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DEVELOPMENT OF AN INTEGRATED CONCEPTUAL AIRCRAFT DESIGN & AIRCRAFT NOISE MODEL FOR CIVIL TRANSPORT AIRCRAFT

R.E. Caves*, L.R. Jenkinson[†], and D.P. Rhodes[‡]

Abstract

Recently environmental factors, such as noise and emissions have begun to a play significant role in the design of new aircraft. Although advances in propulsion technology have reduced source noise levels significantly over the past few decades, it is becoming increasingly difficult to project similar advances for the next few decades. It is likely however that some noise benefits may come from improvements in aircraft performance and from changes in operational procedures. In order for such developments to be analysed at the conceptual design stage, an integrated conceptual aircraft design and aircraft noise model is required that enables the designer to rapidly asses the effect of key design parameters on reference noise levels and noise contour area.

The paper describes the integration of a conceptual design model and integration with the NASA Aircraft Noise Prediction Program (ANOPP). The completed model is applicable to civil transport aircraft with high bypass ratio turbofan engines and was validated using the Boeing 757 and Boeing 747 aircraft at the key certification reference points. Model agreement is shown to be good, particularly in terms of aircraft design and performance characteristics. Accuracy of noise prediction was also encouraging once the data was corrected to account for acoustic treatment of the engine nacelle, a feature present on both of the validation aircraft. The integrated model is then applied in two aircraft design scenarios. The first study shows the effect of changing the thrust/weight ratio on take-off flyover noise levels is analysed. The second study investigates the sensitivity of approach angle to approach noise levels. Results illustrated in the paper show that increasing height during the approach phase can significantly reduce approach noise, provided some increases in descent rate during approach are acceptable.

Introduction

Historically, aircraft were designed with minimum weight as a major design aim. This helped the manufacturer achieve performance guarantees and also helped to minimise acquisition costs. Over the past few decades, aircraft design emphasis has been placed on minimising aircraft operating costs. As a result of this effort, modern aircraft have significantly lower operating costs. This has been achieved in part by the application of advanced technologies in propulsion, airframe and aerodynamic design. Research has also shown that key design parameters such as thrust/weight ratio, wing area and wing aspect ratio have significant effects on design efficiency. To assist with the design process, conceptual aircraft design models have been refined and coupled with optimisers, a typical objective function being direct operating cost.

More recently environmental factors, such as noise and emissions have begun to play a significant role in the design of new aircraft. Although advances in propulsion technology have reduced aircraft source noise levels significantly over the past few decades, it is becoming increasingly difficult to project similar advances for the next few decades. It is likely however that some noise benefits may come from improvements in aircraft performance and from changes in operational procedures. In order for such developments to be analysed at the conceptual design stage, an integrated conceptual aircraft design and aircraft noise model is required that enables the designer to rapidly asses the effect of key design parameters on reference noise levels and noise contour area. Conceptual design models are not new but integration with an appropriate noise model poses several challenges.

The paper describes the integration of a conceptual design model and integration with the NASA Aircraft Noise Prediction Program (ANOPP) developed by Zorumski [1, 2]. The complete model has been developed in conjunction with Rolls Royce Aero Engines Ltd who provided detailed engine performance data necessary for noise modelling of the propulsion system. A validation exercise is briefly described following which the model is applied to two scenarios.

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* Director of Airport Planning
[†] Senior Lecturer in Aircraft Design
[‡] Research Associate

Methodology

The prediction of aircraft noise levels is a complex multi-disciplinary subject. Source noise levels are dependent on the acoustic characteristics of the airframe and propulsion system. Normally, propulsion noise will dominate, but at low power settings encountered during approach operations, airframe or aerodynamic noise is often significant. Once source noise levels have been estimated these must be propagated to ground level. This requires knowledge of sound attenuation and absorption in the atmosphere. However, before such methods can be used it is essential to know the propagation distance between the aircraft and ground at any point during its flight path. Computing flight paths is also a complex task requiring knowledge of the aircraft mass, thrust, aerodynamic and operating characteristics. Figure 1 illustrates the various elements of the complete noise prediction model and the inter-relationships between them.

