Appendix A

Simulation Environment

Simplicity is the ultimate form of sophistication.

Leonardo da Vinci (1452-1519)

Italian Scientist, Mathematician, Engineer, Inventor and Artist

This appendix provides additional information on the vehicle environment including the reference frames used within the optimisation and guidance programs. The density profiles for the world and the Hopper and X-33 vehicles terminal area flight phase are also included along with a comparison of the model errors.

A.1 Coordinate Frames and Transformations

The programs utilised in this study contain many different co-ordinate systems and reference frames used for describing the vehicle dynamics. These reference frames include inertial, geocentric, horizontal, body and velocity co-ordinate systems. A detailed description including diagrams of each reference frame and the transformations between the systems is presented in Schöttle (1979) and Burkhardt (2000).

The position and velocity vectors for the vehicle are given by equations A.1 and A.2 respectively.

$$\vec{r} = \begin{bmatrix} r \\ \lambda \\ \delta \end{bmatrix} \tag{A.1}$$

$$\vec{v} = \begin{bmatrix} v \\ \gamma \\ \chi \end{bmatrix} \tag{A.2}$$

A.2 Density Profiles

The density profiles used within this study are taken from the US Standard 1962 and MSISE 1993 atmospheric models. This section presents the different density profile models for world wide and the individual flight environments pertaining to the vehicle missions as seen in figures A.1, A.2, A.3, A.4, A.5 and A.6. A comparison of the US Standard 1962 and MSISE 1993 density profiles is also presented to show the difference in the models used between the simulator and predictor.

A.3 Wind Profiles

This section presents the wind profiles generated from the Horizontal Wind Model (HWM). The wind profiles are for both the Hopper and X-33 vehicles and their associ-

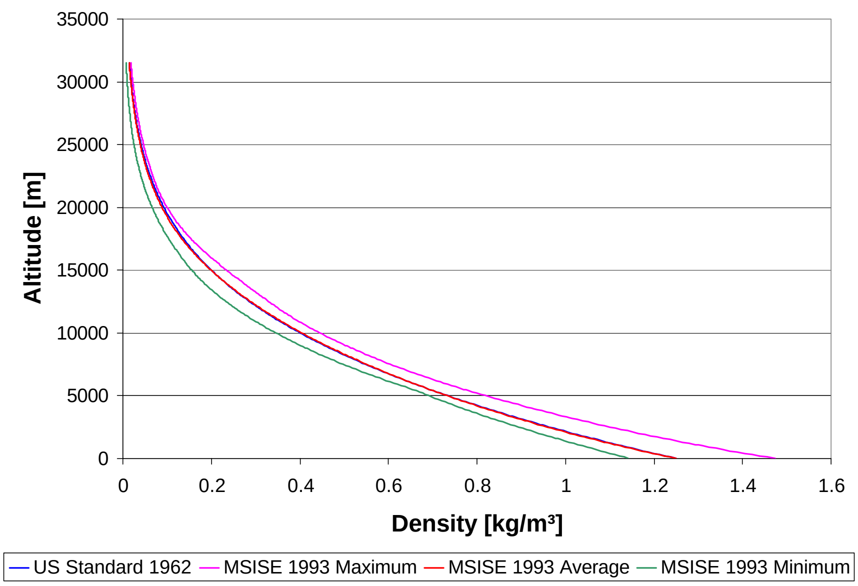

Figure A.1: The density profiles for the world wide models: US Standard 1962 and MSISE 1993

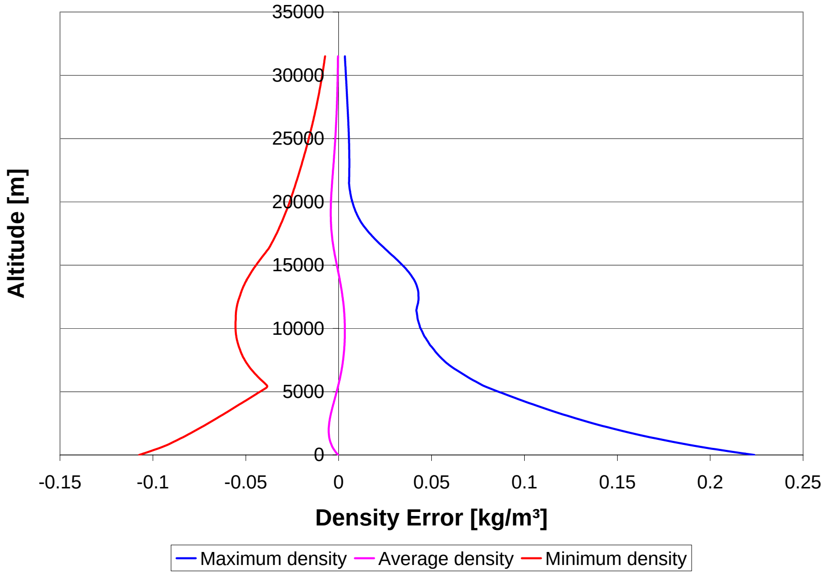

Figure A.2: The density errors for the world wide models: MSISE 1993 - US Standard 1962

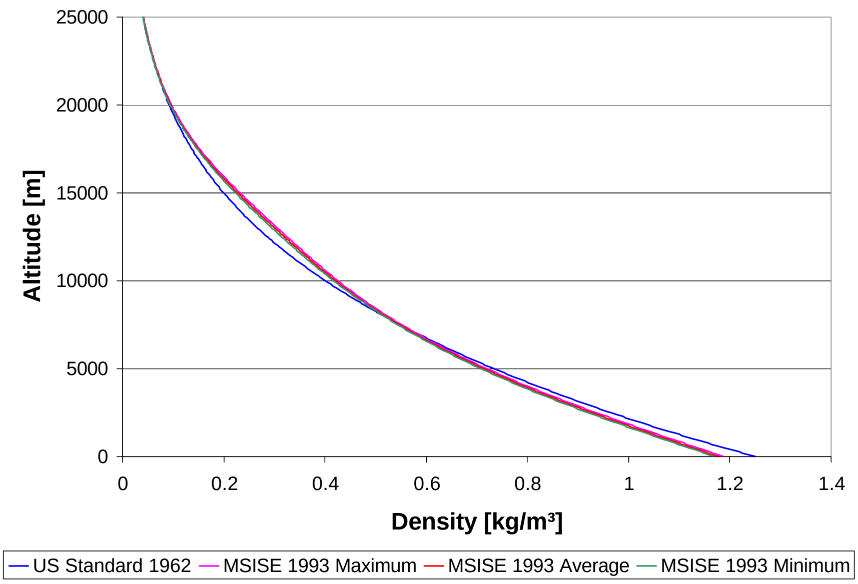

Figure A.3: The density profiles for the Hopper vehicle terminal area flight phase: US Standard 1962 and MSISE 1993

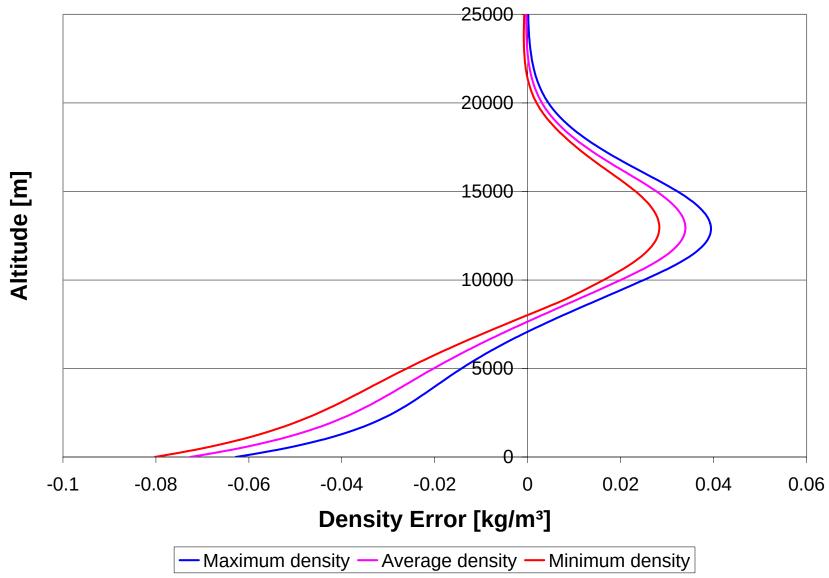

Figure A.4: The density errors for the Hopper vehicle terminal area flight phase: The Hopper vehicle mission MSISE 1993 - US Standard 1962

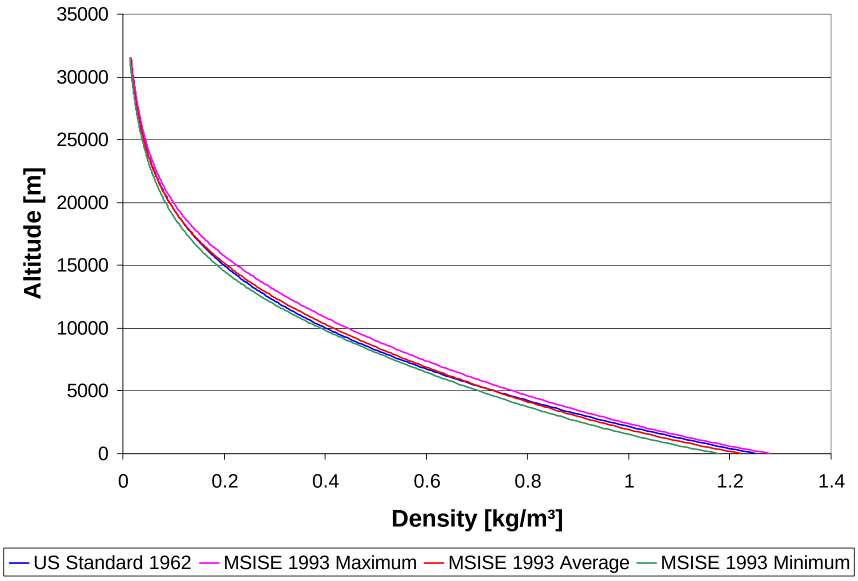

Figure A.5: The density profiles for the X-33 vehicle terminal area flight phase: US Standard 1962 and MSISE 1993

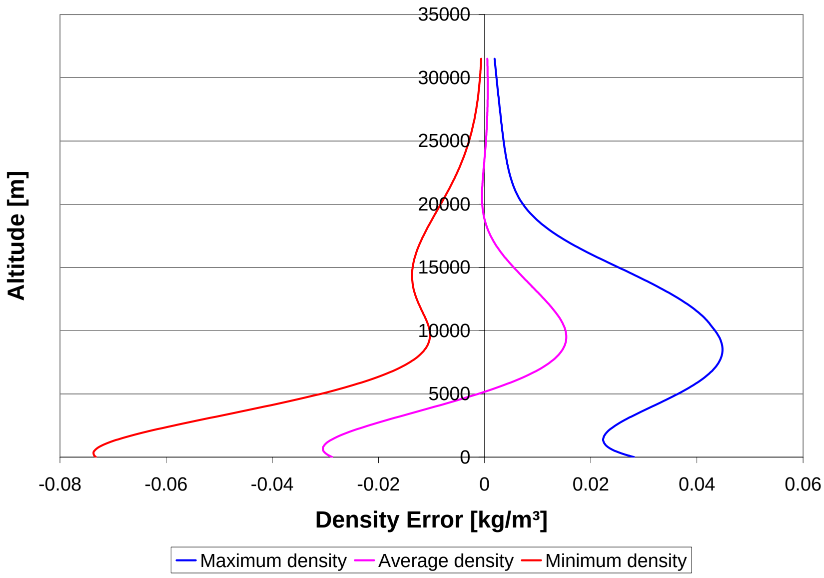

Figure A.6: The density errors for the X-33 vehicle terminal area flight phase: The X-33 vehicle mission MSISE 1993 - US Standard 1962

ated missions. Figures A.11, A.12 and A.13 also include the predictor wind profiles in comparison to those of the HWM.

