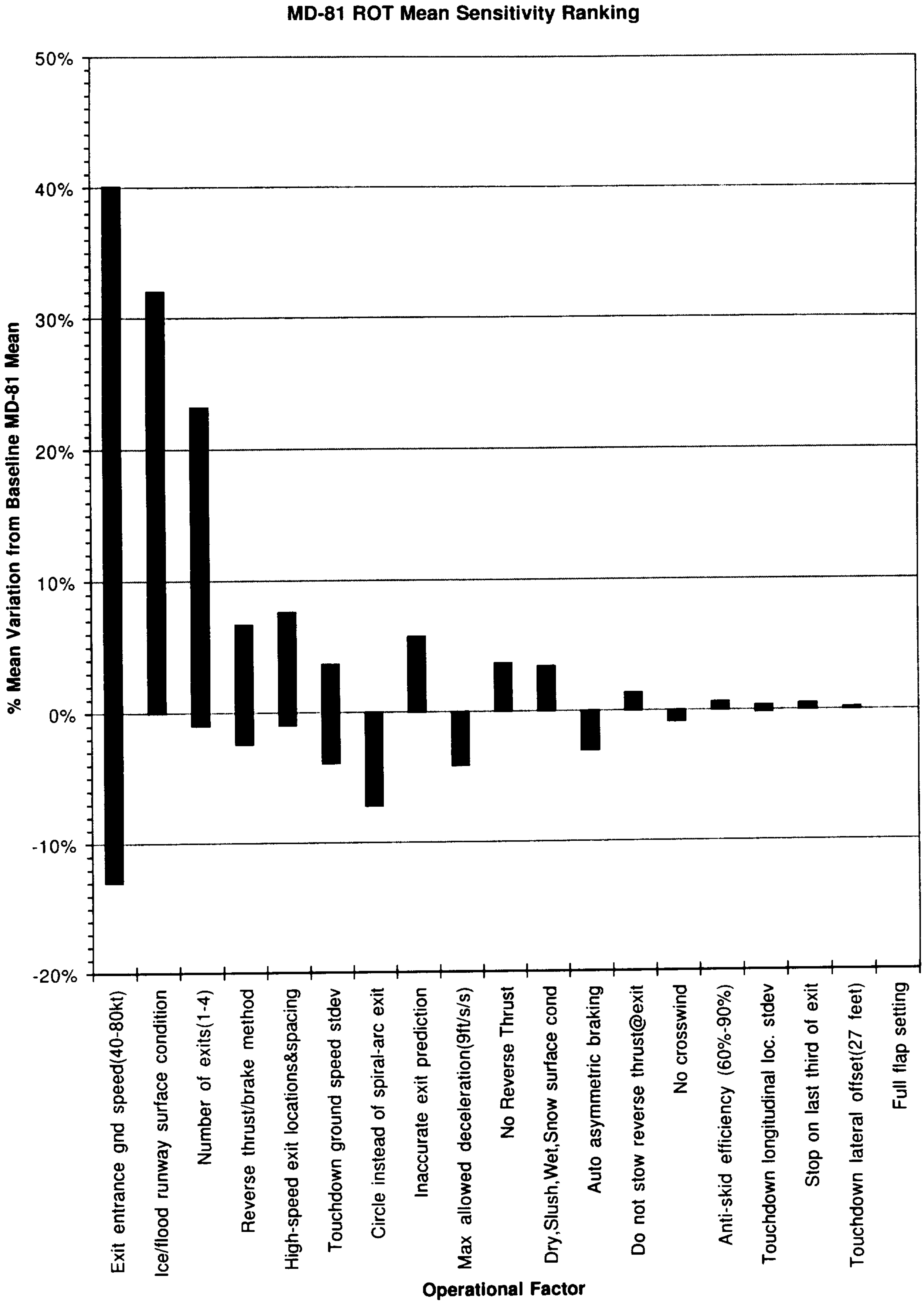
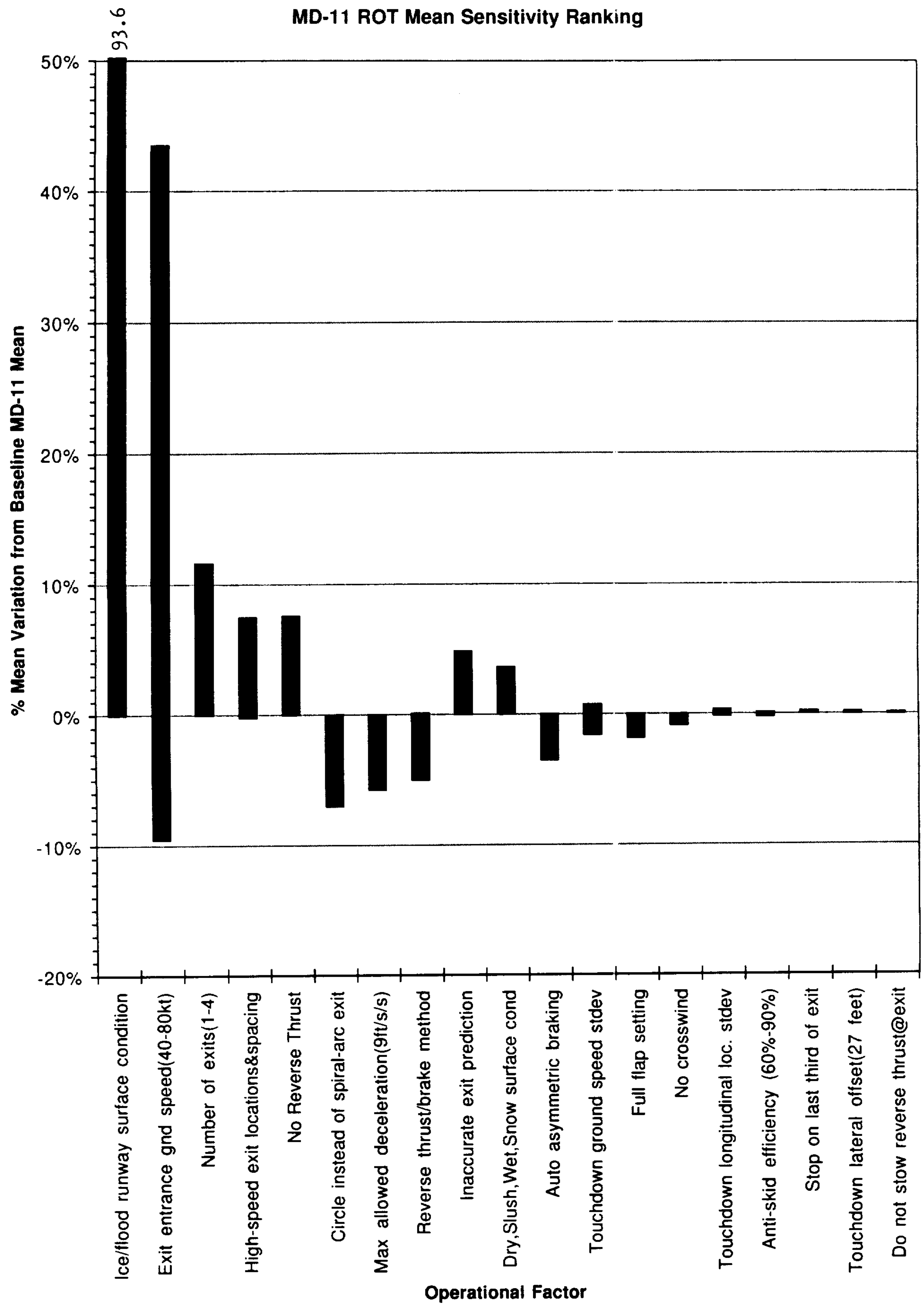

MD-81 ROT Mean Sensitivity Ranking
50%
40%
30%
20%
10%
0%
-10%
-20%
% Mean Variation from Baseline MD-81 Mean
Exit entrance gnd speed(40-80kt)
Ice/flood runway surface condition
Number of exits(1-4)
Reverse thrust/brake method
High-speed exit locations&spacing
Touchdown ground speed stdev
Circle instead of spiral-arc exit
Inaccurate exit prediction
Max allowed deceleration(9ft/s/s)
No Reverse Thrust
Dry,Slush,Wet,Snow surface cond
Auto asymmetric braking
Do not stow reverse thrust@exit
No crosswind
Anti-skid efficiency (60%-90%)
Touchdown longitudinal loc. stdev
Stop on last third of exit
Touchdown lateral offset(27 feet)
Full flap setting
Operational Factor

Figure 7.1b



MD-11 ROT Mean Sensitivity Ranking
93.6
50%
40%
30%
20%
10%
0%
-10%
-20%
% Mean Variation from Baseline MD-11 Mean
Ice/flood runway surface condition
Exit entrance gnd speed(40-80kt)
Number of exits(1-4)
High-speed exit locations&spacing
No Reverse Thrust
Circle instead of spiral-arc exit
Max allowed deceleration(9ft/s/s)
Reverse thrust/brake method
Inaccurate exit prediction
Dry,Slush,Wet,Snow surface cond
Auto asymmetric braking
Touchdown ground speed stdev
Full flap setting
No crosswind
Touchdown longitudinal loc. stdev
Anti-skid efficiency (60%-90%)
Stop on last third of exit
Touchdown lateral offset(27 feet)
Do not stow reverse thrust@exit
Operational Factor

Figure 7.1c

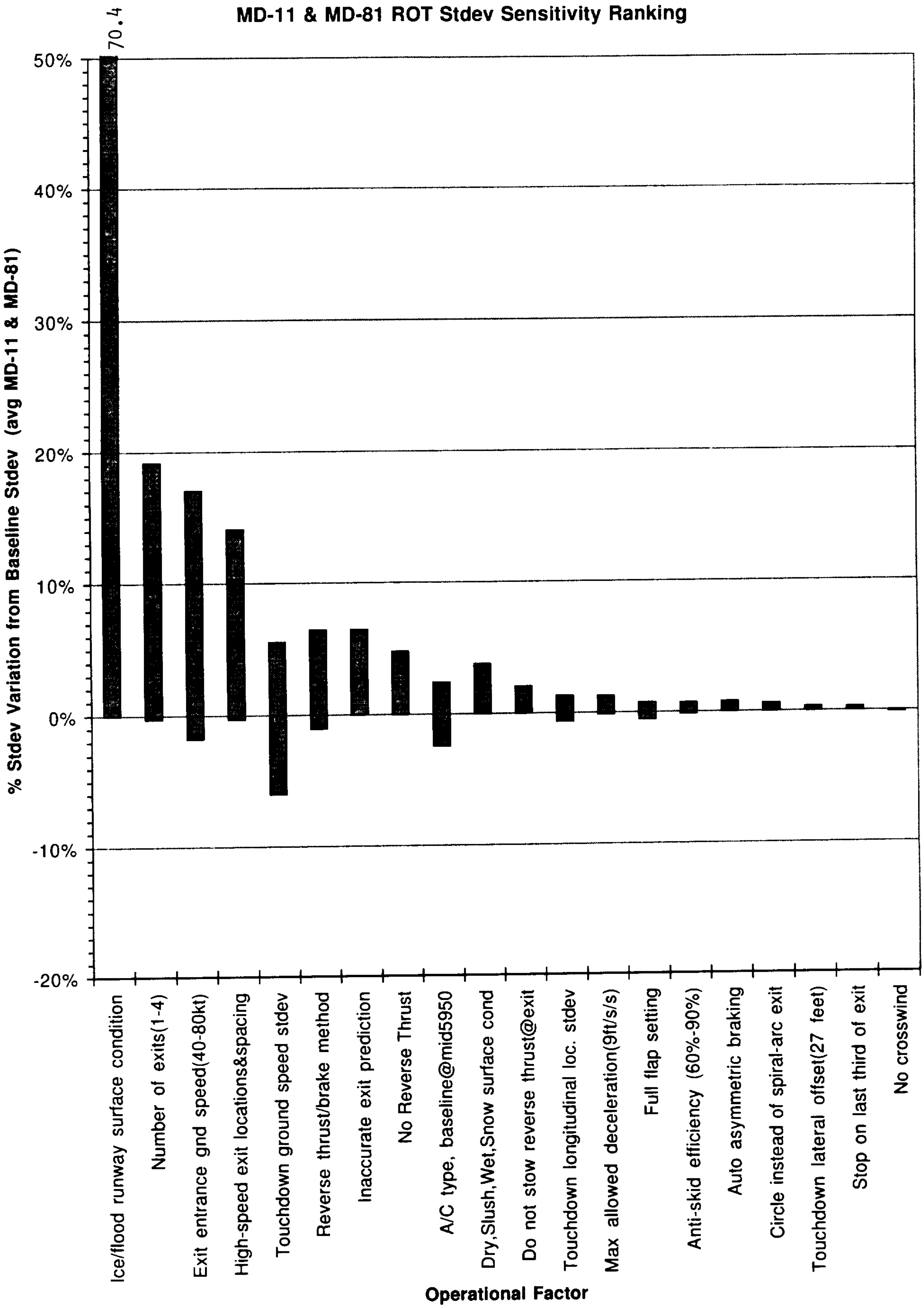
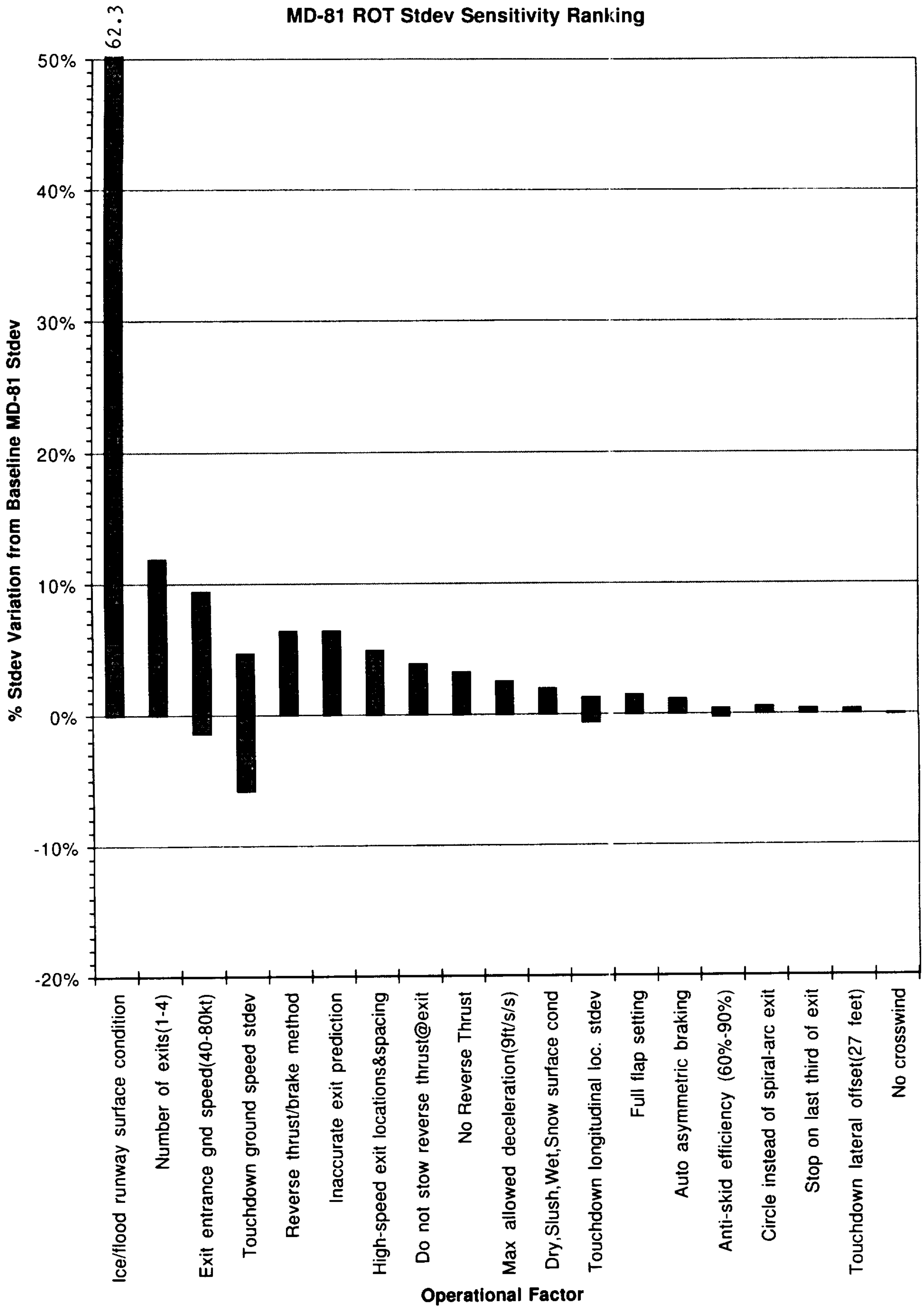
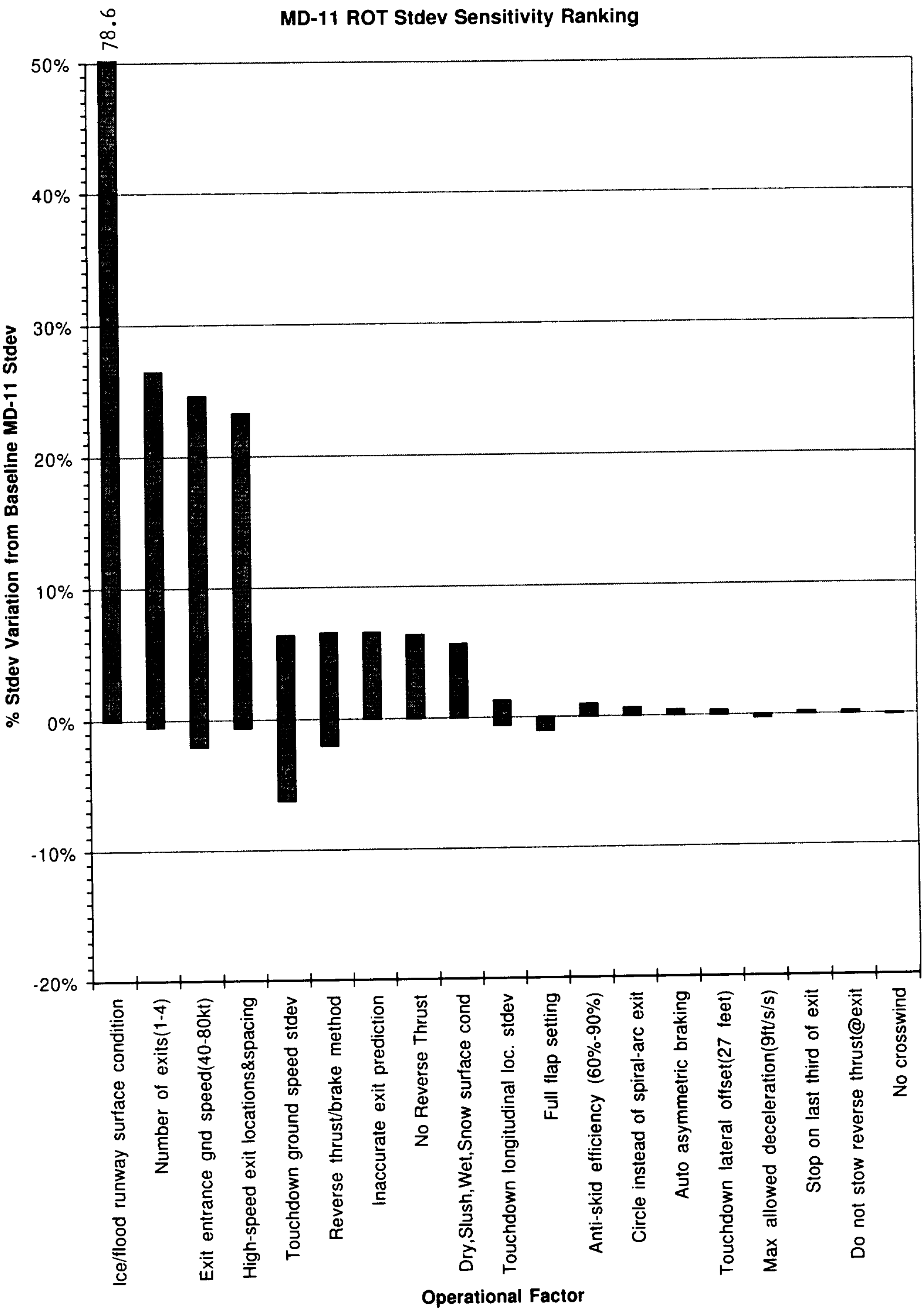