The conceptual aircraft design model consists of sub-models for the prediction of aircraft geometry, mass, aerodynamic characteristics, performance, first cost and direct operating cost (DOC). The latter two elements can be used to compare and optimise designs. Aircraft mass information is computed using methods presented by Torenbeek [3] and Udin et al [4]. Aerodynamic analysis is separated into the two critical elements: prediction of lift and drag. For conventional civil aircraft design models, the lift and drag characteristics are normally analysed for four specific flight regimes, takeoff, landing, engine-out climb and cruise flight. Thus the lift and drag estimation procedures commonly used are based on aerodynamic characteristics with takeoff/landing flap and the clean (cruise) configuration. There is, however, a requirement to estimate lift and drag characteristics for all flap configurations that may be used on a given design during either departure or arrival procedures. In practice this means that flap aerodynamic characteristics must be estimated for all configurations from the clean configuration to full landing flap. Many techniques are available to accomplish this, but for this application they vary from either being overly complex and impractical or too simplistic to illustrate the effects between different flap angles. In addition, estimation is made more complex by the variety of flap configurations and geometry employed on civil aircraft today.

The clean wing stall lift coefficient is predicted using a method presented by Raymer [5]. The total lift coefficient is defined as,

$$C_{L\max} = 0.9 C_{\ell\max} \cos\Lambda$$

where $C_{\ell\max}$ is the 2D maximum lift coefficient and Λ is the wing quarter chord sweep angle. Empirical data has been used to develop an expression for $C_{\ell\max}$.

The contribution from high lift devices is estimated using the method presented by Raymer [5],

$$C_{L\max} = \frac{S_f}{S_{ref}} \Delta C_{\ell\max} \frac{c'}{c} \cos\Lambda_{HL}$$

where S_F is the flapped wing area, S_{ref} the reference wing area, $\Delta C_{\ell\max}$ the 2D lift coefficient increment due to flap deflection, $\frac{c'}{c}$ the wing chord extension ratio and Λ_{HL} is the sweep angle of the flap hinge line. Raymer provides nominal values of $\Delta C_{\ell\max}$ for the various trailing edge flap types with maximum deflection. This data has been expanded on using empirical analysis within the FAA INM database. Figure 2 shows the values of $\Delta C_{\ell\max}$ for various flap configurations and flap deflection angles.

Prediction of aircraft profile drag is based on the component method presented by Haftmann et al [6] The prediction of flap drag is made using a method presented by Lan & Roskam [7]. The method computes the increment in drag from the exposed flap surface and also the drag resulting from the change in wing spanwise lift distribution. This term is dependent on the flap lift increment which is computed using the method described earlier.

Finally, first cost and DOC estimation is performed using the methods from Burns [8] and AEA [9, 10] respectively. The conceptual design model is of the iterative type. An initial mass estimate must be provided to initiate the design calculation. The computed aircraft mass is then substituted for the previous estimate until the residual difference is zero. Convergence typically takes 6-10 iterations.

The aircraft design model is typical of most conceptual models in the performance characteristics estimated. These include takeoff and landing distance, engine-out climb performance and cruise fuel burn. However, in order to compute certification noise levels and/or noise contours a complete flight profile is required for both departure and arrival operations. Although much of the data required to compute such profiles is estimated within the conceptual design model, a related model is needed to generate flight profiles from the aircraft characteristics and operating practices. The model needs to be flexible enough to allow a wide range of procedures to be emulated. The international recommended practice for the construction of flight profiles is described in SAE AIR-1845 [11] and is implemented in the FAA's Integrated Noise Model (INM) [12]. The method describes how a series of straight line segments may be constructed from a set of operating characteristics and aircraft engine and aerodynamic data. Much of this data is not readily available and is thus estimated within the conceptual design model.