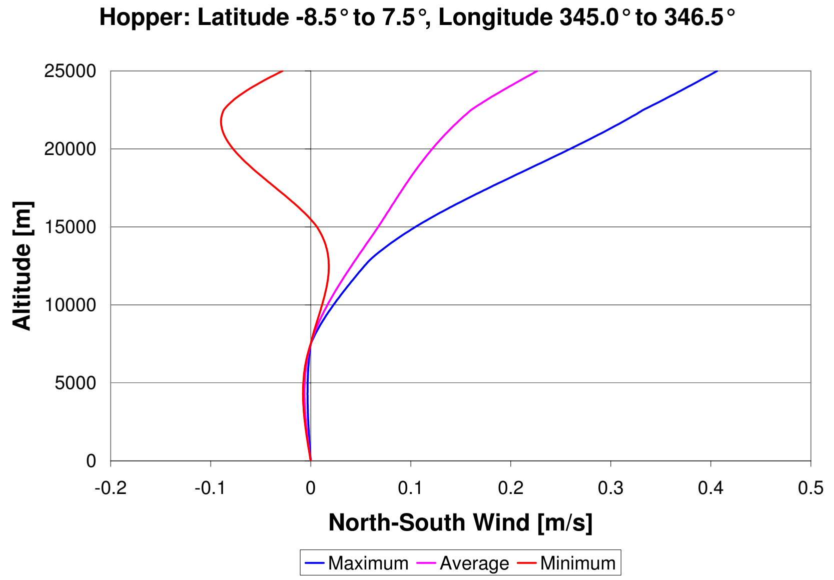

Figure A.7: The HWM profiles for the Hopper vehicle mission with positive values representing a northerly direction wind and negative values a southerly direction wind

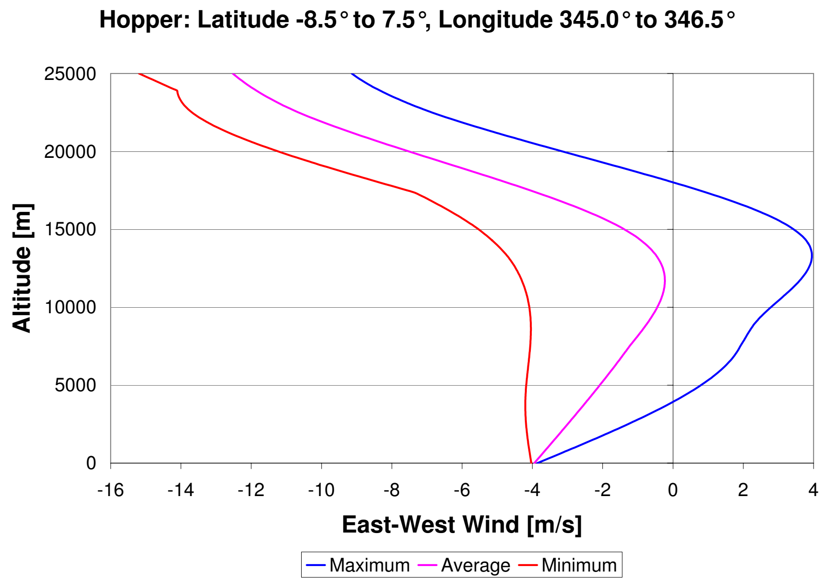

Figure A.8: The HWM profiles for the Hopper vehicle mission with positive values representing a westerly direction wind and negative values an easterly direction wind

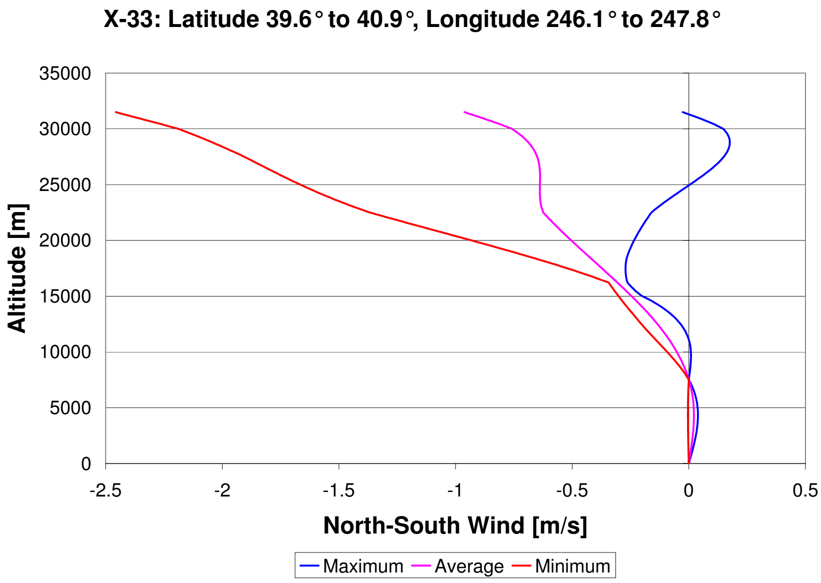

Figure A.9: The HWM profiles for the X-33 vehicle mission with positive values representing a northerly direction wind and negative values a southerly direction wind

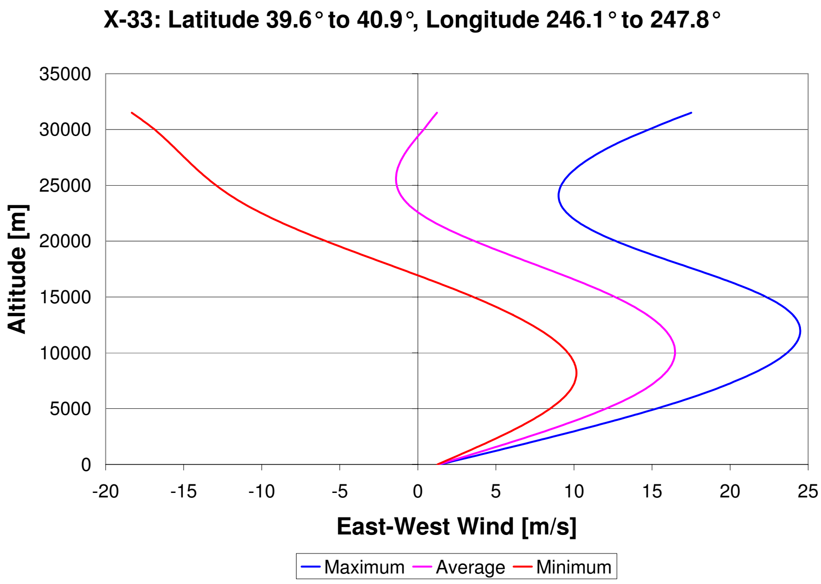

Figure A.10: The HWM profiles for the X-33 vehicle mission with positive values representing a westerly direction wind and negative values an easterly direction wind

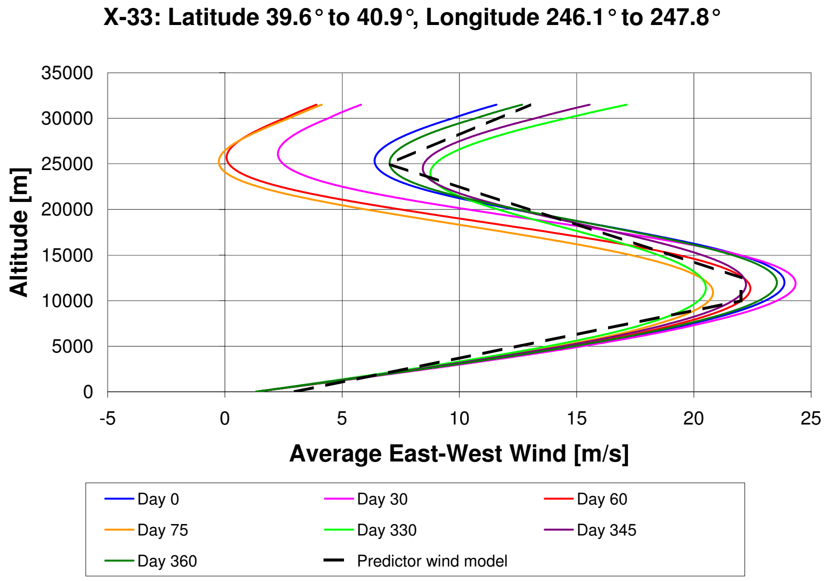

Figure A.11: The HWM profiles for the X-33 vehicle mission with various days and predictor wind model for strong winds. Positive values represent a westerly direction wind and negative values an easterly direction wind

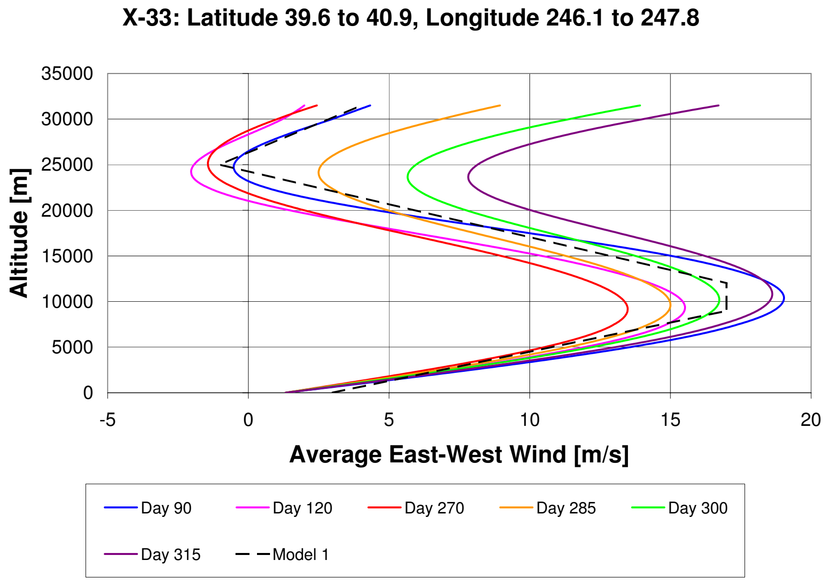

Figure A.12: The HWM profiles for the X-33 vehicle mission with various days and predictor wind model for medium winds. Positive values represent a westerly direction wind and negative values an easterly direction wind

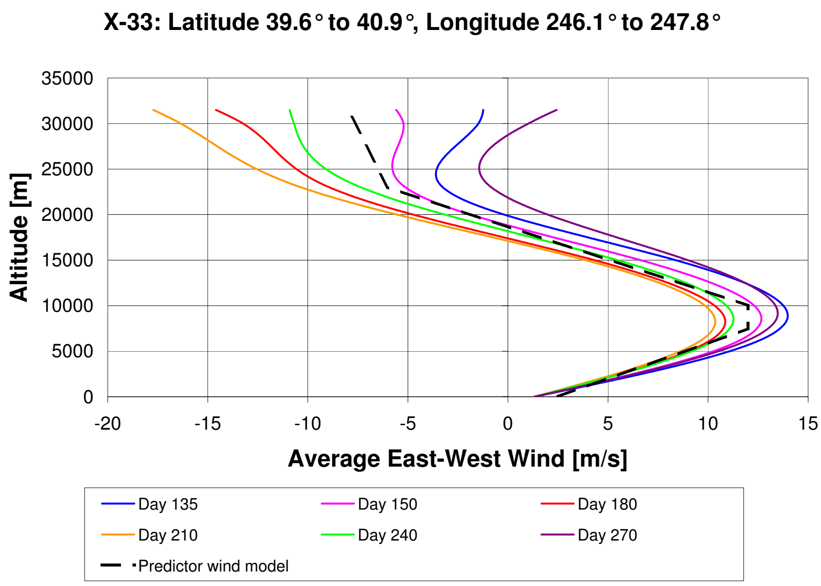

Figure A.13: The HWM profiles for the X-33 vehicle mission with various days and predictor wind model for light winds. Positive values represent a westerly direction wind and negative values an easterly direction wind

Appendix B

Numerical Methods

The latest authors, like the most ancient, strove to subordinate the phenomena of nature to the laws of mathematics.