MD-11 & MD-81 ROT Stdev Sensitivity Ranking
70.4
50%
40%
30%
20%
10%
0%
-10%
-20%
% Stdev Variation from Baseline Stdev (avg MD-11 & MD-81)
Ice/flood runway surface condition
Number of exits(1-4)
Exit entrance gnd speed(40-80kt)
High-speed exit locations&spacing
Touchdown ground speed stdev
Reverse thrust/brake method
Inaccurate exit prediction
No Reverse Thrust
A/C type, baseline@mid5950
Dry,Slush,Wet,Snow surface cond
Do not stow reverse thrust@exit
Touchdown longitudinal loc. stdev
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
Operational Factor

Figure 7.2a



MD-81 ROT Stdev Sensitivity Ranking
62.3
50%
40%
30%
20%
10%
0%
-10%
-20%
% Stdev Variation from Baseline MD-81 Stdev
Ice/flood runway surface condition
Number of exits(1-4)
Exit entrance gnd speed(40-80kt)
Touchdown ground speed stdev
Reverse thrust/brake method
Inaccurate exit prediction
High-speed exit locations&spacing
Do not stow reverse thrust@exit
No Reverse Thrust
Max allowed deceleration(9ft/s/s)
Dry,Slush,Wet,Snow surface cond
Touchdown longitudinal loc. stdev
Full flap setting
Auto asymmetric braking
Anti-skid efficiency (60%-90%)
Circle instead of spiral-arc exit
Stop on last third of exit
Touchdown lateral offset(27 feet)
No crosswind
Operational Factor

Figure 7.2b



MD-11 ROT Stdev Sensitivity Ranking
78.6
50%
40%
30%
20%
10%
0%
-10%
-20%
% 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
Operational Factor

Figure 7.2c

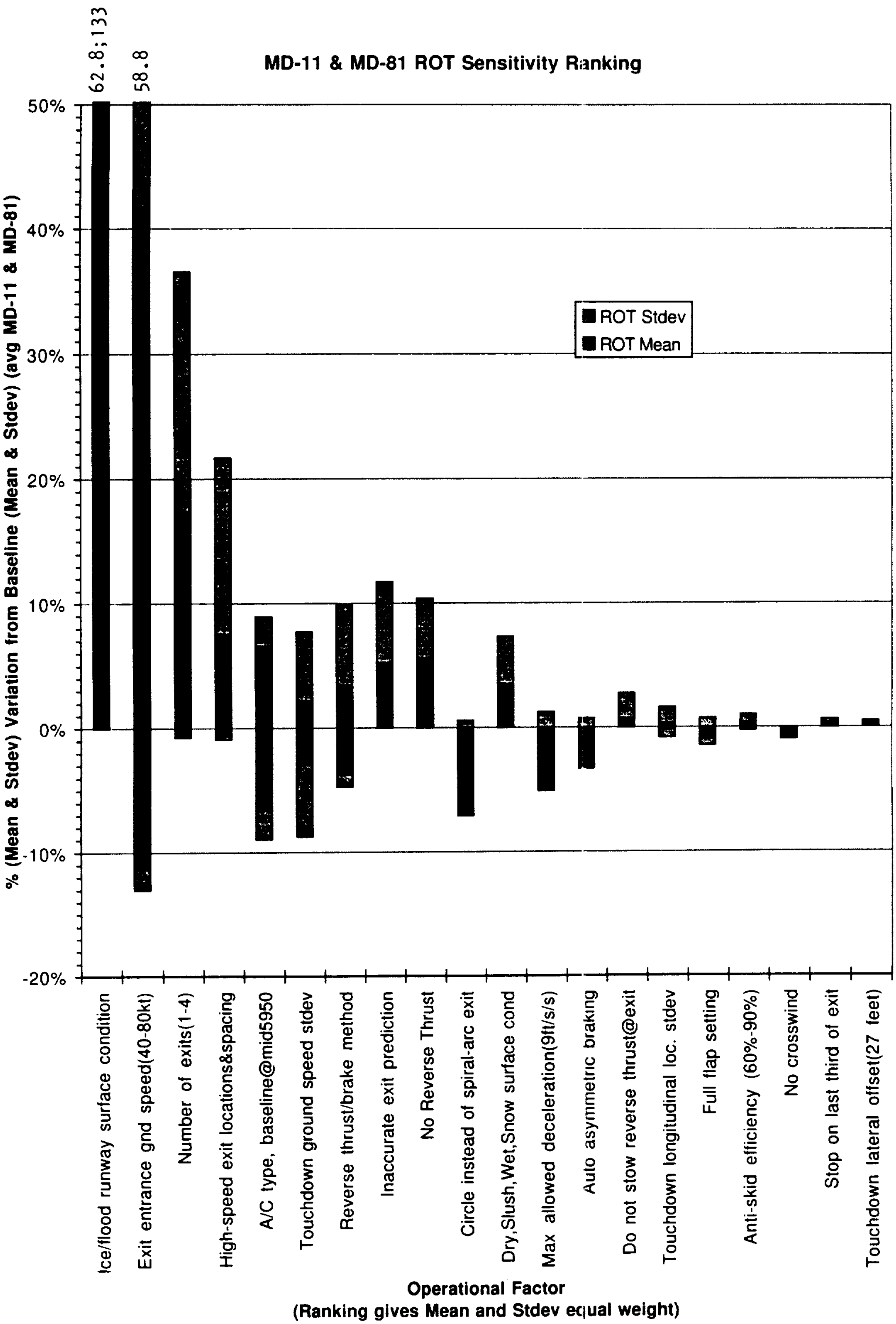
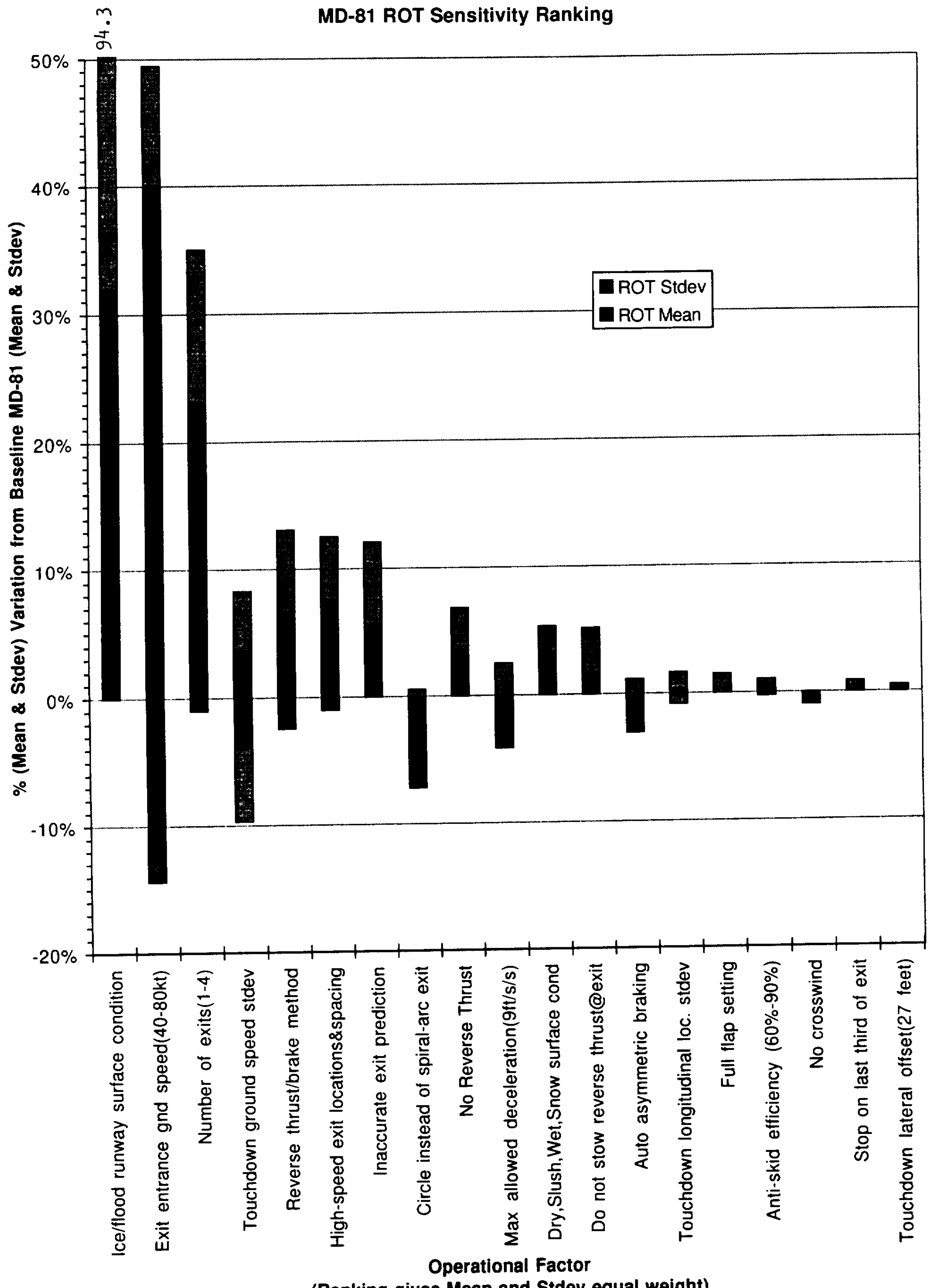

MD-11 & MD-81 ROT Sensitivity Ranking
62.8;133
58.8
50%
40%
30%
20%
10%
0%
-10%
-20%
% (Mean & Stdev) Variation from Baseline (Mean & Stdev) (avg MD-11 & MD-81)
ROT Stdev
ROT Mean
Ice/flood runway surface condition
Exit entrance gnd speed(40-80kt)
Number of exits(1-4)
High-speed exit locations&spacing
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)
Operational Factor
(Ranking gives Mean and Stdev equal weight)

Figure 7.3a



MD-81 ROT Sensitivity Ranking
94.3
50%
40%
30%
20%
10%
0%
-10%
-20%
% (Mean & Stdev) Variation from Baseline MD-81 (Mean & Stdev)
ROT Stdev
ROT Mean
Ice/flood runway surface condition
Exit entrance gnd speed(40-80kt)
Number of exits(1-4)
Touchdown ground speed stdev
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. stdev
Full flap setting
Anti-skid efficiency (60%-90%)
No crosswind
Stop on last third of exit
Touchdown lateral offset(27 feet)
Operational Factor
(Ranking gives Mean and Stdev equal weight)