Many assumptions are made within the SAE method, such as the linear decrease of engine net thrust with increasing speed. Transition from rotation at the end of the ground roll to initial climb is ignored, the flight distance covered being incorporated into an equivalent takeoff distance which is determined empirically. In this model, distance travelled to rotation is computed followed by a circular arc transition manoeuvre to intercept the initial climb flight path. Figure 3 compares the present method with SAE-1845 for a Boeing 757-200 aircraft. Since this aircraft has good climb performance transition is extended and ends at an altitude of about 50m (164ft).

Noise estimation is achieved using the NASA ANOPP methodology [1, 2]. The method estimates the far field mean square acoustic pressure for the airframe, engine fan, combustor, turbine and jet exhaust. Standard methods have then been incorporated to enable a variety of noise metrics to be output including, maximum A-weighted level (LAmax), Sound Exposure Level (SEL), Perceived Noise Level (PNL) and Effective Perceived Noise Level (EPNL). The latter is used for aircraft noise certification and was to used to conduct model validation. Computation of this metric is time consuming and thus it is common to produce noise contours using either LAmax or SEL metrics.

A full description of the conceptual design model and implementation of the NASA ANOPP method is available in ref. [13].

Validation

The completed model is applicable to civil transport aircraft with high bypass ratio turbofan engines and has been validated using the Boeing 757 and Boeing 747 aircraft at the key certification reference points.

Table 1 compares Boeing 747-400 data output from the aircraft design model with manufacturer published values. Correlation is shown to be good for both operating empty (structure) mass and maximum takeoff mass. A large part of the maximum takeoff mass is fuel mass indicating that cruise drag and fuel burn are well predicted.

Table 2 compares the similar output for the Boeing 757 with manufacturer data. Correlation is better than for the Boeing 747-400 with the exception of cruise fuel burn.

	Published Data	Prediction	Error
Mass (kg)			
Ops empty	181529	186192	2.57%
Zero-fuel	242670	247378	1.94%
Maximum takeoff	396830	396587	-0.06%
Performance			
FAR T/O distance (m)	3315	3143	-5.19%
FAR Landing dist. (m)	2130	1949	-8.50%
Cruise fuel burn (kg/hr)	10666	10247	-3.93%
Economics			
First cost ($1994)	140	148.37	5.98%

Table 1: Boeing 747-400 Conceptual Design Data

	Published Data	Prediction	Error
Mass (Tonnes)			
Ops empty	57180	57348	0.29%
Zero-fuel	83460	83698	0.29%
Maximum takeoff	99792	99348	-0.44%
Performance			
Takeoff field length	1646	1668	1.34%
Landing field length	1415	1431	1.13%
Cruise fuel burn	2805	3086	10.02%
Economics			
First cost ($1994)	44.5	47.52	6.79%

Table 2: Boeing 757-200 Conceptual Design Data

Although the aircraft characteristics are known several parameters are required to produce a departure flight profile. For validation, certification flight profiles were constructed for each aircraft, the procedure used being determined from ICAO Annex

16 [14]. Variables such as the height at which takeoff thrust is cutback are then adjusted to produce the lowest flyover noise levels. The resulting height and thrust profiles are shown in Figure 4 and 5 respectively. In each case the profiles are compared with those produced using INM with the same departure procedures. The high correlation confirms that aircraft thrust and aerodynamic characteristics are estimated well within the conceptual design model. Additionally, the comparison illustrates that the simplified methods presented in SAE-AIR-1845 produce results of acceptable accuracy.

Tables 3 and 4 compare predicted certification noise levels with FAA published data [15]. Accuracy of noise prediction is encouraging once the data has been corrected to account for acoustic treatment of the engine nacelle, a feature present on both of the validation aircraft.

Predicted values for the Boeing 747-400 compare well with FAA data. For the Boeing 757-200 there is a general trend towards over prediction. This is in part due to differences between the generic engine performance data used for engine source noise prediction and the engine used on the Boeing 757-200. Much of the over prediction can be attributed to higher fan tip speeds for the generic data increasing flyover noise by approx. 2dB. Additionally the RB211-535E4 engine used for comparison contains an exhaust mixer, whereas the prediction model assumes separate exhaust streams. Data reported by Benito [16] suggests that an exhaust mixer may reduce noise levels by around 2dB. Taking these factors into account the correlation is of a similar order to that for the Boeing 747-400.