Sir Isaac Newton (1642-1727)
English Physicist, Mathematician, Astronomer, Alchemist, and Natural Philosopher

This appendix details the common numerical recipes used during the optimisation and guidance programs. It also defines some of the numerical methods used in evaluating the results.

B.1 Vehicle and Trajectory Characteristics

During the trajectory there are several characteristics and restrictions that the guidance system must cope with. In order to determine whether the trajectory is within these restrictions several different calculations are required. These calculations are detailed below in the following sections and were derived from theoretical and empirical methods.

B.2 Mach Number Calculations

The equation for the Mach number, Ma of the vehicle is shown in figure

$$Ma = \frac{v}{a} \tag{B.1}$$

Where v is the current velocity of the vehicle and the speed of sound, a is given by equation B.2.

$$a = \sqrt{\kappa \cdot R_{Gas} T} \tag{B.2}$$

Where κ is the ratio of specific heats also known as the adiabatic index, 1.402 for air. R is the gas constant, 287.05 $\mathrm{J \cdot kg^{-1} \cdot K^{-1}}$ and T is the temperature in °K.

B.3 Statistics

For the analysis of results common statistical methods including the average and standard deviation were used, these are defined in equations B.3 and B.4. Where n is the number of simulations, x_i the value of the simulation, $\bar{x}$ the average value and σ the standard deviation.

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{B.3}$$

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2} \tag{B.4}$$

B.4 Unit Conversions

Some the data provide for the X-33 vehicle was in non Systéme International (SI) units and consequently conversions were required to transfer these units as given in table B.1.

Unit		Conversion
1ft	=	0.3048 m
1 m	=	3.2808 ft
1 ft/s	=	0.3048 m/s
1 m/s	=	3.2808 ft/s
1 psf	=	0.0478803 kPa
1 kPa	=	20.8854 psf

Table B.1: Unit conversions

Appendix C

Hopper Vehicle Speed Brake Model

Make everything as simple as possible, but not simpler.

Albert Einstein (1879-1955)

Theoretical Physicist

A large modification made to the optimisation and guidance programs was the development and inclusion of the speed brake model for the Hopper vehicle. The model was developed from two major models the HL-20 lifting body vehicle Jackson et al. (1992); Jackson and Cruz (1992) and X-34 demonstration vehicle Pamadi and Brauckmann (1999); Pamadi et al. (2000). Although it might not be a true representation of the actual speed brake model it is used as a guide for further development of the optimisation and guidance programs. The speed brake model provides the increases in the Hopper vehicle drag for increased speed brake settings. The model is a table of additional drag coefficients as a function of angle of attack and Mach number.

The purpose of this study was not to further an aerodynamic model of the Hopper vehicle nor was it to determine the accuracy of a speed brake model, which for this study is a 'best guess' model. However, some important characteristics of the speed brake model are drawn from basic aerodynamic knowledge.

The speed brakes for the Hopper vehicle are placed on the sides of the fuselage above the wings as shown in figure C.1. This placement should cause some disturbance of the flow of the speed brakes for high angles of attack and for transonic speeds traditionally considered Mach 0.8 to 1.2. This was represented in the upper body flap model of the HL-20 lifting body vehicle. However, comparison to the X-34 model

Figure C.1: The Hopper vehicle with speed brakes

which has a rudder mounted speed brake similar to the US Shuttle Orbiter showed that the magnitude of the drag coefficients were lower then should be expected for a speed brake. There were insufficient data points available for the X-34 vehicle model therefore the HL-20 data was biased with respect to the limited X-34 data to provide a better approximation. Figures C.2, C.3, C.4 and C.5 show the increased drag (at maximum setting) with respect to Mach number for different angle of attack settings.

Intermediate data points were determined using either linear or fourth order spline interpolation. However, the original model had too few data points to accurately reproduce all features with spline especially in the transonic flight region of figures C.2, C.3, C.4 and C.5. Consequently an increased number of data points was produced for the transonic region using more data from the HL-20 model, some interpolation and engineering judgement to produce the final models presented here. Tables C.1 and C.2 present the final data in tabular form used for this study. The figures C.2, C.3, C.4, C.5 and tables C.1, C.2 presented the maximum increased drag, that is the increased drag at maximum speed brake setting.The speed brake setting steering variable is defined as a percentage of the maximum possible drag increase. Note it was assumed that a reduction of drag coefficients occurred for the transonic Mach numbers. This was included because it was assumed that the flow over the wing surfaces was disturbed and consequently poor flow over the speed brakes was achieved. This assumption was based upon the information from the HL-20 vehicle upper body flap model Jackson et al.

(1992); Jackson and Cruz (1992).

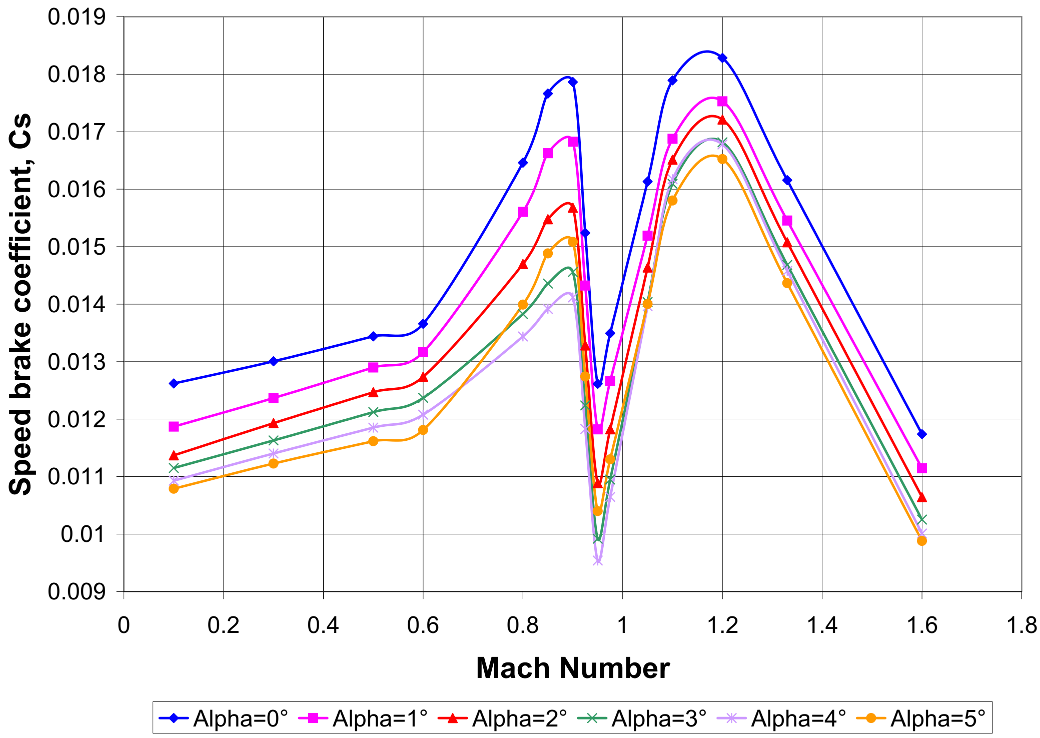

Figure C.2: Speed brake coefficient, C_s vs Mach number for angle of attacks 0 to 5°

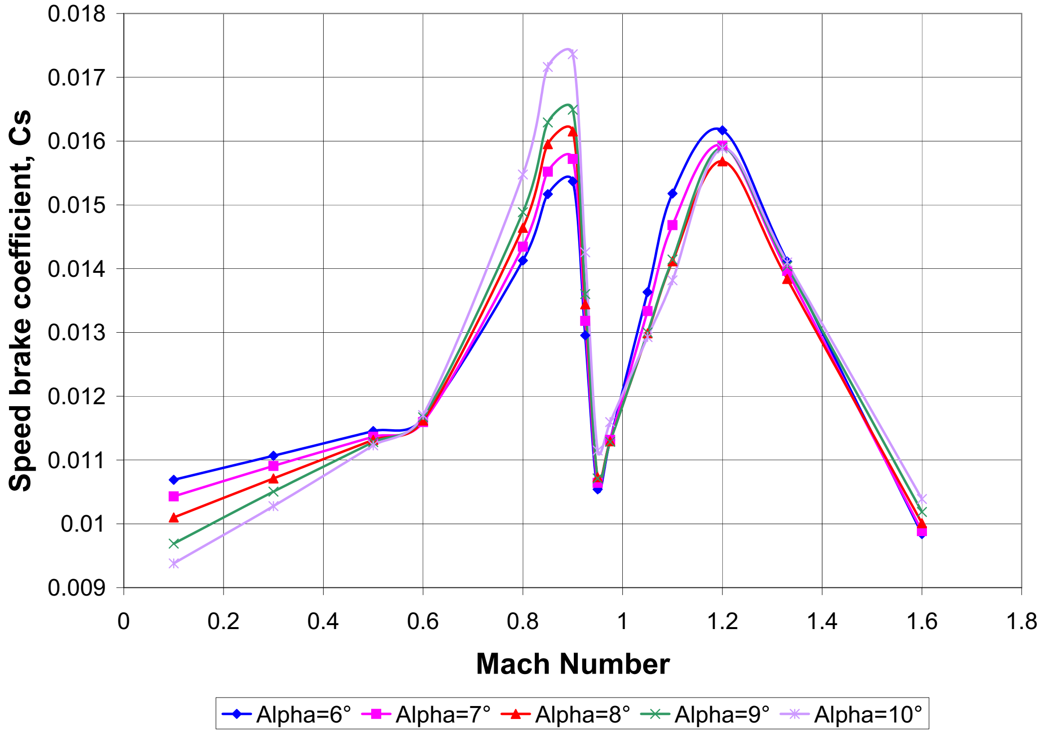

Figure C.3: Speed brake coefficient, C_s vs Mach number for angle of attacks 6 to 10°