Figure 7.3b

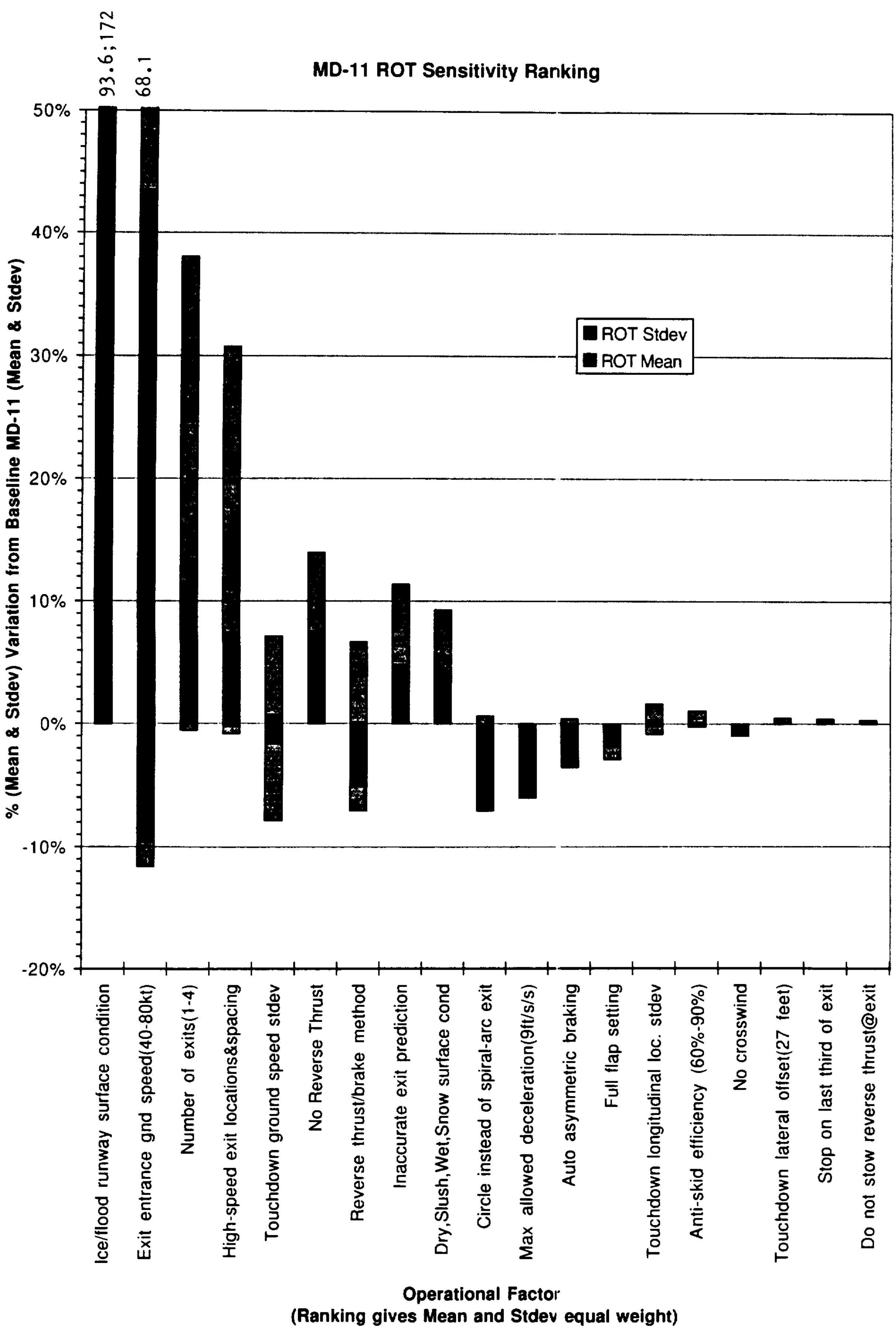
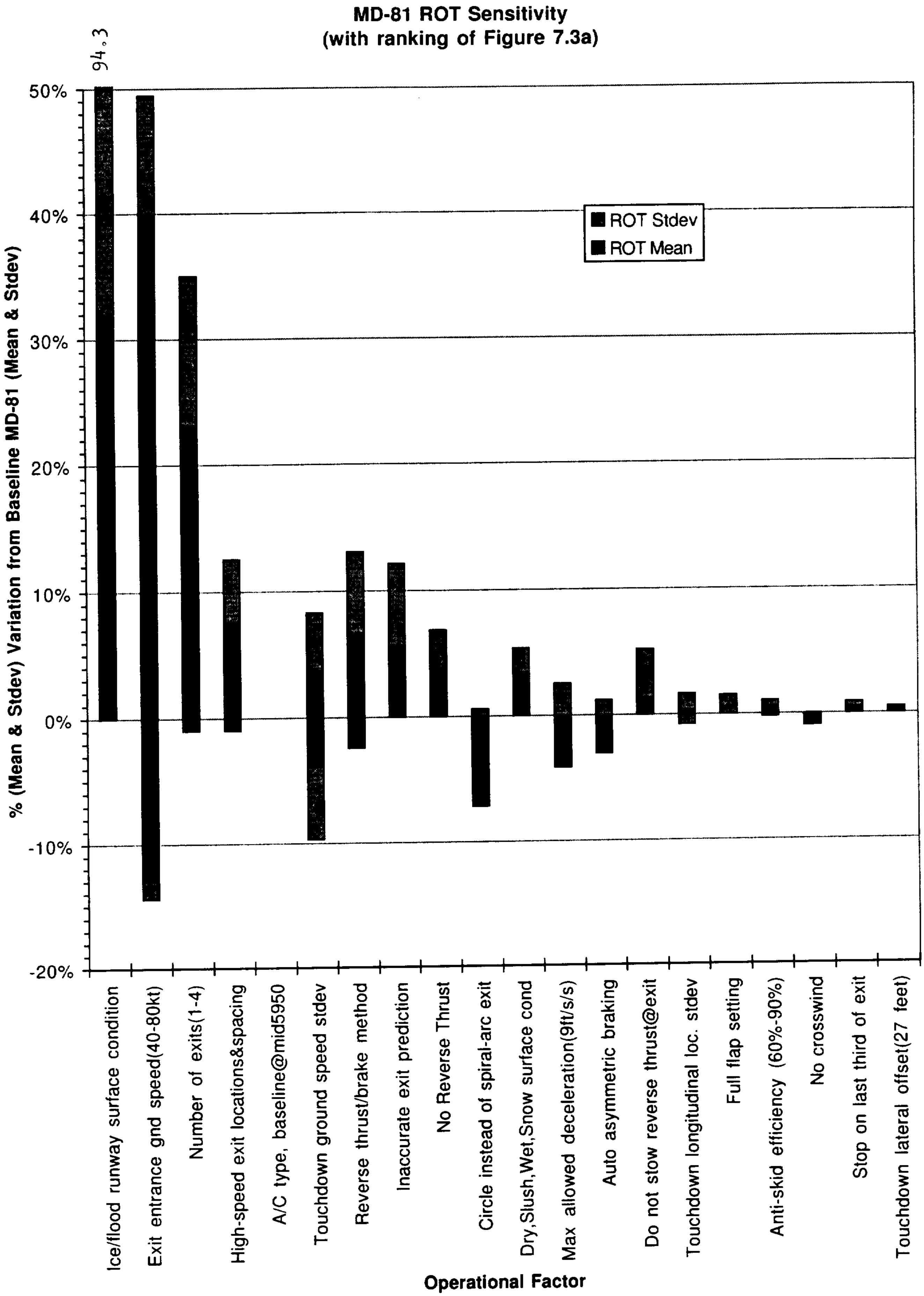

MD-11 ROT Sensitivity Ranking
93.6;172
68.1
50%
40%
30%
20%
10%
0%
-10%
-20%
% (Mean & Stdev) Variation from Baseline MD-11 (Mean & Stdev)
ROT Stdev
ROT Mean
Ice/flood runway surface condition
Exit entrance gnd speed(40-80kt)
Number of exits(1-4)
High-speed exit locations&spacing
Touchdown ground speed stdev
No Reverse Thrust
Reverse thrust/brake method
Inaccurate exit prediction
Dry,Slush,Wet,Snow surface cond
Circle instead of spiral-arc exit
Max allowed deceleration(9ft/s/s)
Auto asymmetric braking
Full flap setting
Touchdown longitudinal loc. stdev
Anti-skid efficiency (60%-90%)
No crosswind
Touchdown lateral offset(27 feet)
Stop on last third of exit
Do not stow reverse thrust@exit
Operational Factor
(Ranking gives Mean and Stdev equal weight)

Figure 7.3c



MD-81 ROT Sensitivity
(with ranking of Figure 7.3a)
94.3
50%
40%
30%
20%
10%
0%
-10%
-20%
ROT Stdev
ROT Mean
% (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)
Operational Factor

Figure 7.3d

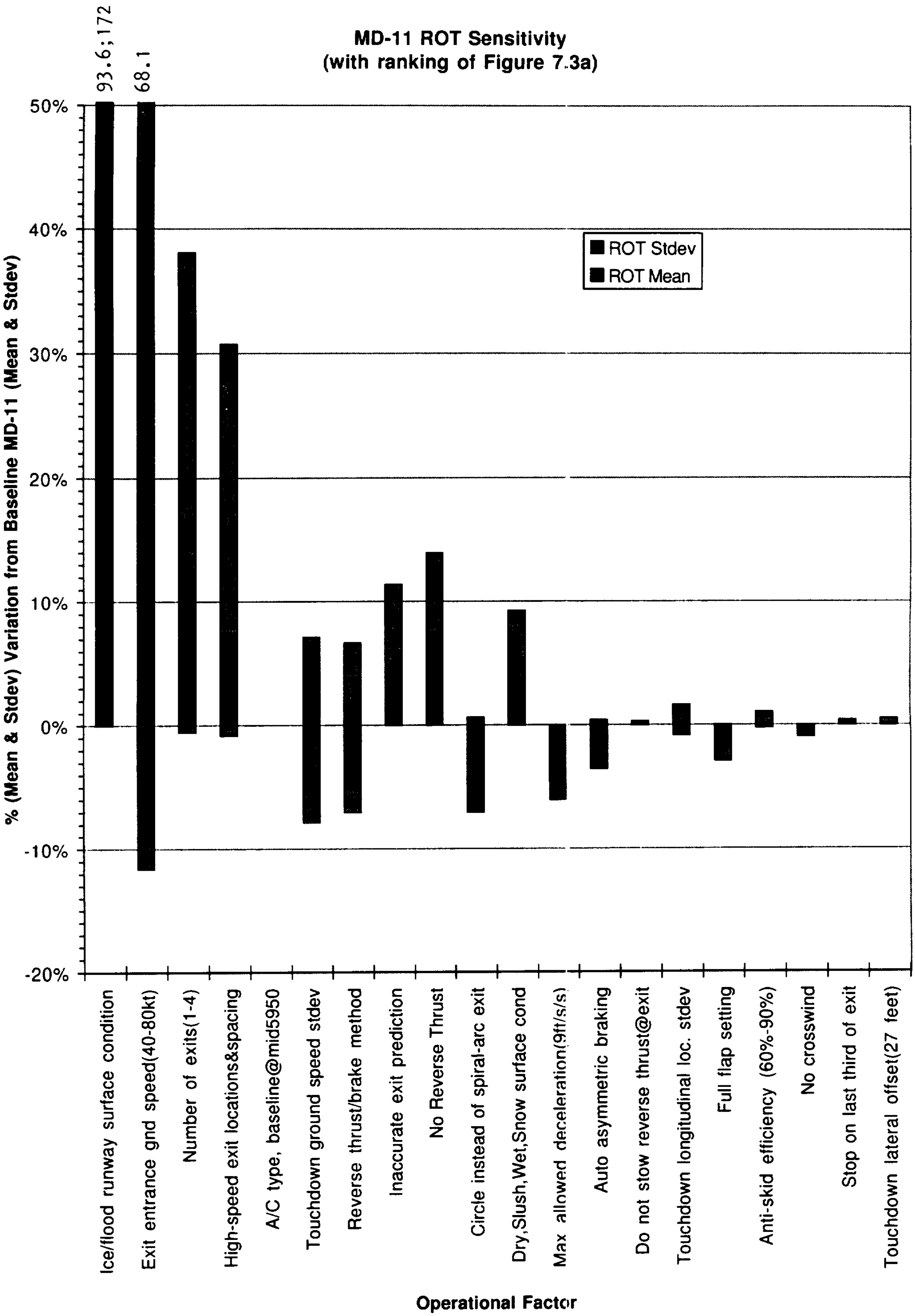

MD-11 ROT Sensitivity
(with ranking of Figure 7.3a)
93.6;172
68.1
50%
40%
30%
20%
10%
0%
-10%
-20%
% (Mean & Stdev) Variation from Baseline MD-11 (Mean & Stdev)
ROT Stdev
ROT Mean
Ice/flood runway surface condition
Exit entrance gnd speed(40-80kt)
Number of exits(1-4)
High-speed exit locations&spacing
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)
Operational Factor

Figure 7.3e

APPENDIX

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.

Page 1; Middle Plot

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.

Page 1; 2nd from Top Plot

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.

Page 1; Top Plot

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.

Please refer to the 3rd and 4th plots on the bottom of plot page 2 for the amounts of available mu being used by the main gear. When runway surface friction decreases below that required (resulting in skidding), anti-skid decreases brake pressure used just until skidding is alleviated. One would not expect 100% supply pressure in use when braking at high speeds on a wet surface. The ROTO simulation used in this study implemented the anti-skid function in the drag code (for modeling complexity reasons), after its proper location in the brake pressure code.

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

Page 2; Bottom Plot

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

Page 2; 2nd from Bottom Plot

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

Page 2; 3rd from Bottom Plot

The left axis plots the amount of μ being used by the aircraft main right gear μ (lower trace). The right axis plots the available aircraft main right gear μ.

Page 2; 4th from Bottom Plot

The left axis plots the amount of μ being used by the aircraft main center gear μ (lower trace). The right axis plots the available aircraft main center gear μ.

Page 2; 3rd from Top Plot

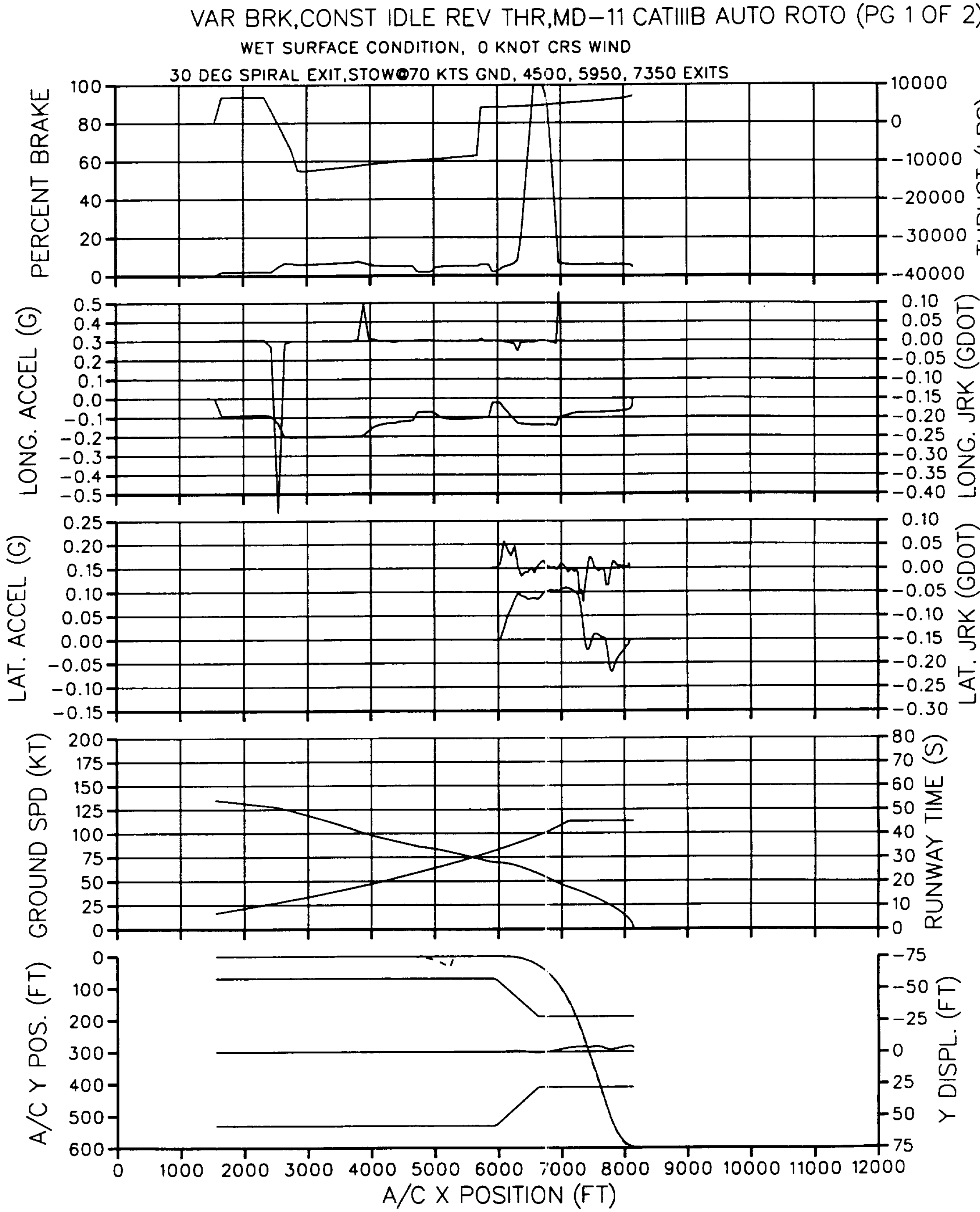
The left axis plots the aircraft track angle relative to the aircraft heading in degrees. The right axis plots the aircraft elevator angle in degrees (gradually rising trace).

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

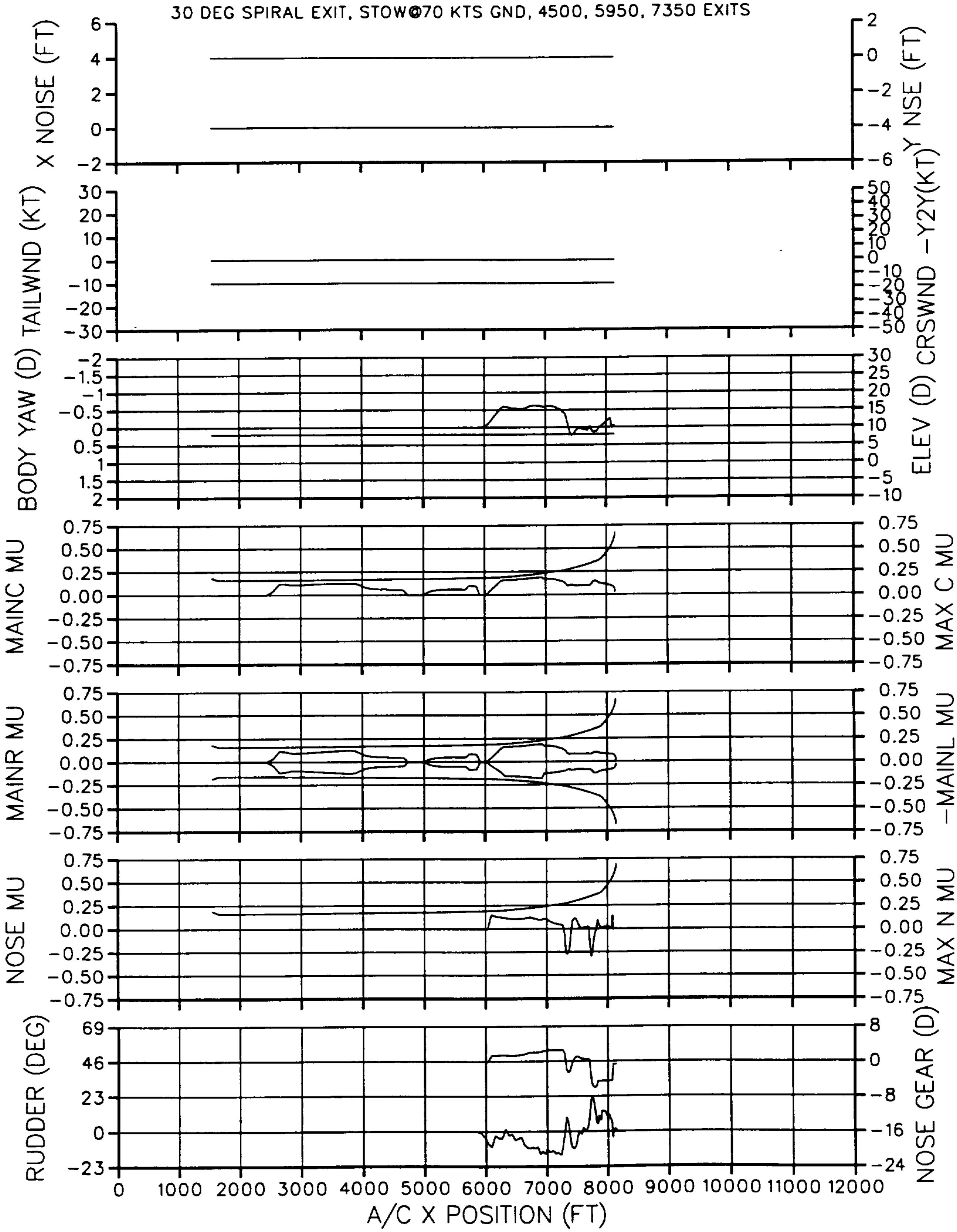
The left axis plots the navigation X position data noise content (lower trace). The right axis plots the navigation Y position data noise content.