Location	Certification (EPNdB)	Prediction (EPNdB)	Difference (EPNdB)
Sideline	99.70	100.4	+0.7
Flyover	101.4	101.5	+0.1
Approach	104.1	105.4	+1.3

Table 3: Boeing 747-400 Predicted Certification Noise Levels

Location	Certification (EPNdB)	Prediction (EPNdB)	Difference (EPNdB)
Sideline	93.3	96.21	+2.91
Flyover	82.2	85.64	+4.49
Approach	95.0	96.08	+1.08

Table 4: Boeing 757-200 Predicted Certification Noise Levels

Application

Takeoff Thrust-Weight Ratio

The first application analyses the effect of changing aircraft thrust/weight ratio on departure noise levels. It would be expected that increasing take-off thrust/weight ratio will improve the initial climb rate and reduce noise levels due to the greater distance of the noise source from the ground. This is because a small increase in takeoff thrust may provide a significant increase in excess thrust available for climbing flight. In contrast reducing thrust/weight ratio will tend to reduce initial climb rates and increase departure noise levels.

Table 5 illustrates the effect of increasing thrust/weight ratio for a Boeing 747-400 type aircraft. Two options are considered, firstly increasing engine size by 10 percent and secondly by 20 percent. The conceptual design model first computes the new design characteristics which results in a new takeoff mass and departure flight profile. Engine mass is assumed to increase in proportion to thrust as the engine mass flow is increased whilst engine bypass ratio and cycle remain constant. Much of the effect of the additional thrust is offset by the associated increased in maximum takeoff mass. However, the increased height at the certification flyover point reduces flyover noise levels by 0.60dB.

	Base case	**+10% thrust**	**+20% thrust**
Airframe:			
Wing area (m^2)	525.88	525.88	525.88
OWE (kg)	186192	193513	200835
MTOW (kg)	396589	410281	424246
Static thrust (kN/eng.)	257.60	283.36	309.12
Wing loading (kg/m^2)	754.14	780.18	806.76
Performance:			
Takeoff field length (m)	3183	3080	3008
Landing field length (m)	1949	1995	2042
Cruise L/D (-)	17.69	17.62	17.52
Cruise fuel burn (kg/hr)	10247	10633	11035
Economics:			
Unit price ($m, 1995)	148.37	156.03	163.71
DOC (cents/ASM)	5.20	5.40	5.60
Noise:			
Sideline (EPNdB)	100.83	100.69	100.63
Flyover (EPNdB)	101.50	100.90	101.04

Table 5: Effect of Increased thrust-weight ratio

Approach Angle

The second application investigates the sensitivity of approach angle to approach noise levels. For this study the Boeing 757-200 was used as the baseline aircraft. The aircraft has a relatively powerful high lift system resulting in a reference approach speed ($1.3V_S$ + 10kts) of 142 knots at maximum landing weight. This enables approach angle to be increased to at least 4° with acceptable descent rates. Above 4°, approach speed must be reduced. This may be achieved by reducing aircraft mass (and hence payload) or by increasing the maximum lift produced. Since the aircraft already has a powerful high lift system it is unlikely that significant gains can be achieved. Instead a simpler option may be to increase wing area.

Four scenarios are compared in Table 6: the baseline case of the original airframe on 3° approaches, the baseline airframe on 4° approaches and modified airframes on 5° and 5.5° approaches.

For the modified designs, wing aspect ratio was analysed for the new aircraft in an attempt to recover some of the lost cruise performance resulting from the larger wing.