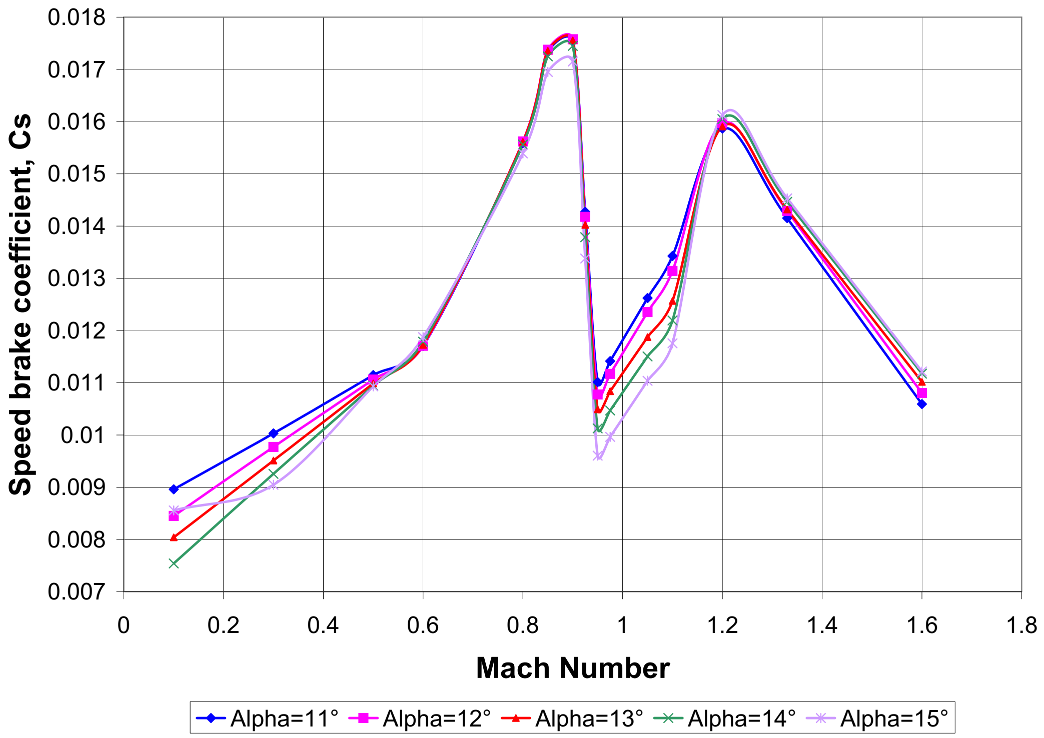

Figure C.4: Speed brake coefficient, C_s vs Mach number for angle of attacks 11 to 15°

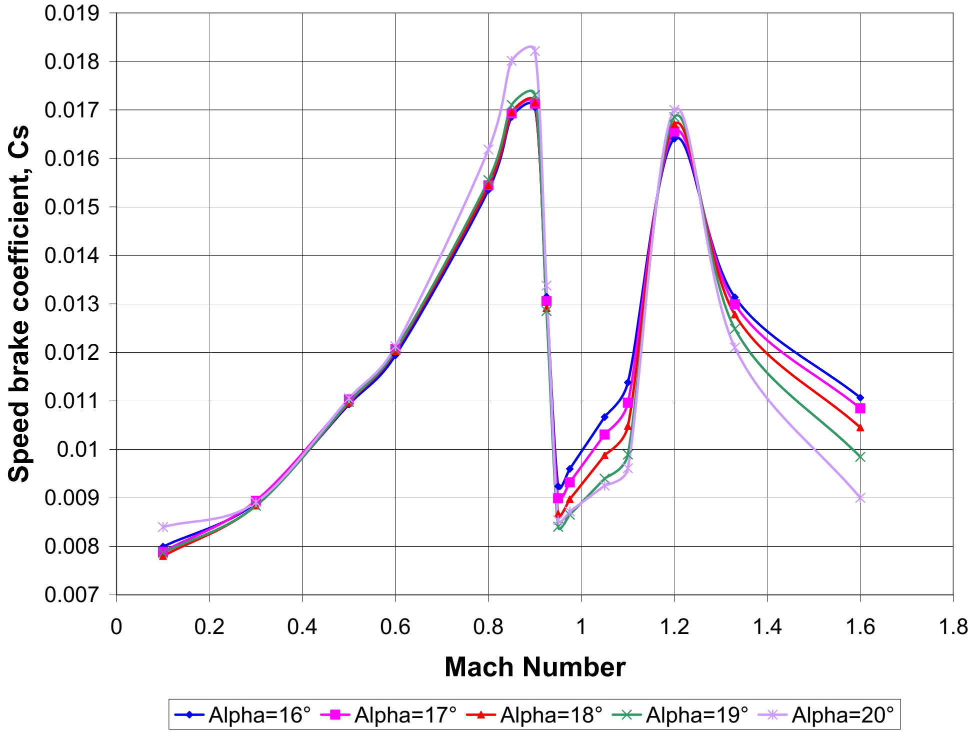

Figure C.5: Speed brake coefficient, C_s vs Mach number for angle of attacks 16 to 20°

	Angle of Attack							
Mach Number	0.1	0.3	0.5	0.6	0.8	0.85	0.9	0.925
0.0	0.01262	0.013006554	0.013440628	0.013657664	0.016461301	0.01766312	0.01786312	0.01523894
1.0	0.01187	0.012367249	0.012898887	0.013164706	0.015605358	0.016625683	0.016825683	0.014323458
2.0	0.01137	0.011930333	0.012467893	0.012736673	0.014697085	0.015477291	0.015677291	0.013281397
3.0	0.01115	0.011629337	0.012122905	0.012369689	0.013828398	0.014357752	0.014557752	0.012239085
4.0	0.01093	0.011402294	0.011852912	0.012078222	0.013437487	0.01391712	0.01411712	0.011829134
5.0	0.01079	0.011227431	0.011616611	0.0118112	0.013992423	0.014883034	0.015083034	0.012741788
6.0	0.01069	0.011067285	0.011454671	0.011648363	0.014127909	0.015167682	0.015367682	0.012954
7.0	0.01043	0.010907093	0.011365788	0.011595136	0.014345028	0.015519975	0.015719975	0.01318106
8.0	0.0101	0.010711827	0.011316514	0.011618857	0.014640575	0.015951434	0.016151434	0.01344102
9.0	0.00969	0.010504927	0.011281511	0.011669803	0.014884264	0.016291494	0.016491494	0.013602273
10.0	0.00938	0.010277891	0.011229652	0.011705532	0.015476395	0.017161826	0.017361826	0.014256046
11.0	0.00896	0.010030756	0.011146322	0.011704105	0.015590046	0.017333017	0.017533017	0.014272882
12.0	0.00845	0.009770405	0.011061184	0.011706573	0.015619735	0.017376315	0.017576315	0.014175901
13.0	0.00804	0.009509937	0.010986228	0.011724373	0.015611101	0.017354466	0.017554466	0.014022547
14.0	0.00754	0.009256615	0.010942888	0.011786025	0.015561597	0.017249382	0.017449382	0.013787515
15.0	0.008556	0.009046567	0.010931133	0.011873417	0.015391403	0.016950396	0.017150396	0.013377776
16.0	0.007995	0.008898986	0.010925701	0.011939059	0.015348946	0.01685389	0.01705389	0.013147195
17.0	0.007887	0.008941357	0.011028708	0.012072384	0.015441988	0.01692679	0.01712679	0.013058753
18.0	0.007798	0.008840426	0.010961996	0.012022781	0.015442072	0.016951718	0.017151718	0.012910754
19.0	0.007863	0.008837408	0.010978925	0.012049684	0.01555184	0.017102919	0.017302919	0.012853567
20.0	0.008399	0.008908228	0.011053476	0.0121261	0.016183586	0.018012329	0.018212329	0.01337622

Table C.1: Speed brake coefficient, C_s for Mach numbers 0.1 to 0.925 and angle of attack 0 to 20°

	Angle of Attack						
Mach Number	0.95	0.975	1.05	1.1	1.2	1.33	1.6
0.0	0.012614761	0.013494396	0.016133299	0.017892567	0.018282731	0.016156203	0.011739567
1.0	0.011821232	0.012663851	0.015191706	0.016876943	0.017528536	0.015453811	0.011144767
2.0	0.010885502	0.011823459	0.01463733	0.016513244	0.017210725	0.015076468	0.01064378
3.0	0.009920418	0.010949264	0.014035803	0.016093495	0.016815346	0.014682667	0.010253256
4.0	0.009541147	0.010646493	0.01396253	0.016173221	0.016777183	0.014577912	0.010010194
5.0	0.010400541	0.011300999	0.014002371	0.015803286	0.016524361	0.014365304	0.009881109
6.0	0.010540318	0.01131327	0.013632129	0.015178034	0.016168553	0.014111652	0.009839625
7.0	0.010642146	0.011315582	0.01333589	0.014682762	0.015928911	0.013964968	0.00988601
8.0	0.010730605	0.011294669	0.012986859	0.014114985	0.015683078	0.013839106	0.010009318
9.0	0.010713051	0.011284792	0.013000013	0.014143494	0.015891395	0.014037204	0.010186192
10.0	0.011150266	0.011594743	0.012928173	0.013817127	0.015882793	0.014097379	0.01038921
11.0	0.011012747	0.011415052	0.012621967	0.013426577	0.01586762	0.014153174	0.010592403
12.0	0.010775486	0.011169743	0.012352514	0.013141028	0.015966551	0.014288307	0.010802722
13.0	0.010490628	0.010836424	0.011873811	0.012565403	0.015907289	0.014317615	0.011015983
14.0	0.010125647	0.010470147	0.011503646	0.012192646	0.016047938	0.014464447	0.011175659
15.0	0.009605155	0.009963598	0.011038927	0.011755813	0.016124836	0.014529461	0.01121599
16.0	0.0092405	0.009596904	0.010666118	0.011378927	0.01640544	0.01313552	0.01106528
17.0	0.008990716	0.009319643	0.010306421	0.010964273	0.01655219	0.01298917	0.01084443
18.0	0.00866979	0.008971396	0.009876216	0.010479429	0.01670384	0.01277792	0.01044928
19.0	0.008404216	0.008652444	0.00939713	0.009893587	0.01685499	0.01248677	0.00984623
20.0	0.008540112	0.008718379	0.009253181	0.009609715	0.017	0.0121	0.009

Table C.2: Speed brake coefficient, C_s for Mach numbers 0.95 to 1.6 and angle of attack 0 to 20°

Appendix D

Steering Profile Modifications

I think Isaac Newton is doing most of the driving now.

Bill Anders (1933 -)
American Astronaut, Apollo 8 Commander, when told that a ground controller's son had asked who was driving the capsule on the return from the Moon to the Earth, 26 December 1968.

This section contains the plots for how each of the steering profiles was modified with respect to the initial solution. The method of adapting the trajectory is discussed in sections 6.1.2 and 6.2.3 for the Hopper and X-33 vehicles respectively. Figures D.1 to D.18 are provided so that future studies of the methodologies used within this study or the terminal area flight phase can determine how the various off-nominal conditions effect the trajectories of the vehicles.