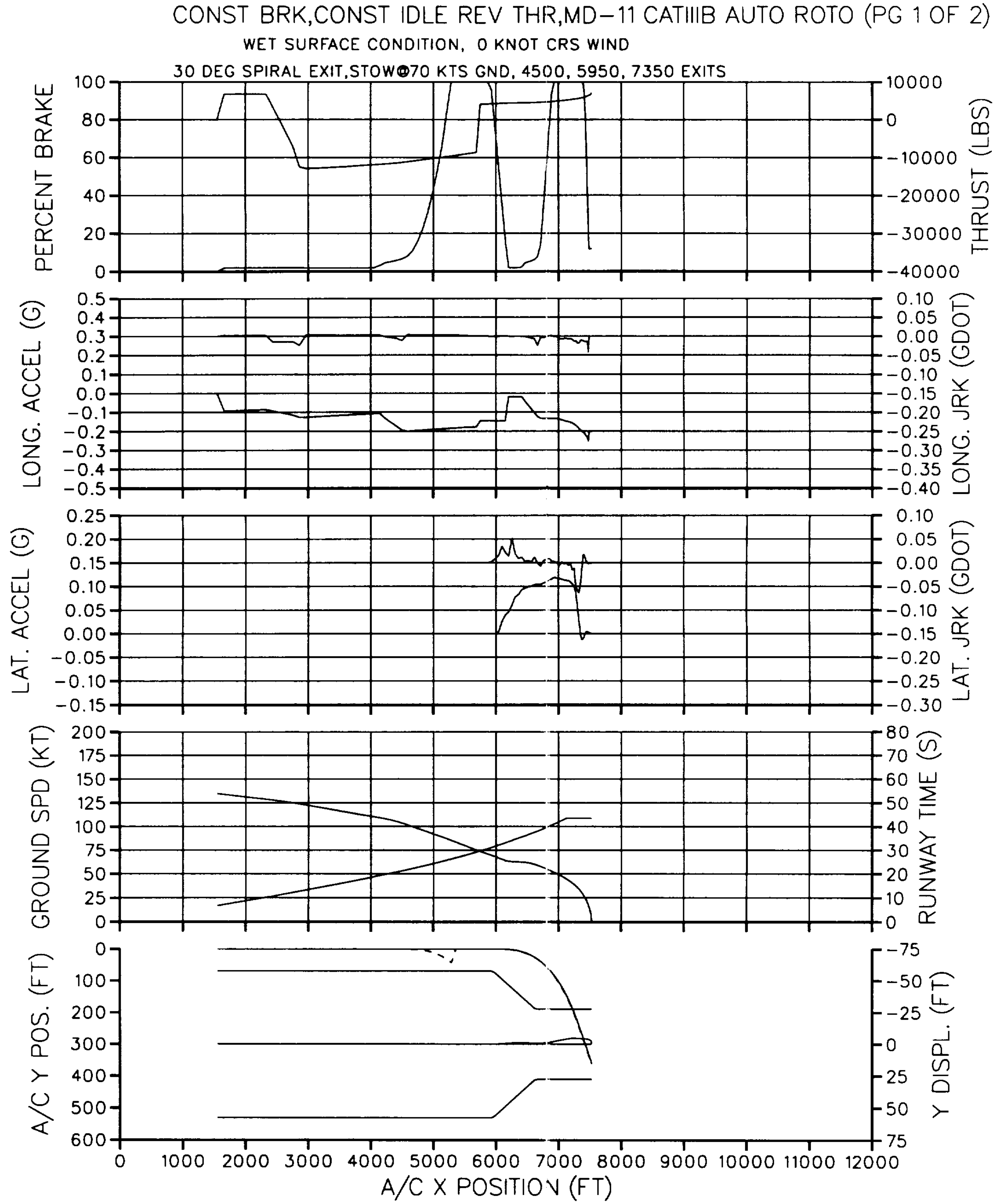

VAR BRK,CONST IDLE REV THR,MD-11 CATIIIB AUTO ROTO (PG 1 OF 2)
WET SURFACE CONDITION, 0 KNOT CRS WIND
30 DEG SPIRAL EXIT,STOW@70 KTS GND, 4500, 5950, 7350 EXITS
PERCENT BRAKE
THRUST (LBS)
LONG. ACCEL (G)
LONG. JRK (GDOT)
LAT. ACCEL (G)
LAT. JRK (GDOT)
GROUND SPD (KT)
RUNWAY TIME (S)
A/C Y POS. (FT)
Y DISPL. (FT)
A/C X POSITION (FT)

VAR BRK,CONST IDLE REV THR,MD−11 CATIIIB AUTO ROTO (PG 2 OF 2)

WET SURFACE CONDITION, 0 KNOT CROSSWIND

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

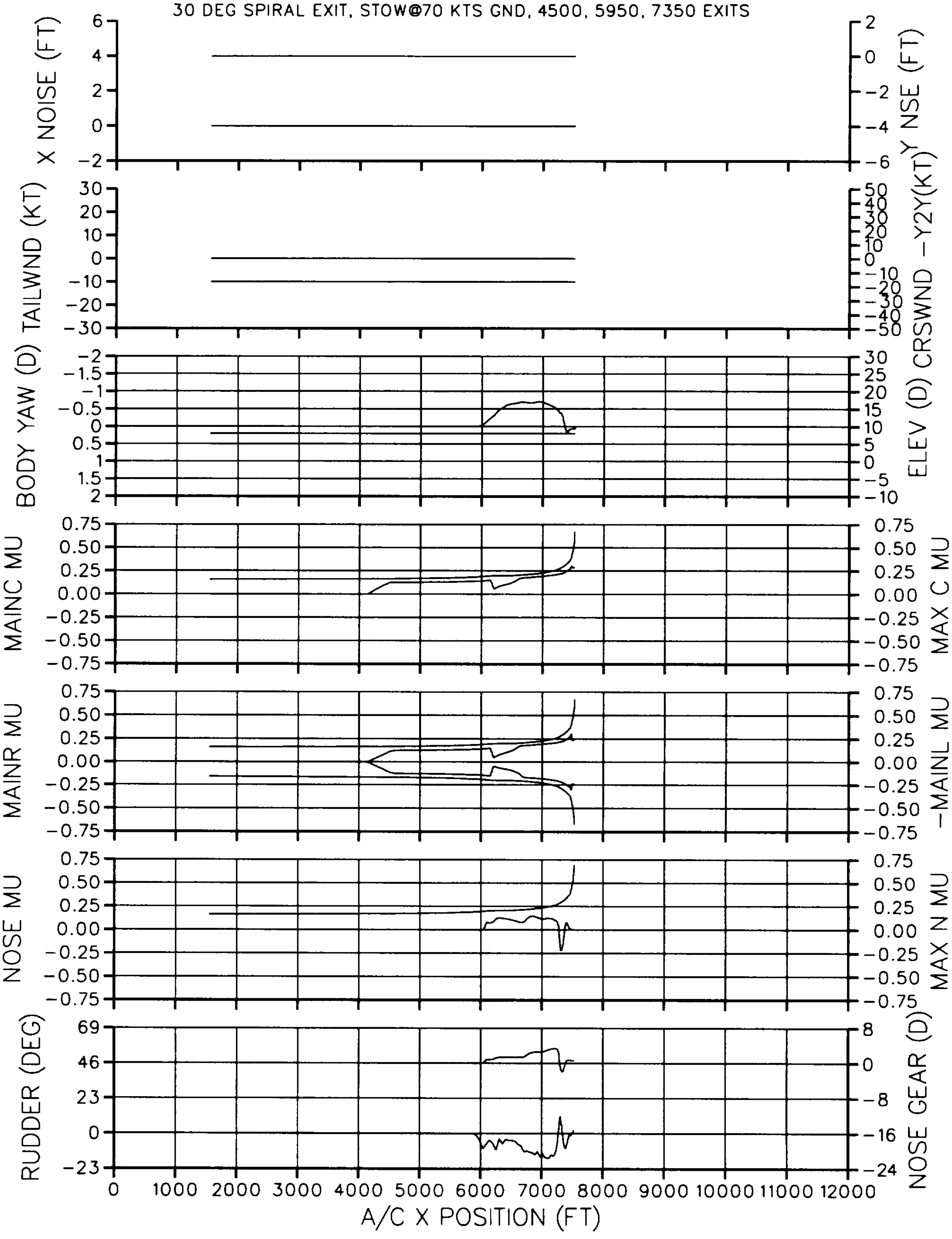



CONST BRK,CONST IDLE REV THR,MD-11 CATIIIB AUTO ROTO (PG 1 OF 2)
WET SURFACE CONDITION, 0 KNOT CRS WIND
30 DEG SPIRAL EXIT,STOW@70 KTS GND, 4500, 5950, 7350 EXITS
PERCENT BRAKE
THRUST (LBS)
LONG. ACCEL (G)
LONG. JRK (GDOT)
LAT. ACCEL (G)
LAT. JRK (GDOT)
GROUND SPD (KT)
RUNWAY TIME (S)
A/C Y POS. (FT)
Y DISPL. (FT)
A/C X POSITION (FT)
0 1000 2000 3000 4000 5000 6000 7000 8000 9000 10000 11000 12000

CONST BRK,CONST IDLE REV THR,MD-11 CATIIIB AUTO ROTO (PG 2 OF 2)