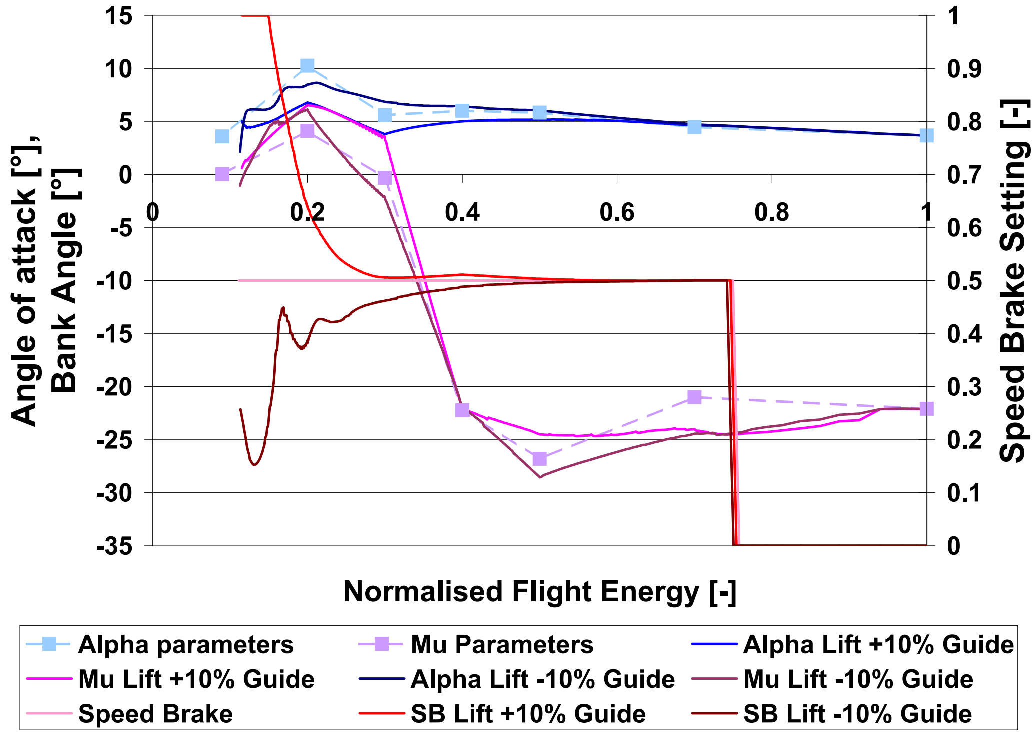

Figure D.1: Hopper vehicle steering profile for the reference trajectory and $C_L \pm 10\%$

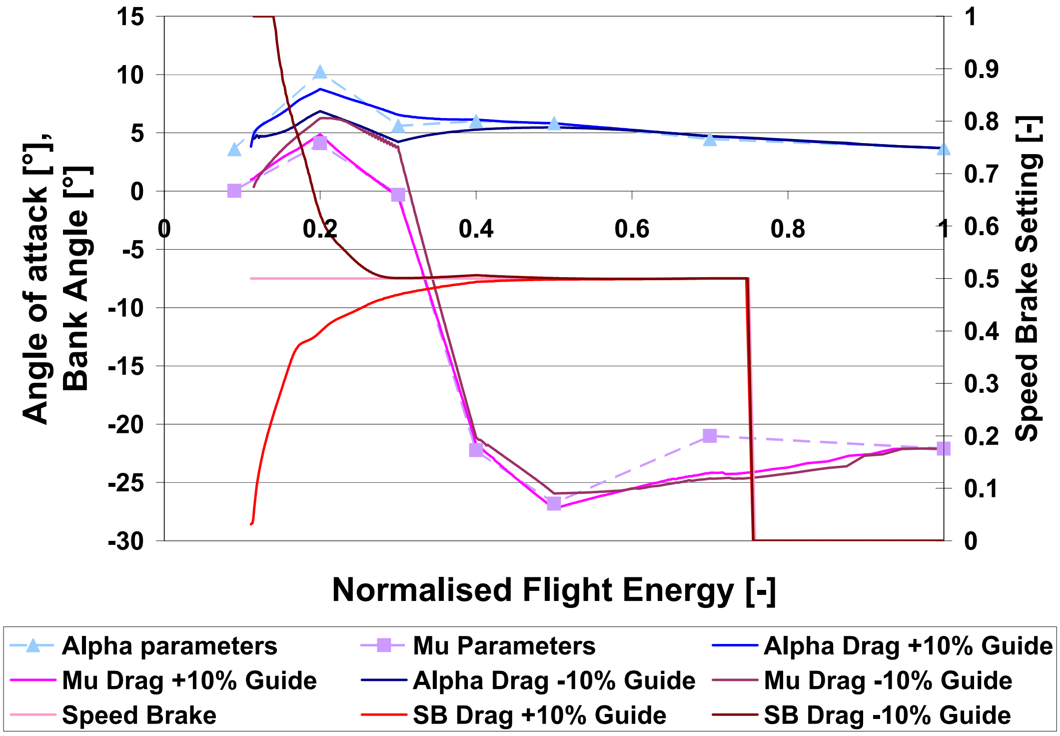

Figure D.2: Hopper vehicle steering profile for the reference trajectory and $C_D \pm 10\%$

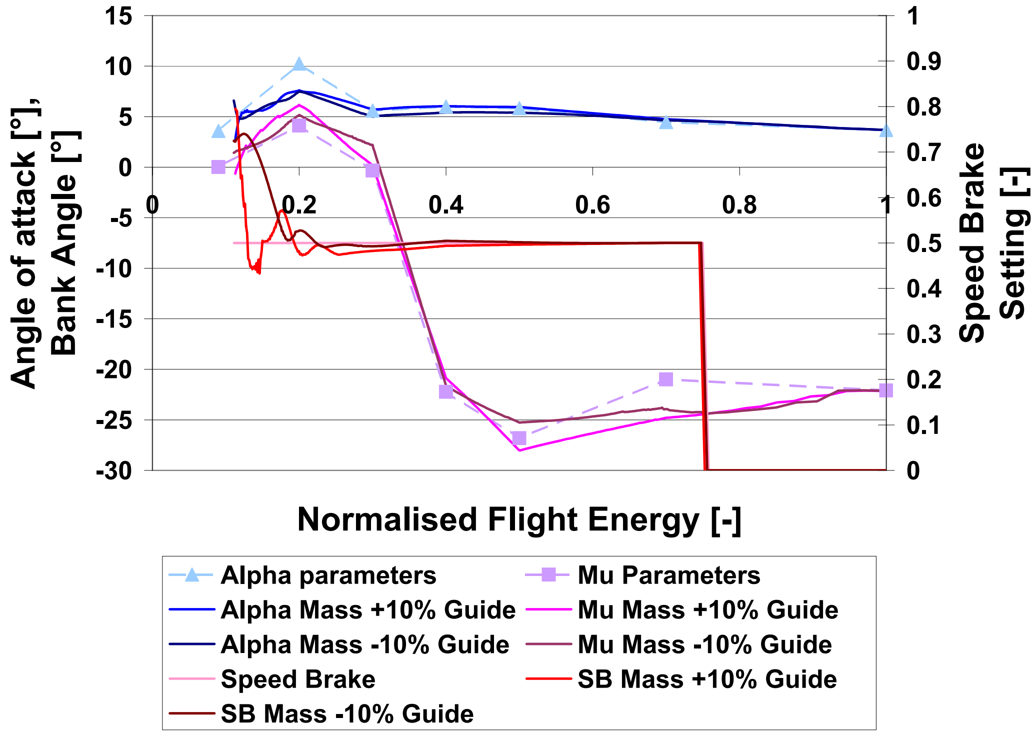

Figure D.3: Hopper vehicle steering profile for the reference trajectory and $m \pm 10\%$

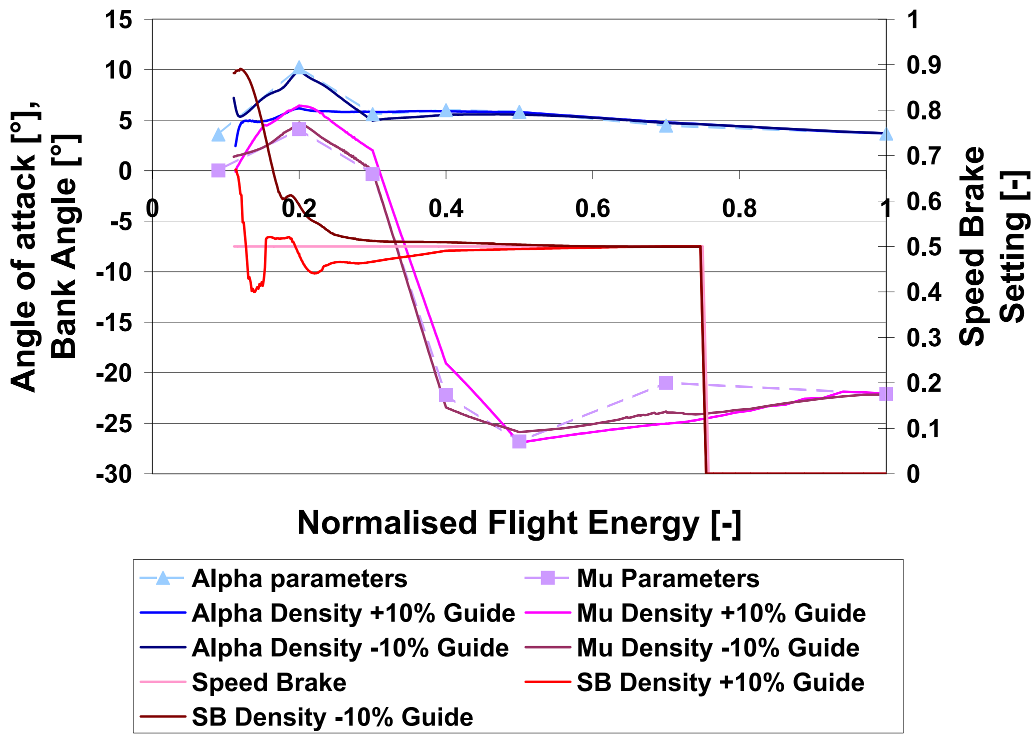

Figure D.4: Hopper vehicle steering profile for the reference trajectory and $\rho \pm 10\%$