WET SURFACE CONDITION, 0 KNOT CROSSWIND

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



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.

```
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 DONDIST 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;
```

```
  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;
 itemp=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))*(PCTMAC-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)+0.00193))/12.;
 else
   cginpre=885.547+cgpre*158.512;
   apre=(cginpre-97.998)/12.;
   bpre=(967.1-cginpre)/12.;
   bcpre=0;
  hcgpre=(83.029-(sqrt(cginpre^2+(5.1)^2))*sin(atan(-5.1/cginpre)+0.018))/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 | ROLL1ST==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(ROLL1ST)
% this represents the autobrake lag, too conservative for var braking
         tempdlagset=tempdset+(tempdlagset-tempdset)*exp(-dtpre/0.4);
          tempdset=tempdlagset;
```

```
        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;
       end;
% Is aircraft past ROTO exit?
      if(i>exitpos)break;end;%L112

% calculate required deceleration
      tempd = ((vexit)^2- futu^2)/(exitpos-i)/2.0;
      deceltemppre=-tempd;
% calculate airspeed, assumes winds are constant
      futut=(futu+tempw)/1.689;
% constant rev thrust is alittle overestimated, subract small value
       tempr=0;
       if(~AUTOREV&ROLL1ST)tempr=0.1;end;
```

```
      if(AUREVCONST-tempr<0)tempr=AUREVCONST;end;
% calculate rev thrust using airspeed & whether braking is engaged
       temp=i;
      if((decelpreon&~ROLL1ST)|~AUTOREV)
        thstmu=functhrust(REVERSE,AUTOREV,futt,futut,temp,exitpos,AUREVCONST-tempr,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,0.          ,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=i;
      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 equalled 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)+futt+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(~ROLL1ST)
        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 aircraft 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 beaking 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
```

```
% provided by otherd (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; %L112

 % 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;
    repL111=0;
    if(~ROLL1ST | CREVTHRLOOP)
% not roll deceleration or trying to find constant reverse thrust setting
%      if(abortearly & ~OCCSTOP)fprintf(fid,'%13.6e %s %i\n',x,'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(~MD11 & ~AUTOREV)
         DONDIST=DONDIST-350*(1+nexit)-1600*dragcrs-lenxdef*2;
        else
         DONDIST=DONDIST-125-1600*dragcrs-lenxdef*2;
        end;
       else
% exit abort is final
        DONDIST=0;
       end;
       break;%L111
      else
       DONDIST=DONDIST+lenxdef*2;
       if(DONDIST<exitpos)
        newexit=1;
        lastdeccalc=0;
        repL111=1;
       end;
      end;

   end;

  if(~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)
    if(AUTOREV | AUREVCONST>0.9)
% exit abort is final
      ...
     break;%L111
    else
      AUREVCONST=AUREVCONST+0.33;
     abortearly=0;
    end;
% This is final constant reverse thrust (AUREVCONST) factor if AUTOREV=false
%     reverse thrust =    AUREVCONST*(max rev thrust - idle rev thrust) + 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\n','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;
 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 tendancy 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=0ft,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				Runway surface condition	Referenced by figure legends	ROT = Runway Occupancy Time	Percent of aircraft exiting at end of runway	Percent of aircraft having a ROT greater than 53.4 sec		Exit number used by aircraft		F figures (vol 1); P pages (vol 2); wet/dry rows avg in F6.Xb,c figures
Deceleration method, exit prediction usage and difference from baseline	first 3 high-speed exit locations			aircraft type	surface condi-tion	Row #	ROT MEAN (sec)	% using end of runway	% ROT > 53.4	ROT STDEV (sec)	Exit # MEAN	Exit # STDEV	Page or Figure Number
							0.00	0.00	0.00	0.00	0.00	0.00	
auto rev thr & var dec, w/ PRED	3500	4950	6550	MD-11;	wet surfa	1	49.00	13.70	13.70	34.10	14.70	2.90	P1,P49 F6.1c,6c
auto rev thr & var dec, w/ PRED	3500	4950	6550	MD-11;	dry surfa	2	48.50	11.40	11.40	32.55	14.45	2.85	P1 F6.1c,6c
auto rev thr & var dec, w/ PRED	3500	4950	6550	MD-81;	wet surfa	3	41.00	0.01	0.00	19.45	9.50	2.60	P1,P51 F6.1b,6b
auto rev thr & var dec, w/ PRED	3500	4950	6550	MD-81;	dry surfa	4	40.60	0.00	0.00	19.33	9.30	2.55	P1 F6.1b,6b
EXIT LOCATION				Average		5	44.78	6.28	6.28	26.36	11.99	2.73	F6.1a F6.6a
auto rev thr & var dec, w/ PRED	3900	5350	6950	MD-11;	wet surfa	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 surfa	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 surfa	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 surfa	9	40.40	0.00	0.00	19.10	7.90	2.65	P2 F6.1b,11b
EXIT LOCATION				Average		10	44.25	2.74	2.74	22.78	10.65	2.83	F6.1a F6.11a

Deceleration method, exit prediction usage and difference from baseline	first 3 high-speed exit locations			aircraft type	surface condi-tion	Row #	ROT MEAN (sec)	% using end of runway	% ROT > 53.4	ROT STDEV (sec)	Exit # MEAN	Exit # STDEV	Page or Figure Number
auto rev thr & var dec, w/ PRED	4500	5950	7350	MD-11;	wet surfa	11	47.20	2.31	2.31	20.80	11.50	3.15	P3,P57 F6.1c,2c,3c,5c,6c,7a,7c,9c,11c,12c
auto rev thr & var dec, w/ PRED	4500	5950	7350	MD-11;	dry surfa	12	46.80	1.72	1.70	20.09	11.20	3.10	P3,P59, F6.1c,2c,3c,5c,6c,7a,7c,9c,11c,12c
auto rev thr & var dec, w/ PRED	4500	5950	7350	MD-81;	wet surfa	13	41.20	0.00	0.10	16.10	6.05	2.10	P3,P61 F6.1b,2b,3b,5b,6b,7a,7b,9b,11b,12b
auto rev thr & var dec, w/ PRED	4500	5950	7350	MD-81;	dry surfa	14	41.20	0.00	0.10	16.10	6.05	2.10	P3,P63 F6.1b,2b,3b,5b,6b,7a,7b,9b,11b,12b
BEST EXIT LOCATION, BASELINE				Average		15	44.10	1.01	1.05	18.27	8.70	2.61	F6.1a,2a,3a,5a,6a,8,9a,10,11a,12a
auto rev thr & var dec, w/ PRED	4300	5950	7550	MD-11;	wet surfa	16	47.70	1.36	6.36	20.65	11.60	2.85	P4,P65 F6.1c
auto rev thr & var dec, w/ PRED	4300	5950	7550	MD-11;	dry surfa	17	47.30	0.94	4.19	20.11	11.30	2.80	P4,F6.1c
auto rev thr & var dec, w/ PRED	4300	5950	7550	MD-81;	wet surfa	18	41.50	0.00	0.00	20.81	6.70	2.40	P4,P67 F6.1b
auto rev thr & var dec, w/ PRED	4300	5950	7550	MD-81;	dry surfa	19	41.20	0.00	0.00	19.83	6.60	2.35	P4,F6.1b
WIDER EXIT SPACING				Average		20	44.43	0.58	2.64	20.35	9.05	2.60	F6.1a

Deceleration method, exit prediction usage and difference from baseline	first 3 high-speed exit locations			aircraft type	surface condi- tion	Row #	ROT MEAN (sec)	% using end of runway	% ROT > 53.4	ROT STDEV (sec)	Exit # MEAN	Exit # STDEV	Page or Figure Number
auto rev thr & var dec, w/ PRED + full flaps	4500	5950	7350	MD-11;	wet surfa	21	46.40	1.36	1.36	19.50	10.95	3.10	P5,P69 F6.11c
auto rev thr & var dec, w/ PRED + full flaps	4500	5950	7350	MD-11;	dry surfa	22	45.90	0.94	0.94	19.24	10.65	3.05	P5,F6.11c
auto rev thr & var dec, w/ PRED + full flaps	4500	5950	7350	MD-81;	wet surfa	23	41.20	0.03	0.60	17.53	5.85	1.90	P5,P71 F6.11b
auto rev thr & var dec, w/ PRED + full flaps	4500	5950	7350	MD-81;	dry surfa	24	41.20	0.00	0.50	17.05	5.80	1.85	P5,F6.11b
FULL FLAPS				Average		25	43.68	0.58	0.85	18.33	8.31	2.48	F6.11a
immediate med rev thr & 6.5 dec, then coast after 70 kts,NO PRED	3500	4950	6550	MD-11;	wet surfa	26	48.50	8.44	8.44	45.05	13.95	2.90	P6,P73
immediate med rev thr & 6.5 dec, then coast after 70 kts,NO PRED	3500	4950	6550	MD-11;	dry surfa	27	46.70	7.07	7.10	40.35	13.85	2.85	P6
immediate med rev thr & 6.5 dec, then coast after 70 kts,NO PRED	3500	4950	6550	MD-81;	wet surfa	28	41.30	0.02	0.00	25.50	9.15	2.70	P6,P75
immediate med rev thr & 6.5 dec, then coast after 70 kts,NO PRED	3500	4950	6550	MD-81;	dry surfa	29	39.90	0.00	0.00	24.44	8.90	2.50	P6
DECEL METHOD, NON-ROTO				Average		30	44.10	3.88	3.89	33.83	11.46	2.74	F6.4

Deceleration method, exit prediction usage and difference from baseline	first 3 high-speed exit locations			aircraft type	surface condi-tion	Row #	ROT MEAN (sec)	% using end of runway	% ROT > 53.4	ROT STDEV (sec)	Exit # MEAN	Exit # STDEV	Page or Figure Number
immediate med rev thr & 6.5 dec, then coast after 70 kts,NO PRED	3900	5350	6950	MD-11;	wet surfa	31	47.30	3.42	13.90	34.15	12.65	3.00	P7,P77
immediate med rev thr & 6.5 dec, then coast after 70 kts,NO PRED	3900	5350	6950	MD-11;	dry surfa	32	45.60	2.60	2.60	30.70	12.50	2.95	P7
immediate med rev thr & 6.5 dec, then coast after 70 kts,NO PRED	3900	5350	6950	MD-81;	wet surfa	33	41.30	0.00	1.50	24.47	7.80	2.75	P7,P79
immediate med rev thr & 6.5 dec, then coast after 70 kts,NO PRED	3900	5350	6950	MD-81;	dry surfa	34	39.50	0.00	0.00	24.48	7.40	2.60	P7
DECEL METHOD, NON-ROTO				Average		35	43.43	1.51	4.50	28.45	10.09	2.83	F6.4
immediate med rev thr & 6.5 dec, then coast after 70 kts,NO PRED	4500	5950	7350	MD-11;	wet surfa	36	46.60	2.09	8.50	30.60	10.80	3.25	P8,P81 F6.3c,5c
immediate med rev thr & 6.5 dec, then coast after 70 kts,NO PRED	4500	5950	7350	MD-11;	dry surfa	37	44.70	0.79	0.80	23.70	10.55	3.05	P8,P83 F6.3c,5c
immediate med rev thr & 6.5 dec, then coast after 70 kts,NO PRED	4500	5950	7350	MD-81;	wet surfa	38	42.50	0.00	0.44	21.70	6.10	2.10	P8,P85 F6.3b,5b
immediate med rev thr & 6.5 dec, then coast after 70 kts,NO PRED	4500	5950	7350	MD-81;	dry surfa	39	40.90	0.00	0.30	20.81	5.75	1.80	P8,P87 F6.3b,5b
DECEL METHOD, NON-ROTO				Average		40	43.68	0.72	2.51	24.20	8.30	2.55	F6.3a F6.4 F6.5a

Deceleration method, exit prediction usage and difference from baseline	first 3 high-speed exit locations			aircraft type	surface condi-tion	Row #	ROT MEAN (sec)	% using end of runway	% ROT > 53.4	ROT STDEV (sec)	Exit # MEAN	Exit # STDEV	Page or Figure Number
cnst rev thr&roll/cnt dec,w/ PRED	4500	5950	7350	MD-11;	wet surfa	41	45.70	2.89	2.89	18.65	11.65	3.20	P9,P89 F6.3c,5c
cnst rev thr&roll/cnt dec,w/ PRED	4500	5950	7350	MD-11;	dry surfa	42	43.60	2.27	2.27	18.10	11.55	3.10	P9,P91 F6.3c,5c
cnst rev thr&roll/cnt dec,w/ PRED	4500	5950	7350	MD-81;	wet surfa	43	41.70	0.00	0.10	18.66	6.55	2.35	P9,P93 F6.3b,5b
cnst rev thr&roll/cnt dec,w/ PRED	4500	5950	7350	MD-81;	dry surfa	44	40.80	0.00	0.10	18.44	6.55	2.35	P9,P95 F6.3b,5b
DECEL METHOD				Average		45	42.95	1.29	1.34	18.46	9.08	2.75	F6.3a,5a
auto rev thr&roll/cnst dec,w/PRED	4500	5950	7350	MD-11;	wet surfa	46	47.10	7.36	7.36	26.35	12.60	3.50	P10,P97 F6.3c
auto rev thr&roll/cnst dec,w/PRED	4500	5950	7350	MD-11;	dry surfa	47	43.80	2.49	2.49	18.25	11.65	3.15	P10,P99 F6.3c
auto rev thr&roll/cnst dec,w/PRED	4500	5950	7350	MD-81;	wet surfa	48	40.80	0.00	0.10	17.85	6.55	2.40	P10,P101 F6.3b
auto rev thr&roll/cnst dec,w/PRED	4500	5950	7350	MD-81;	dry surfa	49	39.60	0.00	0.10	17.70	6.35	2.25	P10,P103 F6.3b
DECEL METHOD				Average		50	42.83	2.46	2.51	20.04	9.29	2.83	F6.3a

Deceleration method, exit prediction usage and difference from baseline	first 3 high-speed exit locations			aircraft type	surface condi-tion	Row #	ROT MEAN (sec)	% using end of runway	% ROT > 53.4	ROT STDEV (sec)	Exit # MEAN	Exit # STDEV	Page or Figure Number
const rev thr & var dec, w/ PRED	4500	5950	7350	MD-11;	wet surfa	51	47.30	2.31	2.31	20.70	11.50	3.15	P11,P105 F6.3c
const rev thr & var dec, w/ PRED	4500	5950	7350	MD-11;	dry surfa	52	46.80	1.72	1.70	20.13	11.20	3.10	P11,P107 F6.3c
const rev thr & var dec, w/ PRED	4500	5950	7350	MD-81;	wet surfa	53	46.70	0.38	7.00	22.04	8.55	3.15	P11,P109 F6.3b
const rev thr & var dec, w/ PRED	4500	5950	7350	MD-81;	dry surfa	54	41.20	0.00	0.10	16.09	6.05	2.10	P11,P111 F6.3b
DECEL METHOD				Average		55	45.50	1.10	2.78	19.74	9.33	2.88	F6.3a
auto rev thr & var dec, w/ PRED 60 knot high speed exit	4500	5950	7350	MD-11;	wet surfa	56	51.60	5.26	37.10	25.95	12.60	3.20	P12,P113 F6.6c
auto rev thr & var dec, w/ PRED 60 knot high speed exit	4500	5950	7350	MD-11;	dry surfa	57	50.10	3.38	23.30	23.26	12.20	3.15	P12,F6.6c
auto rev thr & var dec, w/ PRED 60 knot high speed exit	4500	5950	7350	MD-81;	wet surfa	58	44.60	0.00	0.80	20.01	7.05	2.55	P12,P115 F6.6b
auto rev thr & var dec, w/ PRED 60 knot high speed exit	4500	5950	7350	MD-81;	dry surfa	59	44.00	0.00	0.70	19.42	6.85	2.50	P12,F6.6b
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

Deceleration method, exit prediction usage and difference from baseline	first 3 high-speed exit locations			aircraft type	surface condi-tion	Row #	ROT MEAN (sec)	% using end of runway	% ROT > 53.4	ROT STDEV (sec)	Exit # MEAN	Exit # STDEV	Page or Figure Number
auto rev thr & var dec, w/ PRED 80 knot high speed exit	4500	5950	7350	MD-11;	wet surfa	61	41.80	0.85	0.85	18.90	10.30	3.15	P13,P117 F6.6c
auto rev thr & var dec, w/ PRED 80 knot high speed exit	4500	5950	7350	MD-11;	dry surfa	62	41.30	0.57	0.60	17.83	10.00	3.05	P13,F6.6c
auto rev thr & var dec, w/ PRED 80 knot high speed exit	4500	5950	7350	MD-81;	wet surfa	63	38.10	0.00	0.00	14.96	5.55	1.60	P13,P119 F6.6b
auto rev thr & var dec, w/ PRED 80 knot high speed exit	4500	5950	7350	MD-81;	dry surfa	64	37.60	0.00	0.00	14.95	5.50	1.50	P13,F6.6b
80 KNOT EXIT ENTRANCE SPEED AT MID EXIT LOCATION 5950				Average		65	39.70	0.36	0.36	16.66	7.84	2.33	F6.6a
auto rev thr & var dec, w/ PRED 60 knot high speed exit	5500	6950	8350	MD-11;	wet surfa	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 surfa	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 surfa	68	48.80	0.00	10.43	20.21	5.20	1.00	P14,P123 F6.6b
auto rev thr & var dec, w/ PRED 60 knot high speed exit	5500	6950	8350	MD-81;	dry surfa	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				Average		70	49.45	0.12	13.18	20.47	7.05	2.01	F6.6a

Deceleration method, exit prediction usage and difference from baseline	first 3 high-speed exit locations	aircraft type	surface condi-tion	Row #	ROT MEAN (sec)	% using end of runway	% ROT > 53.4	ROT STDEV (sec)	Exit # MEAN	Exit # STDEV	Page or Figure Number
auto rev thr & var dec, w/ PRED 80 knot high speed exit	3500 4950 6550	MD-11;	wet surfa	71	42.80	6.82	6.82	28.20	13.60	3.00	P15,P125 F6.6c
auto rev thr & var dec, w/ PRED 80 knot high speed exit	3500 4950 6550	MD-11;	dry surfa	72	42.20	5.46	5.46	26.31	13.35	2.95	P15,F6.6c
auto rev thr & var dec, w/ PRED 80 knot high speed exit	3500 4950 6550	MD-81;	wet surfa	73	36.10	0.00	0.00	19.47	8.25	2.70	P15,P127 F6.6b
auto rev thr & var dec, w/ PRED 80 knot high speed exit	3500 4950 6550	MD-81;	dry surfa	74	35.60	0.00	0.00	19.01	8.15	2.65	P15,F6.6b
80 KNOT EXIT ENTRANCE SPEED AT MID EXIT LOCATION 4950		Average		75	39.18	3.07	3.07	23.25	10.84	2.83	F6.6a
auto rev thr & var dec, w/ PRED dispersion sigma = 375	4500 5950 7350	MD-11;	wet surfa	76	47.20	2.93	2.96	22.35	11.50	3.30	P16,P129
auto rev thr & var dec, w/ PRED dispersion sigma = 375	4500 5950 7350	MD-11;	dry surfa	77	46.80	2.24	2.30	21.61	11.20	3.30	P16,P131
auto rev thr & var dec, w/ PRED dispersion sigma = 375	4500 5950 7350	MD-81;	wet surfa	78	41.50	0.00	0.20	16.91	6.20	2.20	P16,P133
auto rev thr & var dec, w/ PRED dispersion sigma = 375	4500 5950 7350	MD-81;	dry surfa	79	41.50	0.00	0.20	16.91	6.20	2.20	P16,P135
TOUCHDOWN DISPERSION SIGMA		Average		80	44.25	1.29	1.42	19.44	8.78	2.75	F6.8

Deceleration method, exit prediction usage and difference from baseline	first 3 high-speed exit locations			aircraft type	surface condi-tion	Row #	ROT MEAN (sec)	% using end of runway	% ROT > 53.4	ROT STDEV (sec)	Exit # MEAN	Exit # STDEV	Page or Figure Number
auto rev thr & var dec, w/ PRED dispersion sigma = 100	4500	5950	7350	MD-11;	wet surfa	81	47.20	1.97	1.97	20.10	11.50	3.10	P17,P137
auto rev thr & var dec, w/ PRED dispersion sigma = 100	4500	5950	7350	MD-11;	dry surfa	82	46.70	1.51	1.50	19.36	11.15	3.00	P17,P139
auto rev thr & var dec, w/ PRED dispersion sigma = 100	4500	5950	7350	MD-81;	wet surfa	83	41.10	0.00	0.10	15.65	6.00	2.00	P17,P141
auto rev thr & var dec, w/ PRED dispersion sigma = 100	4500	5950	7350	MD-81;	dry surfa	84	41.10	0.00	0.10	15.65	6.00	2.00	P17,P143
TOUCHDOWN GROUND SPEED SIGMA				Average		85	44.03	0.87	0.92	17.69	8.66	2.53	F6.8
auto rev thr & var dec, w/ PRED gnd speed sigma = 17	4500	5950	7350	MD-11;	wet surfa	86	47.60	7.22	7.22	27.45	11.60	4.05	P18,P145 F6.9c
auto rev thr & var dec, w/ PRED gnd speed sigma = 17	4500	5950	7350	MD-11;	dry surfa	87	47.10	5.92	5.90	26.51	11.25	4.00	P18,P147 F6.9c
auto rev thr & var dec, w/ PRED gnd speed sigma = 17	4500	5950	7350	MD-81;	wet surfa	88	42.70	0.00	1.40	19.86	6.70	2.65	P18,P149 F6.9b
auto rev thr & var dec, w/ PRED gnd speed sigma = 17	4500	5950	7350	MD-81;	dry surfa	89	42.70	0.00	1.40	19.86	6.70	2.65	P18,P151 F6.9b
TOUCHDOWN GROUND SPEED SIGMA				Average		90	45.03	3.29	3.98	23.42	9.06	3.34	F6.9a

Deceleration method, exit prediction usage and difference from baseline	first 3 high-speed exit locations			aircraft type	surface condi-tion	Row #	ROT MEAN (sec)	% using end of runway	% ROT > 53.4	ROT STDEV (sec)	Exit # MEAN	Exit # STDEV	Page or Figure Number
auto rev thr & var dec, w/ PRED gnd speed sigma = 5	4500	5950	7350	MD-11;	wet surfa	91	46.40	0.00	0.00	15.00	11.10	2.10	P19,P153 F6.9c
auto rev thr & var dec, w/ PRED gnd speed sigma = 5	4500	5950	7350	MD-11;	dry surfa	92	46.10	0.00	0.00	13.15	10.75	1.85	P19,P155 F6.9c
auto rev thr & var dec, w/ PRED gnd speed sigma = 5	4500	5950	7350	MD-81;	wet surfa	93	39.60	0.00	0.00	11.44	5.40	1.35	P19,P157 F6.9b
auto rev thr & var dec, w/ PRED gnd speed sigma = 5	4500	5950	7350	MD-81;	dry surfa	94	39.60	0.00	0.00	11.44	5.40	1.35	P19,P159 F6.9b
TOUCHDOWN GROUND SPEED SIGMA				Average		95	42.93	0.00	0.00	12.76	8.16	1.66	F6.9a
auto rev thr & var dec, w/ PRED no crosswind	4500	5950	7350	MD-11;	wet surfa	96	46.70	2.24	2.24	20.45	11.45	3.15	P20,P161
auto rev thr & var dec, w/ PRED no crosswind	4500	5950	7350	MD-11;	dry surfa	97	46.20	1.51	1.51	19.92	11.10	3.10	P20
auto rev thr & var dec, w/ PRED no crosswind	4500	5950	7350	MD-81;	wet surfa	98	41.10	0.00	0.10	16.29	6.20	2.15	P20,P163
auto rev thr & var dec, w/ PRED no crosswind	4500	5950	7350	MD-81;	dry surfa	99	40.90	0.00	0.10	16.11	6.05	2.05	P20
NO CROSSWIND				Average		100	43.73	0.94	1.98	18.19	8.70	2.61	F6.10

Deceleration method, exit prediction usage and difference from baseline	first 3 high-speed exit locations			aircraft type	surface condi-tion	Row #	ROT MEAN (sec)	% using end of runway	% ROT > 53.4	ROT STDEV (sec)	Exit # MEAN	Exit # STDEV	Page or Figure Number
auto rev thr & var dec, w/ PRED gusting crosswind 12.5+/-2.5 & sensor noise	4500	5950	7350	MD-11;	wet surfa	101	46.80	2.44	2.44	21.00	11.50	3.15	P21,P165
auto rev thr & var dec, w/ PRED gusting crosswind 12.5+/-2.5 & sensor noise	4500	5950	7350	MD-11;	dry surfa	102	46.20	1.59	1.59	20.39	11.20	3.15	P21
auto rev thr & var dec, w/ PRED gusting crosswind 12.5+/-2.5 & sensor noise	4500	5950	7350	MD-81;	wet surfa	103	41.40	0.00	0.10	17.00	6.40	2.30	P21,P167
auto rev thr & var dec, w/ PRED gusting crosswind 12.5+/-2.5 & sensor noise	4500	5950	7350	MD-81;	dry surfa	104	40.80	0.00	0.10	16.01	6.05	2.05	P21
GUSTING CROSSWIND				Average		105	43.80	1.01	1.06	18.60	8.79	2.66	F6.10
auto rev thr & var dec, w/ PRED predict TD location error +300	4500	5950	7350	MD-11;	wet surfa	106	49.20	4.86	5.25	22.55	12.55	3.20	P22,P169 F6.5c
auto rev thr & var dec, w/ PRED predict TD location error +300	4500	5950	7350	MD-11;	dry surfa	107	48.90	3.82	4.56	21.60	12.25	3.15	P22,F6.5c
auto rev thr & var dec, w/ PRED predict TD location error +300	4500	5950	7350	MD-81;	wet surfa	108	43.30	0.00	0.10	18.59	7.05	2.55	P22,P171 F6.5b
auto rev thr & var dec, w/ PRED predict TD location error +300	4500	5950	7350	MD-81;	dry surfa	109	42.90	0.00	0.12	17.88	6.95	2.50	P22,F6.5b
EXIT PREDICTION ERROR, VARIABLE DECEL				Average		110	46.08	2.17	2.51	20.15	9.70	2.85	F6.5a

Deceleration method, exit prediction usage and difference from baseline	first 3 high-speed exit locations			aircraft type	surface condi-tion	Row #	ROT MEAN (sec)	% using end of runway	% ROT > 53.4	ROT STDEV (sec)	Exit # MEAN	Exit # STDEV	Page or Figure Number
cnst rev thr&roll/cnt dec,w/PRED predict TD location error +300	4500	5950	7350	MD-11;	wet surfa	111	47.70	5.64	5.64	22.50	12.70	3.20	P23,P173 F6.5c
cnst rev thr&roll/cnt dec,w/PRED predict TD location error +300	4500	5950	7350	MD-11;	dry surfa	112	45.90	4.86	4.86	19.85	12.60	3.15	P23,F6.5c
cnst rev thr&roll/cnt dec,w/PRED predict TD location error +300	4500	5950	7350	MD-81;	wet surfa	113	44.10	0.00	0.30	20.19	7.45	2.65	P23,P175 F6.5b
cnst rev thr&roll/cnt dec,w/PRED predict TD location error +300	4500	5950	7350	MD-81;	dry surfa	114	43.10	0.00	0.15	19.59	7.45	2.65	P23,F6.5b
EXIT PREDICTION INPUT ESTIMATION ERROR, CONSTANT DECEL				Average		115	45.20	2.63	2.74	20.53	10.05	2.91	F6.5a
auto rev thr & var dec, w/ PRED constant 2900 ft exit radius	4500	5950	7350	MD-11;	wet surfa	116	44.00	2.31	2.31	21.65	11.50	3.15	P24,P177 F6.2c
auto rev thr & var dec, w/ PRED constant 2900 ft exit radius	4500	5950	7350	MD-11;	dry surfa	117	43.40	1.72	1.72	20.50	11.20	3.10	P24,F6.2c
auto rev thr & var dec, w/ PRED constant 2900 ft exit radius	4500	5950	7350	MD-81;	wet surfa	118	38.60	0.00	0.00	16.82	6.20	2.20	P24,P179 F6.2b