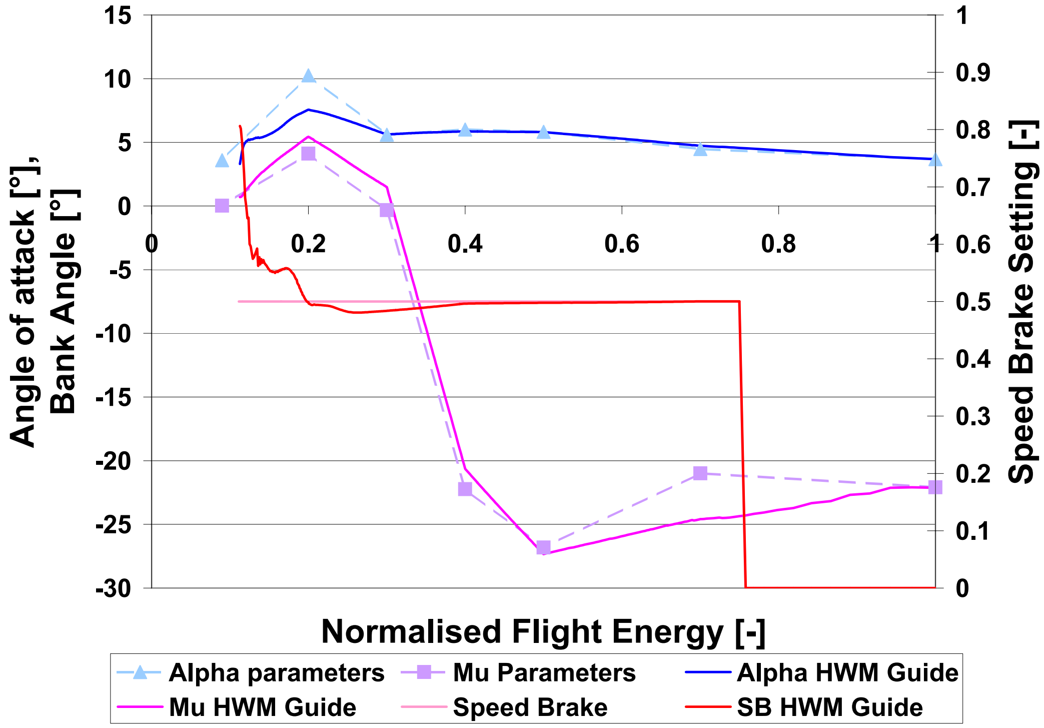

Figure D.5: Hopper vehicle steering profile for the reference trajectory and HWM

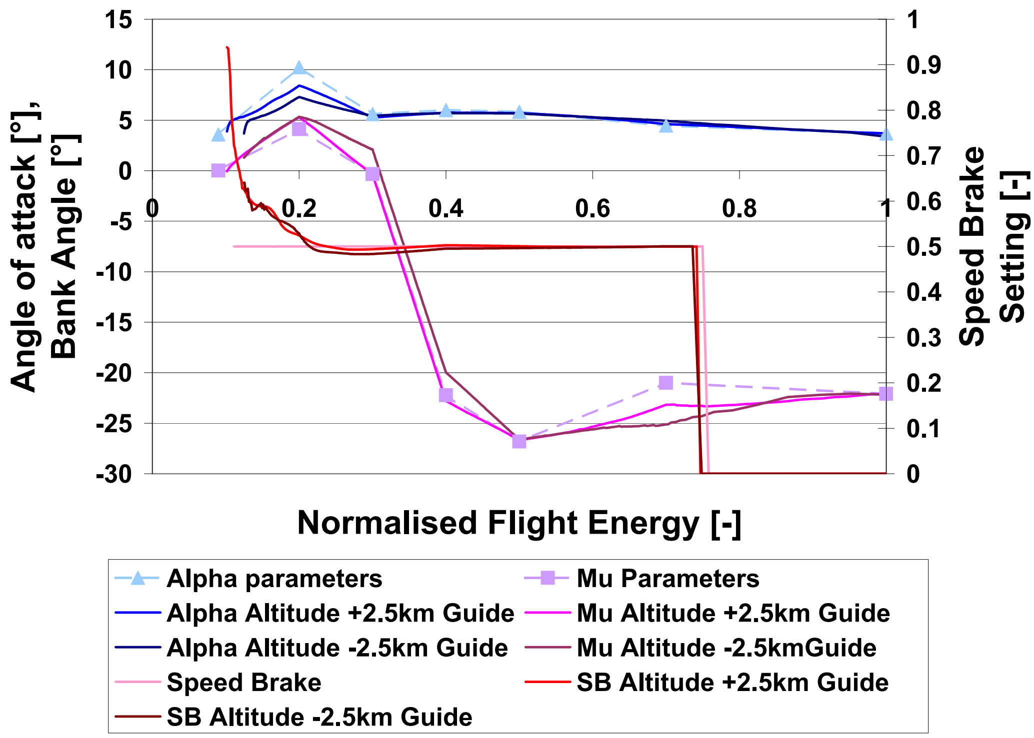

Figure D.6: Hopper vehicle steering profile for the reference trajectory and $h \pm 2.5\text{km}$

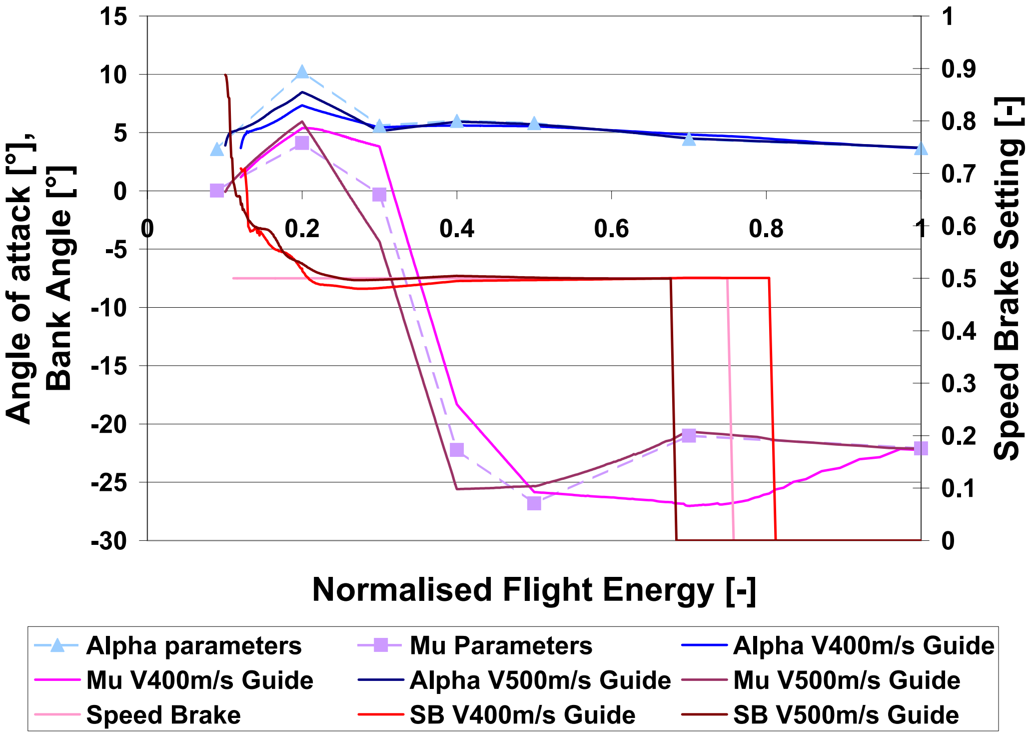

Figure D.7: Hopper vehicle steering profile for the reference trajectory and $v = 400 / 500$ m/s

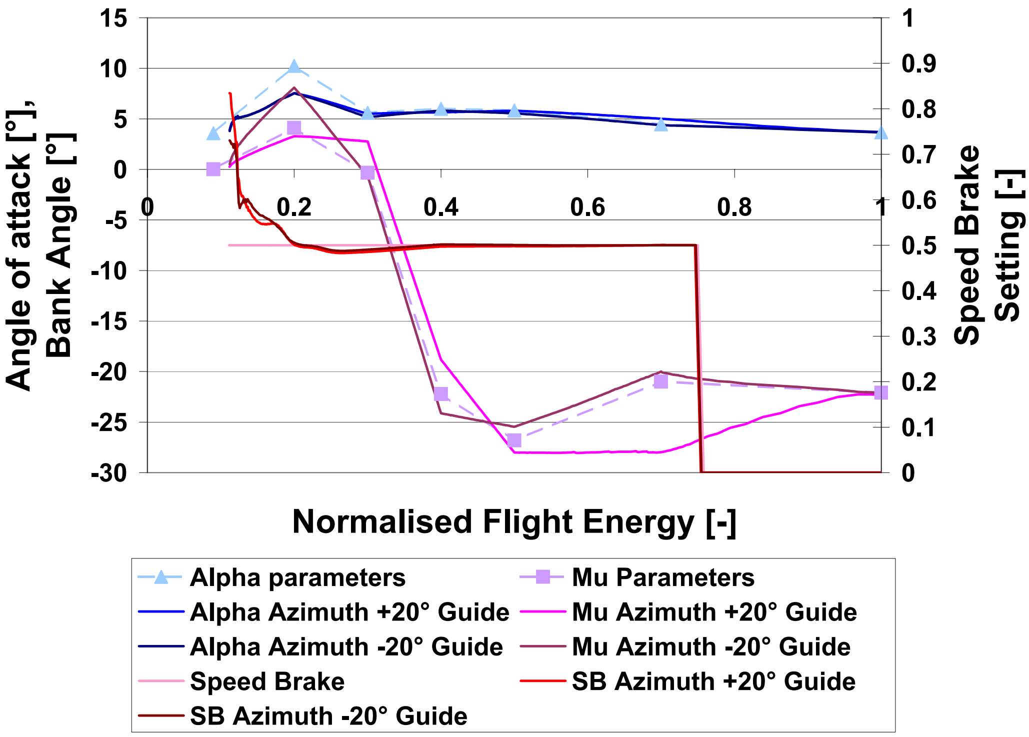

Figure D.8: Hopper vehicle steering profile for the reference trajectory and $\chi \pm 20°$

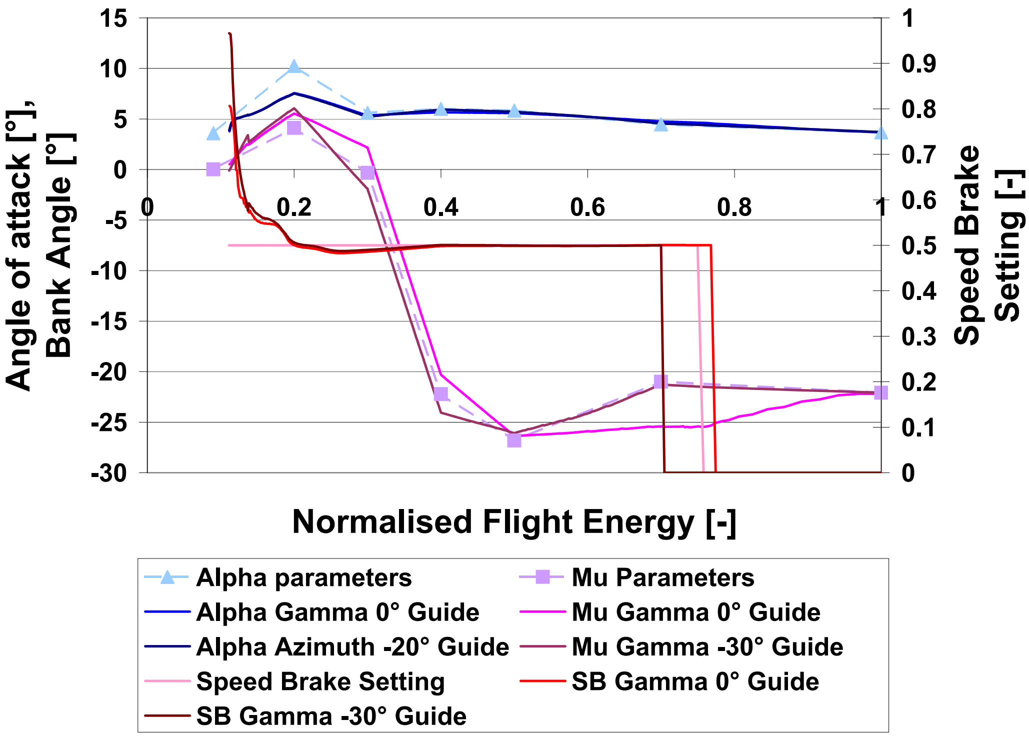

Figure D.9: Hopper vehicle steering profile for the reference trajectory and $\gamma = 0/-30^{\circ}$

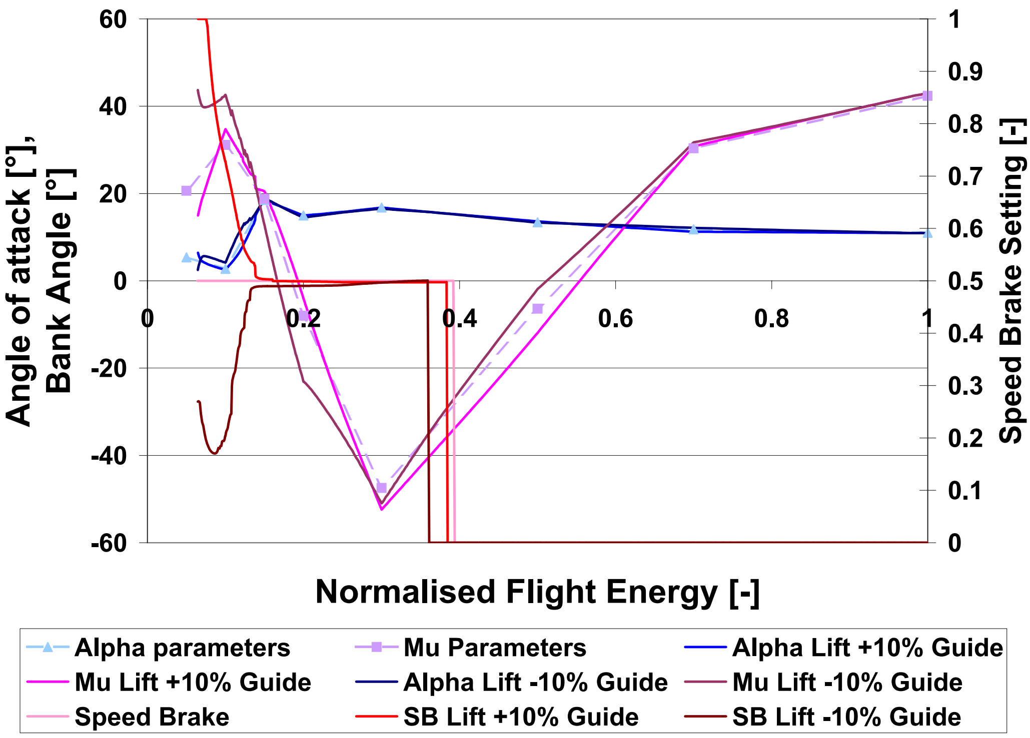

Figure D.10: X-33 vehicle steering profile for the reference trajectory and $C_L \pm 10\%$

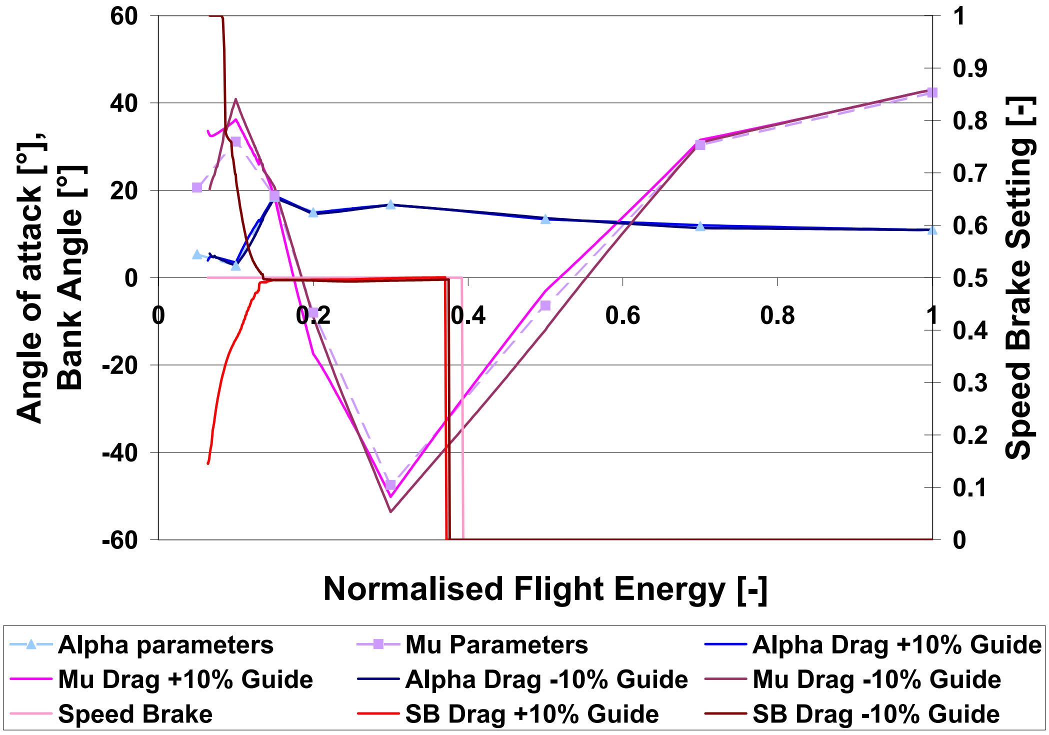

Figure D.11: X-33 vehicle steering profile for the reference trajectory and $C_D \pm 10\%$

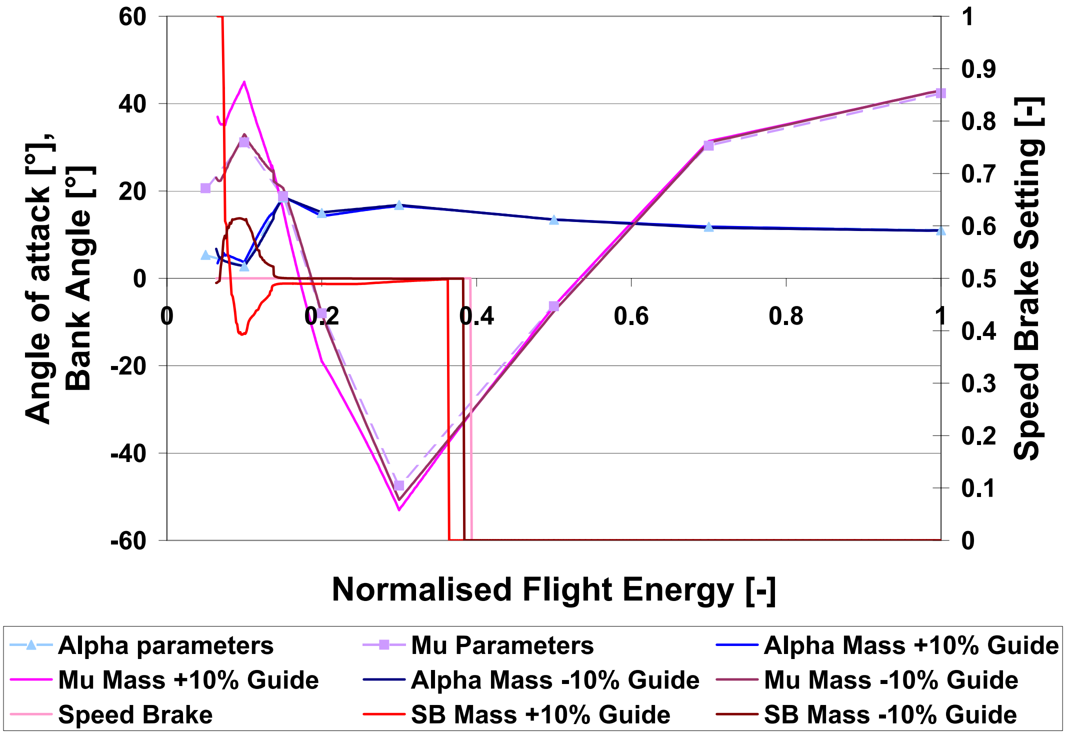

Figure D.12: X-33 vehicle steering profile for the reference trajectory and $m \pm 10\%$

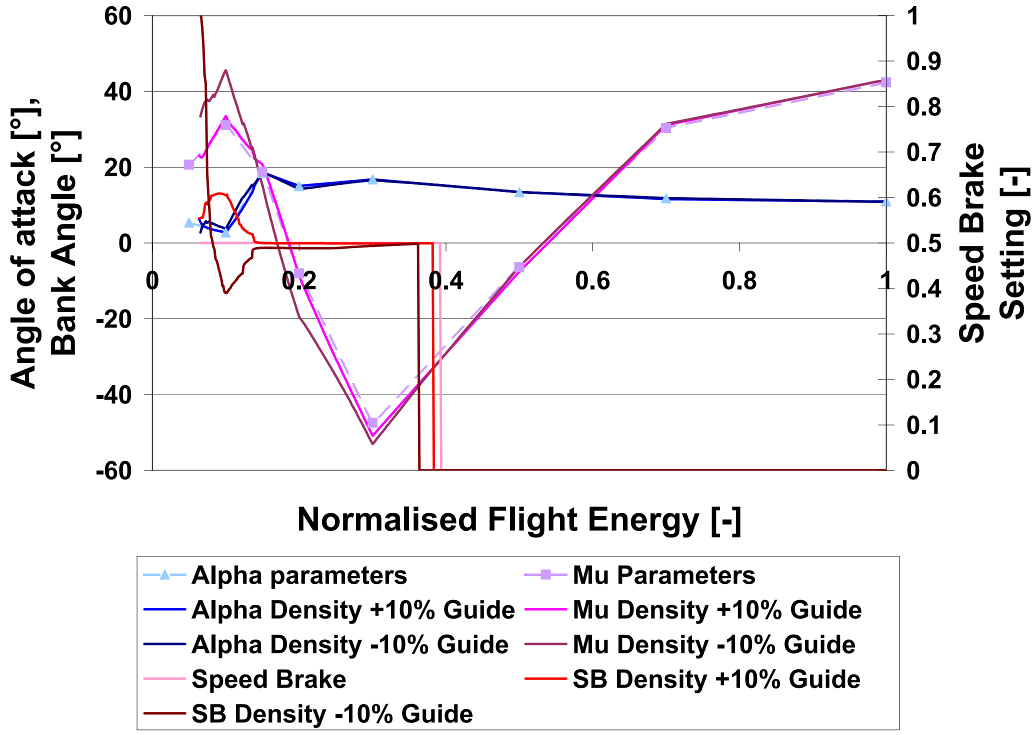

Figure D.13: X-33 vehicle steering profile for the reference trajectory and ρ ± 10%