auto rev thr & var dec, w/ PRED constant 2900 ft exit radius	4500	5950	7350	MD-81;	dry surfa	119	37.90	0.00	0.00	16.27	6.05	2.10	P24,F6.2b
CONSTANT RADIUS EXIT SHAPE				Average		120	40.98	1.01	1.01	18.81	8.74	2.64	F6.2a

Deceleration method, exit prediction usage and difference from baseline	first 3 high-speed exit locations	aircraft type	surface condi-tion	Row #	ROT MEAN (sec)	% using end of runway	% ROT > 53.4	ROT STDEV (sec)	Exit # MEAN	Exit # STDEV	Page or Figure Number
auto rev thr & var dec, w/ PRED	3100 4550 6150	MD-11;	wet surfa	121	50.90	26.40	26.40	45.25	15.90	2.80	P25,P181 F6.1c
auto rev thr & var dec, w/ PRED	3100 4550 6150	MD-11;	dry surfa	122	50.10	22.60	22.60	43.21	15.65	2.75	P25,F6.1c
auto rev thr & var dec, w/ PRED	3100 4550 6150	MD-81;	wet surfa	123	41.10	0.14	0.10	20.61	10.80	2.55	P25,P183 F6.1b
auto rev thr & var dec, w/ PRED	3100 4550 6150	MD-81;	dry surfa	124	40.80	0.08	0.08	19.48	10.70	2.45	P25,F6.1b
NEAREST EXIT LOCATION		Average		125	45.73	12.31	12.30	32.14	13.26	2.64	F6.1a
auto rev thr & var dec, w/ PRED	5100 6550 7750	MD-11;	wet surfa	126	47.10	0.77	0.80	20.35	9.45	3.15	P26,P185 F6.1c,6c
auto rev thr & var dec, w/ PRED	5100 6550 7750	MD-11;	dry surfa	127	46.70	0.47	0.47	19.29	9.15	3.10	P26 F6.1c,6c
auto rev thr & var dec, w/ PRED	5100 6550 7750	MD-81;	wet surfa	128	44.40	0.00	2.10	17.29	5.30	1.15	P26,P187 F6.1b,6b
auto rev thr & var dec, w/ PRED	5100 6550 7750	MD-81;	dry surfa	129	44.30	0.00	2.07	17.69	5.25	1.05	P26 F6.1b,6b
FURTHEST EXIT LOCATION		Average		130	45.63	0.31	1.36	18.65	7.29	2.11	F6.1a,6a

Deceleration method, exit prediction usage and difference from baseline	first 3 high-speed exit locations	aircraft type	surface condi-tion	Row #	ROT MEAN (sec)	% using end of runway	% ROT > 53.4	ROT STDEV (sec)	Exit # MEAN	Exit # STDEV	Page or Figure Number
auto rev thr & var dec, w/ PRED	4500 5950 7350......	MD-11;	ice surfa	131	90.60	84.80	95.80	88.50	21.70	4.30	P27,P189 F6.7a,7c
auto rev thr & var dec, w/ PRED	4500 5950 7350......	MD-11;	snow su	132	48.50	5.44	5.44	25.75	12.05	3.45	P27,P191 F6.7a,7c
auto rev thr & var dec, w/ PRED	4500 5950 7350......	MD-11;	slush su	133	46.70	1.72	1.72	20.30	11.20	3.10	P27,P193 F6.7a,7c
auto rev thr & var dec, w/ PRED	4500 5950 7350......	MD-11;	flood sur	134	71.10	61.40	85.00	99.00	18.40	5.15	P27,P195 F6.7a,7c
MD-11 SURFACE FRICTION		Not Averaged									
auto rev thr & var dec, w/ PRED	4500 5950 7350......	MD-81;	ice surfa	136	54.40	9.23	37.00	66.20	10.20	4.90	P28,P197 F6.7a,7b
auto rev thr & var dec, w/ PRED	4500 5950 7350......	MD-81;	snow su	137	42.60	0.00	0.10	17.67	6.60	2.40	P28,P199 F6.7a,7b
auto rev thr & var dec, w/ PRED	4500 5950 7350......	MD-81;	slush su	138	41.30	0.00	0.10	15.75	6.10	2.10	P28,P201 F6.7a,7b
auto rev thr & var dec, w/ PRED	4500 5950 7350......	MD-81;	flood sur	139	46.70	1.42	10.00	29.70	8.35	3.45	P28,P203 F6.7a,7b
MD-81 SURFACE FRICTION		Not Averaged									

Deceleration method, exit prediction usage and difference from baseline	first 3 high-speed exit locations			aircraft type	surface condi-tion	Row #	ROT MEAN (sec)	% using end of runway	% ROT > 53.4	ROT STDEV (sec)	Exit # MEAN	Exit # STDEV	Page or Figure Number
auto rev thr & var dec, w/ PRED, Reverse Thrust Idle on Exit	4500	5950	7350	MD-11;	wet surfa	141	47.30	2.31	2.31	21.00	11.50	3.15	P29,P205 F6.2c,12c
auto rev thr & var dec, w/ PRED, Reverse Thrust Idle on Exit	4500	5950	7350	MD-11;	dry surfa	142	46.80	1.72	1.72	20.25	11.20	3.10	P29 F6.2c,12c
auto rev thr & var dec, w/ PRED, Reverse Thrust Idle on Exit	4500	5950	7350	MD-81;	wet surfa	143	41.90	0.00	0.90	19.55	6.20	2.20	P29,P207 F6.2b,12b
auto rev thr & var dec, w/ PRED, Reverse Thrust Idle on Exit	4500	5950	7350	MD-81;	dry surfa	144	41.60	0.00	0.93	18.82	6.10	2.10	P29 F6.2b,12b
REVERSE THRUST IDLE ON EXIT				Average		145	44.40	1.01	1.47	19.90	8.75	2.64	F6.2a F6.12a
auto rev thr & var dec, w/ PRED	5225	6650		MD-11;	wet surfa	146	48.40	11.40	11.40	31.90	9.00	3.10	P30,P209 F6.1c
auto rev thr & var dec, w/ PRED	5225	6650		MD-11;	dry surfa	147	47.70	9.34	9.34	30.14	8.75	3.05	P30,F6.1c
auto rev thr & var dec, w/ PRED	5225	6650		MD-81;	wet surfa	148	45.10	0.00	3.10	17.78	5.20	0.95	P30,P211 F6.1b
auto rev thr & var dec, w/ PRED	5225	6650		MD-81;	dry surfa	149	44.90	0.00	3.06	17.83	5.15	0.90	P30,F6.1b
2 EXIT LOCATIONS CENTERED AT 5950 FEET				Average		150	46.53	5.19	6.73	24.41	7.03	2.00	F6.1a

Deceleration method, exit prediction usage and difference from baseline	first 3 high-speed exit locations	aircraft type	surface condi- tion	Row #	ROT MEAN (sec)	% using end of runway	% ROT > 53.4	ROT STDEV (sec)	Exit # MEAN	Exit # STDEV	Page or Figure Number
auto rev thr & var dec, w/ PRED	5950	MD-11;	wet surfa	151	53.00	35.00	35.30	48.45	6.75	2.40	P31,P213 F6.1c
auto rev thr & var dec, w/ PRED	5950	MD-11;	dry surfa	152	51.90	30.50	30.90	46.52	6.55	2.30	P31,F6.1c
auto rev thr & var dec, w/ PRED	5950	MD-81;	wet surfa	153	50.90	0.30	21.00	25.47	5.00	0.25	P31,P215 F6.1b
auto rev thr & var dec, w/ PRED	5950	MD-81;	dry surfa	154	50.60	0.21	21.10	25.81	5.00	0.25	P31,F6.1b
1 EXIT LOCATION AT 5950 FEET		Average		155	51.60	16.50	27.08	36.56	5.83	1.30	F6.1a
auto rev thr & var dec, w/ PRED	3900 5350 6950 830	MD-11;	wet surfa	156	47.60	0.08	5.07	19.85	13.45	3.00	P32,P217 F6.1c
auto rev thr & var dec, w/ PRED	3900 5350 6950 830	MD-11;	dry surfa	157	47.00	0.02	3.75	19.98	13.15	3.00	P32,F6.1c
auto rev thr & var dec, w/ PRED	3900 5350 6950 830	MD-81;	wet surfa	158	41.10	0.00	0.00	19.47	8.15	2.70	P32,P219 F6.1b
auto rev thr & var dec, w/ PRED	3900 5350 6950 830	MD-81;	dry surfa	159	40.50	0.00	0.00	19.00	7.90	2.65	P32,F6.1b
MID EXIT LOCATION AT 5350, 4th EXIT LOCATION AT 8300 FEET		Average		160	44.05	0.03	2.21	19.57	10.66	2.84	F6.1a

Deceleration method, exit prediction usage and difference from baseline	first 3 high-speed exit locations			aircraft type	surface condi-tion	Row #	ROT MEAN (sec)	% using end of runway	% ROT > 53.4	ROT STDEV (sec)	Exit # MEAN	Exit # STDEV	Page or Figure Number
auto rev thr & var dec, w/ PRED lateral touchdown offset = 27 feet	4500	5950	7350	MD-11;	wet surfa	161	47.30	2.31	2.31	21.05	11.50	3.15	P33,P221
auto rev thr & var dec, w/ PRED lateral touchdown offset = 27 feet	4500	5950	7350	MD-11;	dry surfa	162	46.70	1.06	1.06	20.30	11.20	3.10	P33
auto rev thr & var dec, w/ PRED lateral touchdown offset = 27 feet	4500	5950	7350	MD-81;	wet surfa	163	41.50	0.00	0.10	17.17	6.20	2.20	P33,P223
auto rev thr & var dec, w/ PRED lateral touchdown offset = 27 feet	4500	5950	7350	MD-81;	dry surfa	164	41.20	0.21	0.12	15.76	6.10	2.10	P33
LATERAL TOUCHDOWN OFFSET= 27 FEET				Average		165	44.18	0.90	0.90	18.57	8.75	2.64	F6.10
auto rev thr & var dec, w/ PRED aircraft cg stops on exit@Y=480 ft	4500	5950	7350	MD-11;	wet surfa	166	47.40	2.31	2.31	21.05	11.50	3.15	P34,P225
auto rev thr & var dec, w/ PRED aircraft cg stops on exit@Y=480 ft	4500	5950	7350	MD-11;	dry surfa	167	46.80	1.72	1.72	20.25	11.20	3.10	P34
auto rev thr & var dec, w/ PRED aircraft cg stops on exit@Y=480 ft	4500	5950	7350	MD-81;	wet surfa	168	41.50	0.00	0.10	17.11	6.20	2.20	P34,P227
auto rev thr & var dec, w/ PRED aircraft cg stops on exit@Y=480 ft	4500	5950	7350	MD-81;	dry surfa	169	41.30	0.00	0.12	15.71	6.10	2.10	P34
AIRCRAFT CG STOPS ON EXIT AT Y = 480 FEET				Average		170	44.25	1.01	1.06	18.53	8.75	2.64	F6.10

Deceleration method, exit prediction usage and difference from baseline	first 3 high-speed exit locations			aircraft type	surface condi-tion	Row #	ROT MEAN (sec)	% using end of runway	% ROT > 53.4	ROT STDEV (sec)	Exit # MEAN	Exit # STDEV	Page or Figure Number
auto rev thr & var dec, w/ PRED max allowable decel=9ft/s/s	3900	5350	6950	MD-11;	wet surfa	171	45.40	1.72	1.72	22.50	12.10	2.90	P35,P229 F6.11c
auto rev thr & var dec, w/ PRED max allowable decel=9ft/s/s	3900	5350	6950	MD-11;	dry surfa	172	43.20	0.07	0.07	17.85	10.95	2.60	P35 F6.11c
auto rev thr & var dec, w/ PRED max allowable decel=9ft/s/s	3900	5350	6950	MD-81;	wet surfa	173	40.50	0.00	0.23	18.51	7.75	2.65	P35,P231 F6.11b
auto rev thr & var dec, w/ PRED max allowable decel=9ft/s/s	3900	5350	6950	MD-81;	dry surfa	174	38.50	0.00	0.00	17.71	6.85	2.45	P35 F6.11b
ALLOW FOR MAXIMUM DECELERATION OF 9 FT/S/S				Average		175	41.90	0.45	0.51	19.14	9.41	2.65	F6.11a
auto rev thr & var dec, w/ PRED anti-skid eff.=90%	3900	5350	6950	MD-11;	wet surfa	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 surfa	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 surfa	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 surfa	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				Average		180	44.20	2.58	2.58	22.44	10.61	2.83	F6.11a

Deceleration method, exit prediction usage and difference from baseline	first 3 high-speed exit locations			aircraft type	surface condi-tion	Row #	ROT MEAN (sec)	% using end of runway	% ROT > 53.4	ROT STDEV (sec)	Exit # MEAN	Exit # STDEV	Page or Figure Number
auto rev thr & var dec, w/ PRED anti-skid eff.=60%	4500	5950	7350	MD-11;	wet surfa	181	47.40	3.39	3.39	22.55	11.75	3.25	P37,P237 F6.11c
auto rev thr & var dec, w/ PRED anti-skid eff.=60%	4500	5950	7350	MD-11;	dry surfa	182	46.70	1.72	1.72	20.30	11.20	3.10	P37 F6.11c
auto rev thr & var dec, w/ PRED anti-skid eff.=60%	4500	5950	7350	MD-81;	wet surfa	183	41.70	0.00	0.20	17.10	6.30	2.25	P37,P239 F6.11b
auto rev thr & var dec, w/ PRED anti-skid eff.=60%	4500	5950	7350	MD-81;	dry surfa	184	41.20	0.00	0.11	15.76	6.10	2.10	P37 F6.11b
ANTI-SKID EFFICIENCY EQUALS 60% AT MID EXIT LOCATION 5950				Average		185	44.25	1.28	1.36	18.93	8.84	2.68	F6.11a
auto rev thr & var dec, w/ PRED 60 knot high speed exit	3500	4950	6550	MD-11;	wet surfa	186	54.00	23.50	24.10	42.80	15.65	2.85	P38,P241 F6.6c
auto rev thr & var dec, w/ PRED 60 knot high speed exit	3500	4950	6550	MD-11;	dry surfa	187	52.60	19.30	19.30	40.51	15.30	2.80	P38,F6.6c
auto rev thr & var dec, w/ PRED 60 knot high speed exit	3500	4950	6550	MD-81;	wet surfa	188	44.70	0.07	0.40	20.87	10.45	2.55	P38,P243 F6.6b
auto rev thr & var dec, w/ PRED 60 knot high speed exit	3500	4950	6550	MD-81;	dry surfa	189	44.20	0.04	0.00	19.62	10.30	2.40	P38,F6.6b
60 KNOT EXIT ENTRANCE SPEED AT MID EXIT LOCATION 4950				Average		190	48.88	10.73	10.95	30.95	12.93	2.65	F6.6a

Deceleration method, exit prediction usage and difference from baseline	first 3 high-speed exit locations			aircraft type	surface condi-tion	Row #	ROT MEAN (sec)	% using end of runway	% ROT > 53.4	ROT STDEV (sec)	Exit # MEAN	Exit # STDEV	Page or Figure Number