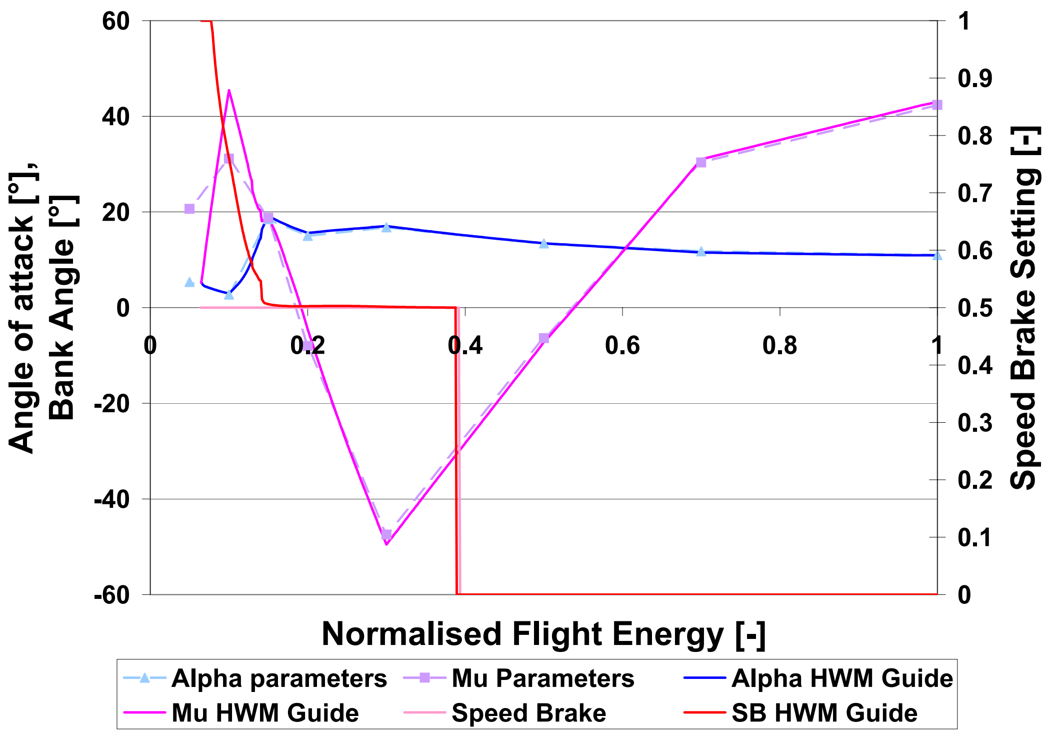

Figure D.14: X-33 vehicle steering profile for the reference trajectory and HWM

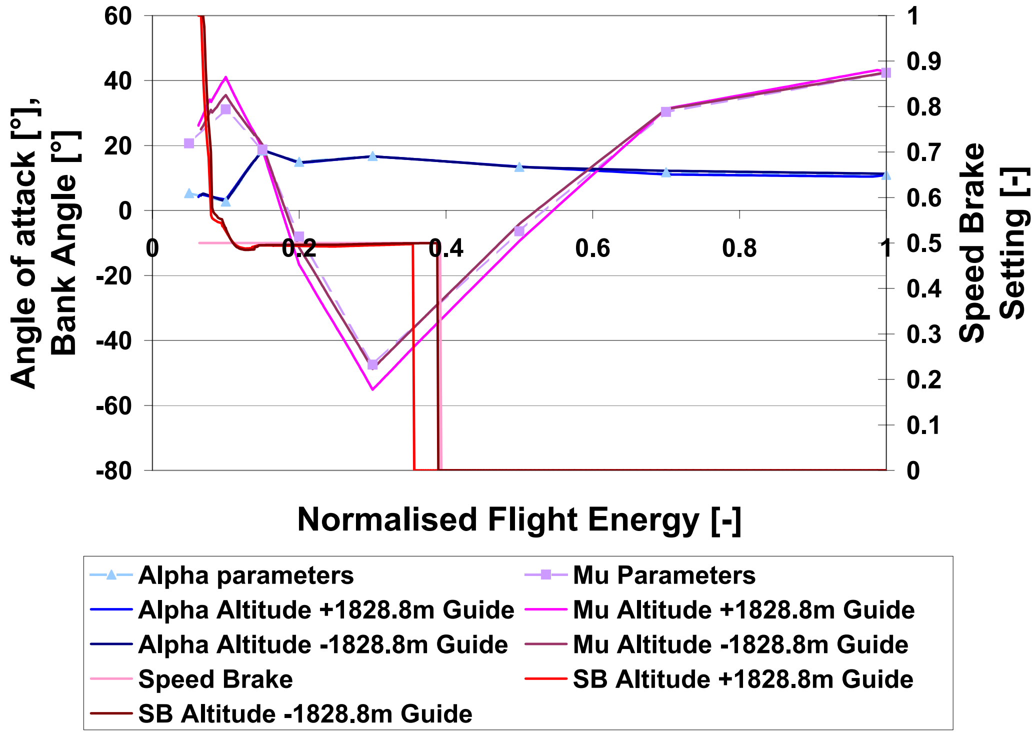

Figure D.15: X-33 vehicle steering profile for the reference trajectory and $h \pm 1828.8m$

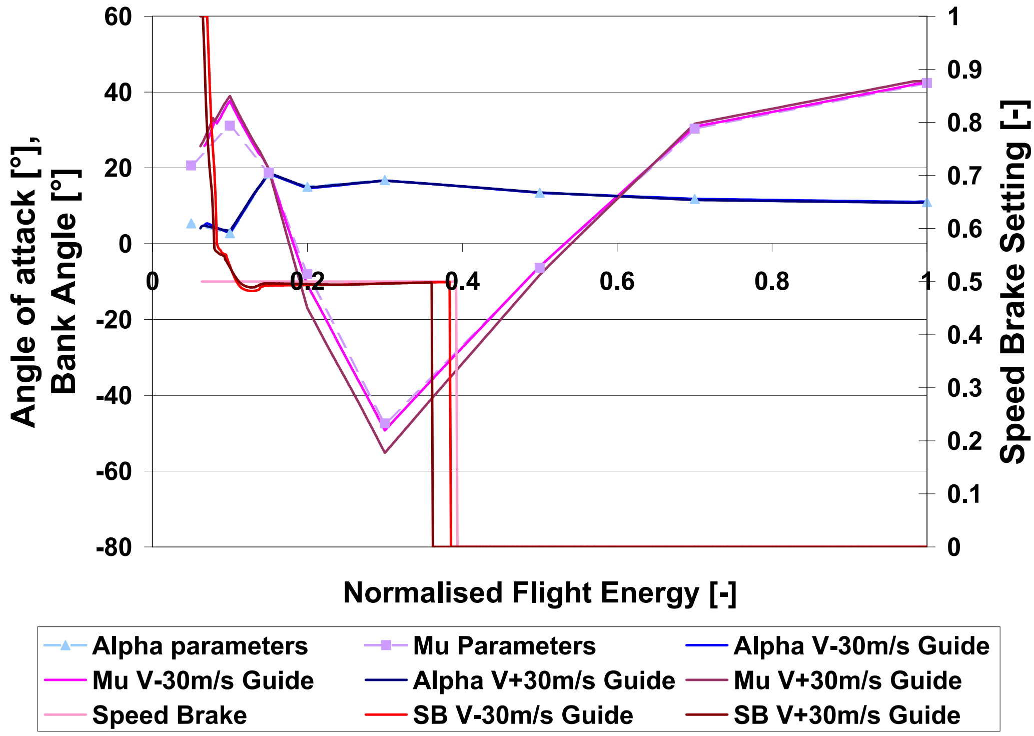

Figure D.16: X-33 vehicle steering profile for the reference trajectory and $v \pm 30m/s$

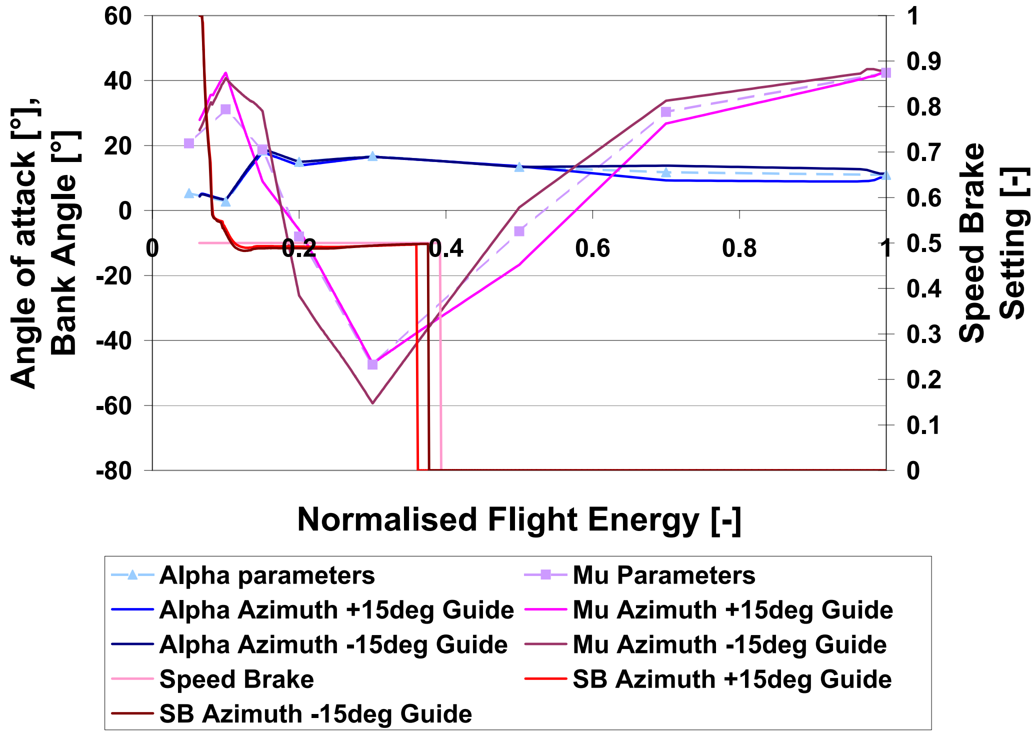

Figure D.17: X-33 vehicle steering profile for the reference trajectory and $\chi \pm 15°$

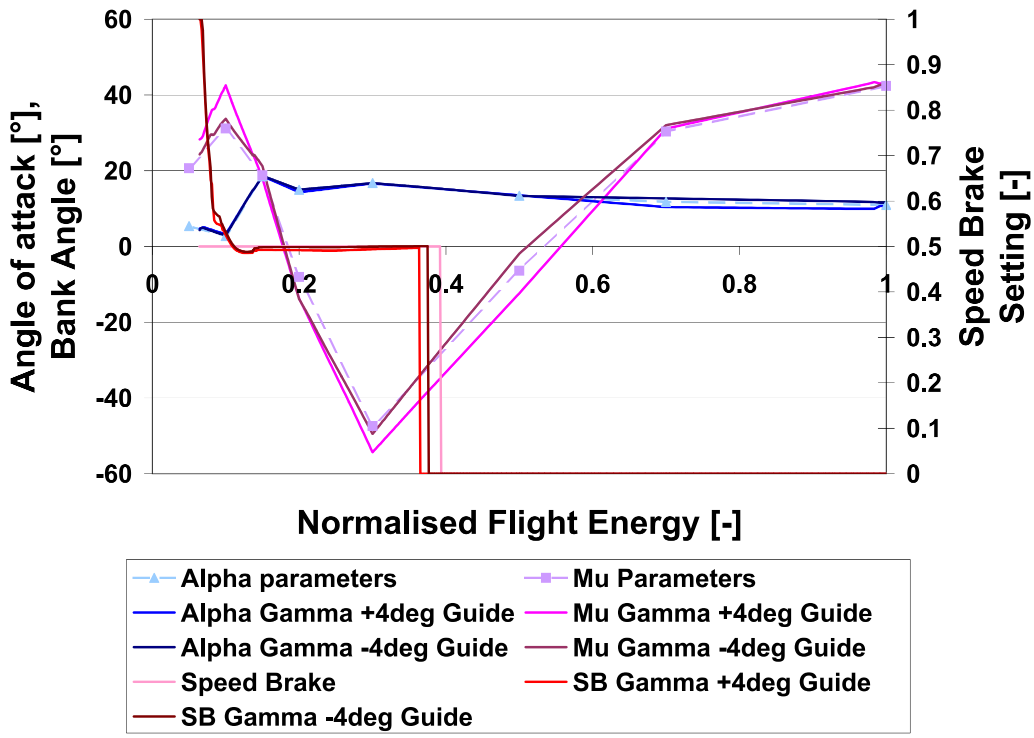

Figure D.18: X-33 vehicle steering profile for the reference trajectory and $\gamma \pm 4°$

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