auto rev thr & var dec, w/ PRED 40 knot high speed exit	4500	5950	7350	MD-11;	wet surfa	191	66.10	15.10	99.60	37.40	14.35	3.25	P39,P245 F6.6c
auto rev thr & var dec, w/ PRED 40 knot high speed exit	4500	5950	7350	MD-11;	dry surfa	192	64.00	9.64	99.30	33.96	13.75	3.15	P39,F6.6c
auto rev thr & var dec, w/ PRED 40 knot high speed exit	4500	5950	7350	MD-81;	wet surfa	193	57.80	0.01	76.00	23.80	8.65	2.65	P39,P247 F6.6b
auto rev thr & var dec, w/ PRED 40 knot high speed exit	4500	5950	7350	MD-81;	dry surfa	194	57.10	0.00	72.00	23.48	8.35	2.65	P39,F6.6b
40 KNOT EXIT ENTRANCE SPEED AT MID EXIT LOCATION 5950				Average		195	61.25	6.19	86.73	29.66	11.28	2.93	F6.6a
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	P40 F6.2c,12c
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	P40 F6.2b,12b
REVERSE THRUST NOT STOWED ON EXIT				Average		200	44.40	1.01	1.52	19.93	8.75	2.64	F6.2a,12a

Deceleration method, exit prediction usage and difference from baseline	first 3 high-speed exit locations			aircraft type	surface condi-tion	Row #	ROT MEAN (sec)	% using end of runway	% ROT > 53.4	ROT STDEV (sec)	Exit # MEAN	Exit # STDEV	Page or Figure Number
auto rev thr & var dec, w/ PRED, Rev Thr Idle on Runway	4500	5950	7350	MD-11;	wet surfa	201	48.80	5.67	5.67	25.20	12.20	3.45	P41,P253 F6.12c
auto rev thr & var dec, w/ PRED, Rev Thr Idle on Runway	4500	5950	7350	MD-11;	dry surfa	202	46.80	1.72	1.72	20.20	11.25	3.10	P41 F6.12c
auto rev thr & var dec, w/ PRED, Rev Thr Idle on Runway	4500	5950	7350	MD-81;	wet surfa	203	41.70	0.00	0.11	17.52	6.30	2.25	P41,P255 F6.12b
auto rev thr & var dec, w/ PRED, Rev Thr Idle on Runway	4500	5950	7350	MD-81;	dry surfa	204	41.20	0.00	0.11	15.76	6.10	2.10	P41 F6.12b
REVERSE THRUST IDLE ON RUNWAY				Average		205	44.63	1.85	1.90	19.67	8.96	2.73	F6.12a
auto rev thr & var dec, w/ PRED, NO Reverse Thrust	4500	5950	7350	MD-11;	wet surfa	206	53.30	20.30	36.00	33.05	14.40	3.70	P42,P257 F6.12c
auto rev thr & var dec, w/ PRED, NO Reverse Thrust	4500	5950	7350	MD-11;	dry surfa	207	47.80	2.60	2.60	20.87	11.75	3.10	P42 F6.12c
auto rev thr & var dec, w/ PRED, NO Reverse Thrust	4500	5950	7350	MD-81;	wet surfa	208	43.70	0.12	2.20	21.44	7.45	2.90	P42,P259 F6.12b
auto rev thr & var dec, w/ PRED, NO Reverse Thrust	4500	5950	7350	MD-81;	dry surfa	209	41.70	0.00	0.00	15.95	6.45	2.30	P42 F6.12b
NO REVERSE THRUST				Average		210	46.63	5.76	10.20	22.83	10.01	3.00	F6.12a

Deceleration method, exit prediction usage and difference from baseline	first 3 high-speed exit locations			aircraft type	surface condi-tion	Row #	ROT MEAN (sec)	% using end of runway	% ROT > 53.4	ROT STDEV (sec)	Exit # MEAN	Exit # STDEV	Page or Figure Number
immediate max rev thr & 6.5 dec, then coast after 70 kts,NO PRED	3500	4950	6550	MD-11;	wet surfa	211	48.00	8.50	8.61	44.45	13.90	2.95	P43,P261
immediate max rev thr & 6.5 dec, then coast after 70 kts,NO PRED	3500	4950	6550	MD-11;	dry surfa	212	46.90	5.94	5.94	36.35	13.55	2.90	P43
immediate max rev thr & 6.5 dec, then coast after 70 kts,NO PRED	3500	4950	6550	MD-81;	wet surfa	213	40.80	0.01	0.00	23.27	9.00	2.65	P43,P263
immediate max rev thr & 6.5 dec, then coast after 70 kts,NO PRED	3500	4950	6550	MD-81;	dry surfa	214	39.70	0.00	0.00	21.04	8.50	2.60	P43
DECEL METHOD, NON-ROTO				Average		215	43.85	3.61	3.64	31.28	11.24	2.78	F6.4
immediate max rev thr & 6.5 dec, then coast after 70 kts,NO PRED	3900	5350	6950	MD-11;	wet surfa	216	46.90	3.37	10.20	32.95	12.60	3.05	P44,P265
immediate max rev thr & 6.5 dec, then coast after 70 kts,NO PRED	3900	5350	6950	MD-11;	dry surfa	217	46.00	2.13	2.77	27.45	12.20	3.00	P44
immediate max rev thr & 6.5 dec, then coast after 70 kts,NO PRED	3900	5350	6950	MD-81;	wet surfa	218	40.50	0.00	0.30	22.69	7.50	2.70	P44,P267
immediate max rev thr & 6.5 dec, then coast after 70 kts,NO PRED	3900	5350	6950	MD-81;	dry surfa	219	39.50	0.00	0.00	20.87	7.00	2.50	P44
DECEL METHOD, NON-ROTO				Average		220	43.23	1.38	3.32	25.99	9.83	2.81	F6.4

Deceleration method, exit prediction usage and difference from baseline	first 3 high-speed exit locations			aircraft type	surface condi-tion	Row #	ROT MEAN (sec)	% using end of runway	% ROT > 53.4	ROT STDEV (sec)	Exit # MEAN	Exit # STDEV	Page or Figure Number
immediate max rev thr & 6.5 dec, then coast after 70 kts,NO PRED	4500	5950	7350	MD-11;	wet surfa	221	45.90	1.14	6.28	25.20	10.60	3.10	P45,P269 F6.3c,5c
immediate max rev thr & 6.5 dec, then coast after 70 kts,NO PRED	4500	5950	7350	MD-11;	dry surfa	222	45.30	0.67	0.75	21.50	10.25	3.05	P45,P271 F6.3c,5c
immediate max rev thr & 6.5 dec, then coast after 70 kts,NO PRED	4500	5950	7350	MD-81;	wet surfa	223	41.90	0.00	0.30	20.33	5.85	1.90	P45,P273 F6.3b,5b
immediate max rev thr & 6.5 dec, then coast after 70 kts,NO PRED	4500	5950	7350	MD-81;	dry surfa	224	41.00	0.00	0.20	18.68	5.60	1.60	P45,P275 F6.3b,5b
DECEL METHOD, NON-ROTO				Average		225	43.53	0.45	1.88	21.43	8.08	2.41	F6.3a F6.4 F6.5a
auto rev thr & var dec, w/ PRED auto asymmetric braking on exit	4500	5950	7350	MD-11;	wet surfa	226	45.70	2.31	2.31	21.25	11.50	3.15	P46,P277 F6.2c
auto rev thr & var dec, w/ PRED auto asymmetric braking on exit	4500	5950	7350	MD-11;	dry surfa	227	45.00	1.72	1.72	20.45	11.20	3.10	P46,F6.2c
auto rev thr & var dec, w/ PRED auto asymmetric braking on exit	4500	5950	7350	MD-81;	wet surfa	228	40.30	0.00	0.10	17.12	6.20	2.20	P46,P279 F6.2b
auto rev thr & var dec, w/ PRED auto asymmetric braking on exit	4500	5950	7350	MD-81;	dry surfa	229	39.60	0.00	0.11	16.92	6.10	2.10	P46,F6.2b
AUTO ASYMMETRIC BRAKING ON EXIT				Average		230	42.65	1.01	1.06	18.93	8.75	2.64	F6.2a

Deceleration method, exit prediction usage and difference from baseline	first 3 high-speed exit locations	aircraft type	surface condi-tion	Row #	ROT MEAN (sec)	% using end of runway	% ROT > 53.4	ROT STDEV (sec)	Exit # MEAN	Exit # STDEV	Page or Figure Number
auto rev thr & var dec, w/ PRED anti-skid eff.=90%	4500 5950 7350	MD-11;	wet surfa	231	47.10	1.99	1.99	20.60	11.40	3.15	P47,P281 F6.11c
auto rev thr & var dec, w/ PRED anti-skid eff.=90%	4500 5950 7350	MD-11;	dry surfa	232	46.70	1.72	1.72	20.30	11.20	3.10	P47 F6.11c
auto rev thr & var dec, w/ PRED anti-skid eff.=90%	4500 5950 7350	MD-81;	wet surfa	233	41.50	0.00	0.11	16.05	6.15	2.15	P47,P283 F6.11b
auto rev thr & var dec, w/ PRED anti-skid eff.=90%	4500 5950 7350	MD-81;	dry surfa	234	41.20	0.00	0.12	15.76	6.10	2.10	P47 F6.11b
ANTI-SKID EFFICIENCY EQUALS 90% AT MID EXIT LOCATION 5950		Average		235	44.13	0.93	0.99	18.18	8.71	2.63	F6.11a
auto rev thr & var dec, w/ PRED 40 knot high speed exit	3900 5350 6950	MD-11;	wet surfa	236	68.60	27.80	99.30	47.00	15.95	2.85	P48,P285 F6.6c
auto rev thr & var dec, w/ PRED 40 knot high speed exit	3900 5350 6950	MD-11;	dry surfa	237	66.30	20.70	96.90	44.20	15.45	2.80	P48,F6.6c
auto rev thr & var dec, w/ PRED 40 knot high speed exit	3900 5350 6950	MD-81;	wet surfa	238	58.20	0.11	86.10	23.93	10.70	2.50	P48,P287 F6.6b
auto rev thr & var dec, w/ PRED 40 knot high speed exit	3900 5350 6950	MD-81;	dry surfa	239	57.20	0.05	81.30	23.45	10.40	2.50	P48,F6.6b
40 KNOT EXIT ENTRANCE SPEED AT MID EXIT LOCATION 5350		Average		240	62.58	12.17	90.90	34.64	13.13	2.66	F6.6a

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 summaries 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.

Aircraft Data	**Runway & exit #**	**Surface Condition**	**ROT mean (sec)**	**ROT stdev (sec)**
Assume all landings have equal probability.				
Actual MD-8x landings	13R, 1	dry	46.5	1.72
Each landing does not have equal probability.				
Simulated MD-81 dispersion	13R, 1	dry	45.6	5.04
Simulated MD-11 dispersion	13R, 1	dry	44.0	8.76
Simulated MD-81 dispersion	13R, 1	wet	45.7	5.27
Simulated MD-11 dispersion	13R, 1	wet	51	12
Simulated MD-81 dispersion	study, 3	dry	41.2	3.22
Simulated MD-11 dispersion	study, 3	dry	46.8	4.02
Simulated MD-81 dispersion	study, 3	wet	41.2	3.22
Simulated MD-11 dispersion	study, 3	wet	47.2	4.16

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.

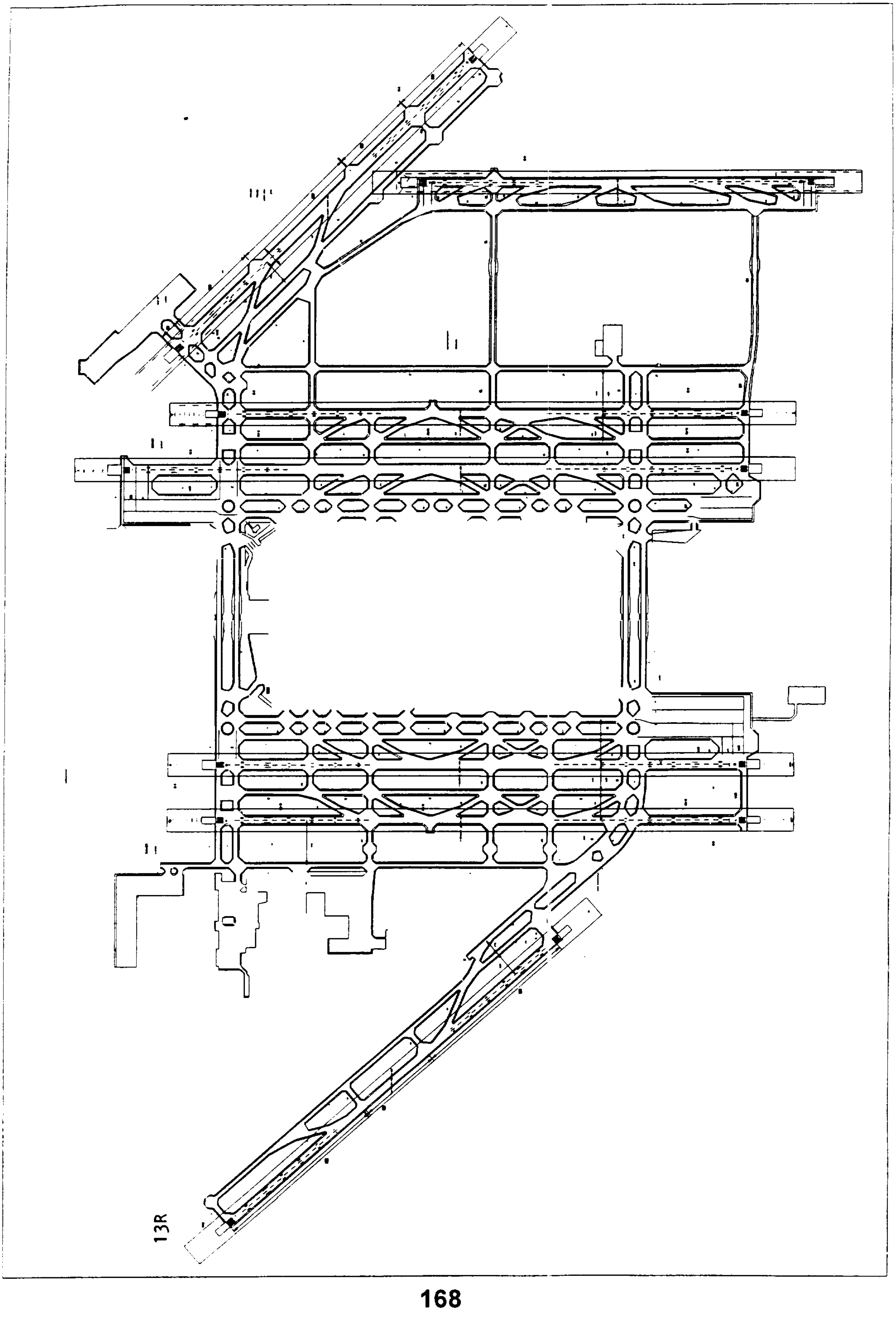
Officially, there are no procedures nor training for the use of high-speed exits, at the flight crew's discretion, under daylight VMC conditions with no runway/exit surface contamination. If runway productivity would benefit, perhaps official training would also allow pilots to apply their manual skills 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.

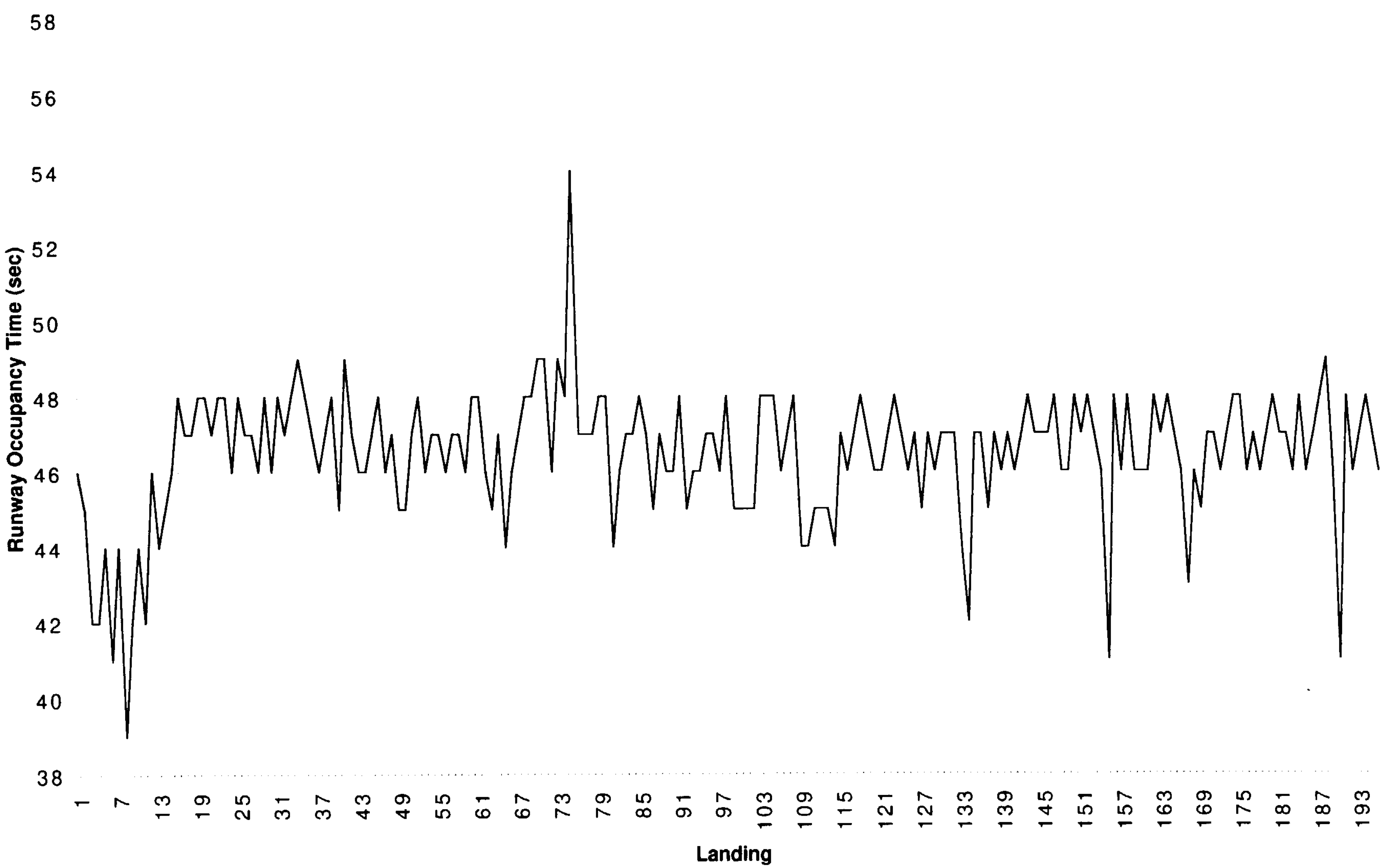
Exit prediction logic could select the appropriate aircraft longitudinal touchdown point based on the predicted aircraft touchdown ground speed and the runway's high-speed exit location. Unlike ILS's stationary glideslope beam, DGPS and navigation software could allow for a variable longitudinal touchdown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

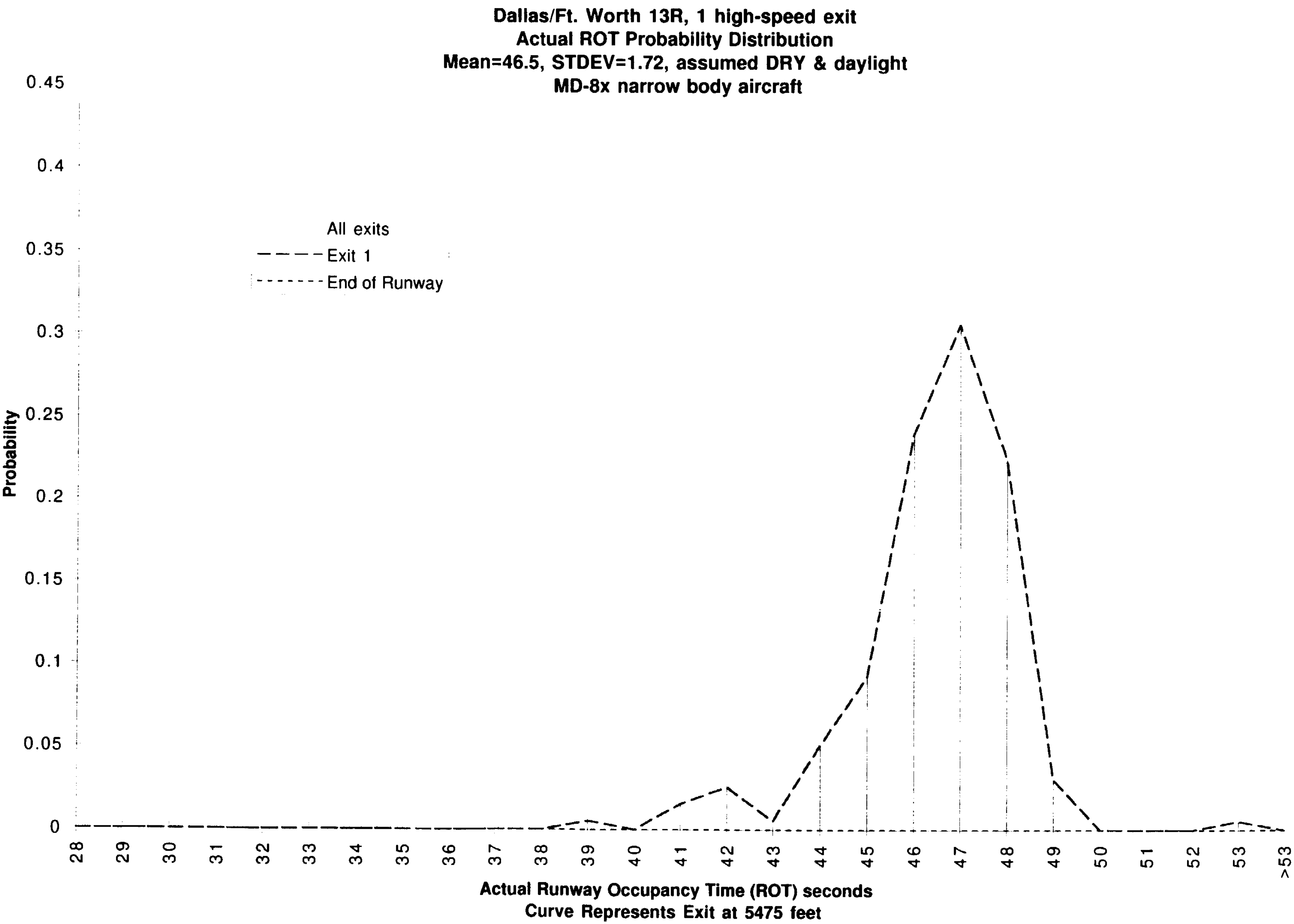
In addition to single high-speed exit runways having a lower construction cost, they also benefit from there being no immediate contention on the parallel taxi-way. In this situation, aircraft would not need to stop on the high-speed exit, and should not for continuous ROTO operations with aircraft spacing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


13R

Dallas/Ft. Worth 13R Actual Runway Occupancy Times
MD-8x narrow body aircraft





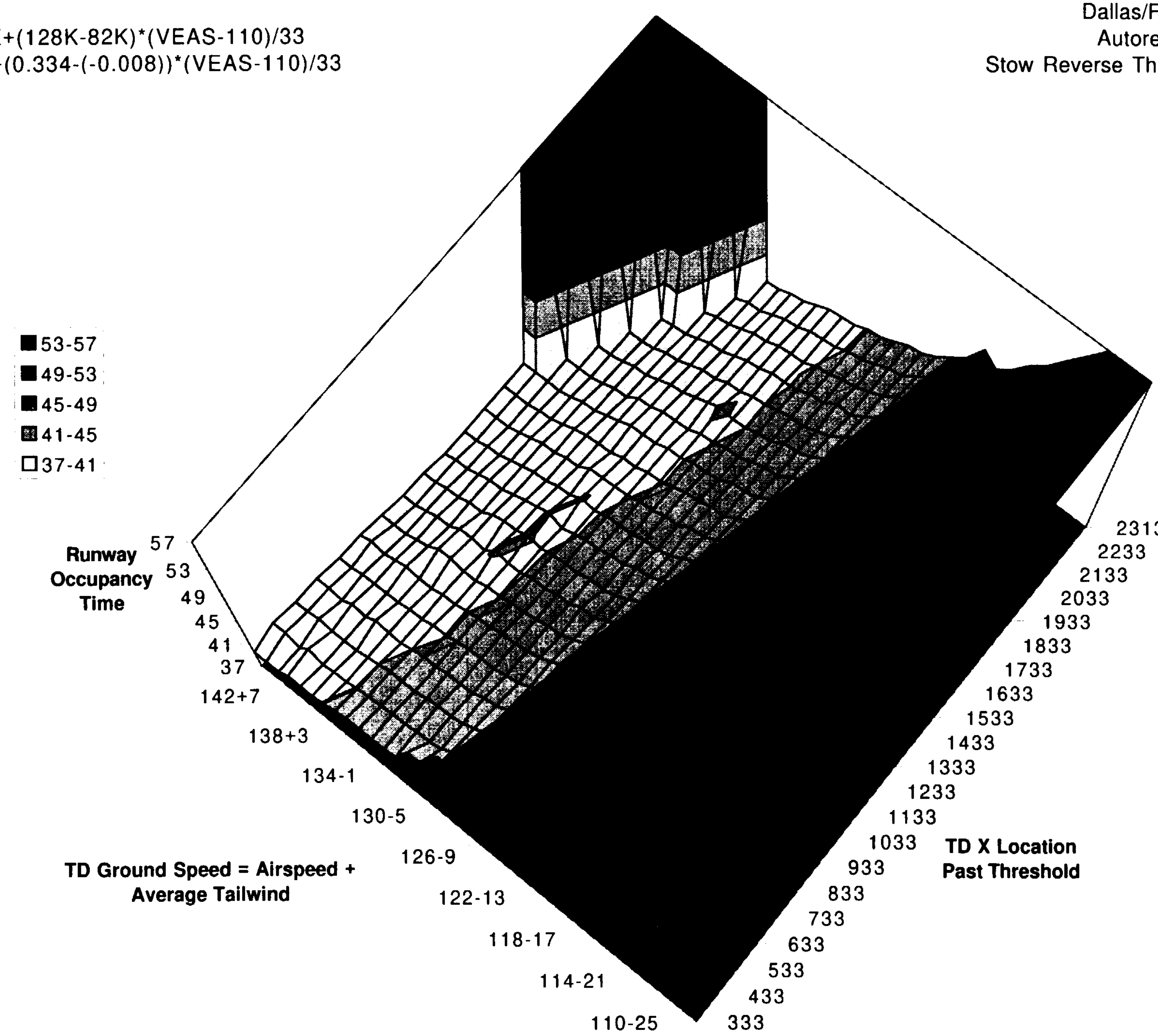
Dallas/Ft. Worth 13R, 1 high-speed exit
Actual ROT Probability Distribution
Mean=46.5, STDEV=1.72, assumed DRY & daylight
MD-8x narrow body aircraft
All exits
Exit 1
End of Runway
Probability
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
>53
Actual Runway Occupancy Time (ROT) seconds
Curve Represents Exit at 5475 feet

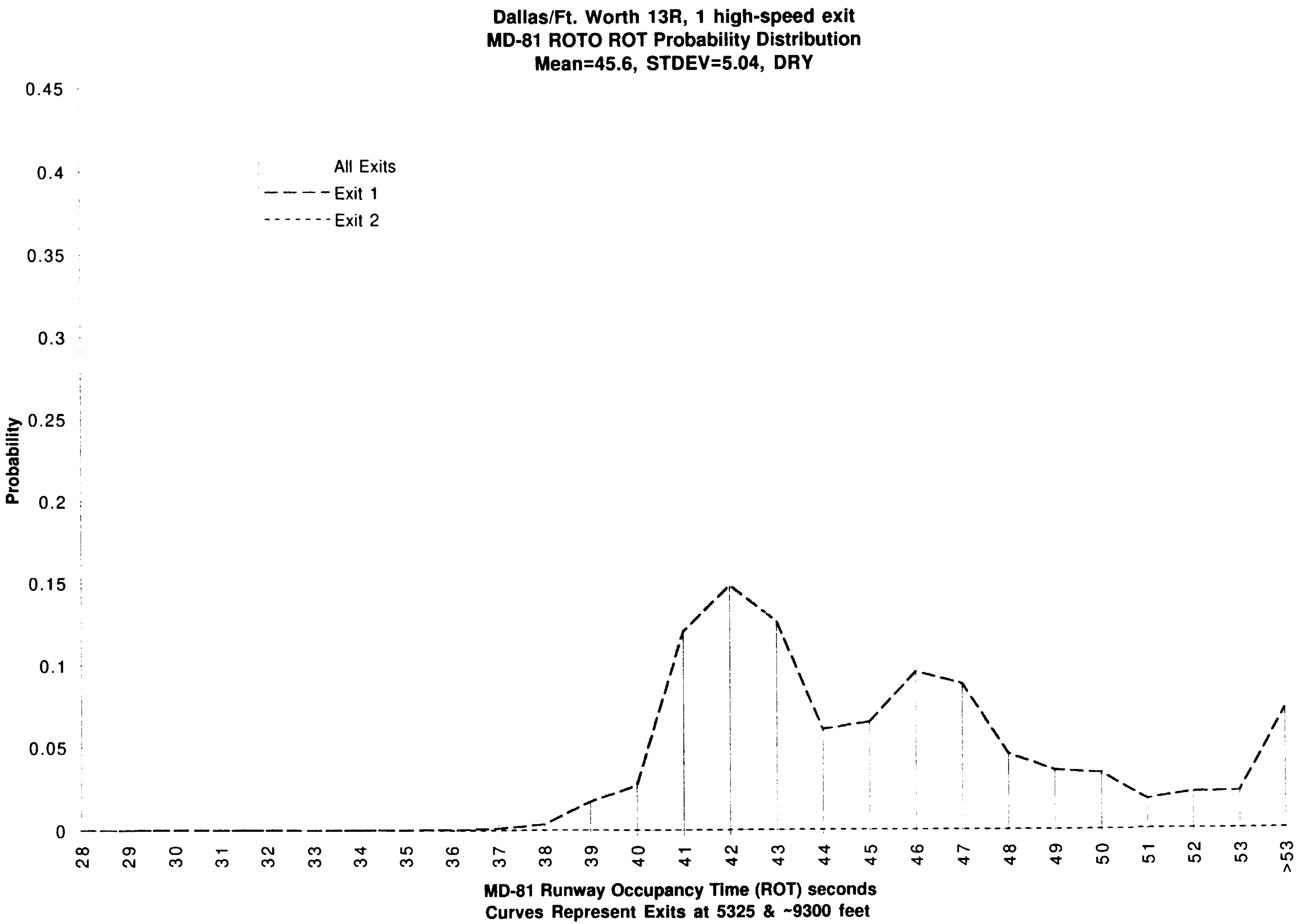
Predict exit prior to TD

MD-81 ROTO Occupancy Time

Dry,Exits=5325, 9300
Dallas/Ft. Worth 13R
Autoreverse Thrust
Stow Reverse Thrust=70 kt gd

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





Dallas/Ft. Worth 13R, 1 high-speed exit
MD-81 ROTO ROT Probability Distribution
Mean=45.6, STDEV=5.04, DRY
All Exits
Exit 1
Exit 2
Probability
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 >53
MD-81 Runway Occupancy Time (ROT) seconds
Curves Represent Exits at 5325 & ~9300 feet

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13. ABSTRACT *(Maximum 200 words)*

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.

14. SUBJECT TERMS
Rollout and Turnoff, Runway Occupancy Time, Low Visibility Landing and Surface Operations, Terminal Area Transport Aircraft Operations, Airport Capacity, rollout and turnoff guidance, Runway Occupancy Time Sensitivity

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