	Boeing 757-200 - 3°	Boeing 757-200 - 4°	5° Design	5.5° Design
Geometry:				
Wing Area (m²)	185.25	185.25	207.95	258.18
Wing Aspect Ratio (-)	7.81	7.81	6.75	6.25
Engine Thrust (kN)	178.4	178.4	187.0	185.0
Mass:				
Operating empty mass (kg)*	57190	57190	55037	57956
Max zero fuel mass (kg)*	83540	83540	81387	84306
Max take-off mass (kg)*	99113	99113	99243	101725
Performance:				
FAR Take-off Field length (m)*	1589	1589	1499	1329
FAR Landing field Length (m)*	1428	1337	1241	1198
Cruise lift to Drag ratio (-)*	16.79	16.79	15.12	15.87
Thrust/weight ratio (-)	0.363	0.363	0.384	0.371
Wing Loading (kg/m²)	541.47	541.47	477.25	394.01
Fuel Consumption (kg/hr)*	3076	3076	3370	3313
Approach Characteristics:				
Approach Angle (°)	3	4	5	5.5
Approach Speed (V2+10) (knots)	142	142	134	123
Approach T/W (-)*	0.064	0.050	0.048	0.030
Thrust (kN)*	56.43	42.26	41.67	30.31
Thrust Setting (%)*	18.96%	14.21%	13.27%	9.60%
Economics:				
Purchase cost ($mil)*	47.42	47.42	46.77	48.40
Direct operating cost (Cents/ASM)*	5.56	5.56	5.60	5.69
Approach Noise:				
Airframe (EPNdB)*	85.81	83.79	81.01	78.27
Total Noise Level (EPNdB)*	96.08	90.88	88.40	85.57

Table 6: Approach Angle Study Data (* denotes estimated data for standard aircraft)

The 4° approach option is seen to reduce approach noise levels by 5.2dB. Assuming a typical sound energy decay rate of 5dB per doubling of distance, the height difference would have been expected to reduce noise levels by 2.38dB. The difference, 2.8dB is thus associated with the reduction in thrust levels from the 3° to 4° approach procedure.

To achieve an approach angle of 5° the approach speed is reduced to 134 knots. This is achieved by increasing the wing area to 208m^2 (+12%). The wing aspect ratio is reduced to 6.75 (-14%) to recover some of the weight penalty associated with the larger wing and results in a minimum DOC design, although DOC increases to 5.60 cents/ASM (+0.7%), this increase associated with higher cruise fuel burn. Total approach noise level reduces to 88.40dB, a reduction of 7.68dB. The additional height accounts for approx. 4.24dB, the remainder (3.44dB) due to thrust reduction. Airframe noise, however, actually decreases by 4.8dB the extra 0.56dB associated with the approach speed reduction.

For 5.5°, approach speed is reduced further to 123 knots. This necessitates an increase in wing area to 258m^2 (+39%). Again, to recover some of the associated weight penalty, the wing aspect ratio is reduced further to 6.25 (-20%) to produce the minimum DOC design, although DOC has increased by 2.33 percent relative to the original airframe. Approach noise levels are reduced by 10.51dB. Increased height accounts for approx. 5.03dB, the remaining 5.48dB due to thrust reduction, approach thrust levels are now half the level for 3° approaches. The reduction in airframe noise levels is actually 7.54dB, showing that 2.5dB of this is associated with the reduced approach speed.

Further Work

Currently the noise prediction model requires engine manufacturer's data to describe the characteristics of the key engine components at both on-design and off-design conditions. This effectively limits the application of the model to aircraft for which data can be obtained from engine manufacturers. A more ideal solution would be to develop an internal engine cycle model that could predict engine characteristics at both on-design and off-design conditions. This would break the reliance on engine manufacturer data and enable the global model to be applied to a wider range of aircraft. Recently, however, some models have been developed by third party companies, one example being a model developed at the DLR Institut für Antriebstechnik. The model was developed for predicting fuel flow and emissions using the ICAO LTO cycle and is briefly described in a paper presented by Deidewig et al [17].

There are also opportunities to include the social costs of aircraft noise in the DOC model. This will create the ability to optimise aircraft designs for minimum social cost. The difficulty here lies in quantifying such costs. Initially data may be taken from noise charges levied at some airports and also from costs associated with airport noise insulation schemes.

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Conclusions

Initial validation of the complete model is encouraging. Further work is required to enable the model to be applied to a wider range of aircraft and thereby strengthen confidence in the overall model. The inclusion of a detailed flight profile generator provides the ability to analyse many different procedures for both departure and arrival operations. Coupling this feature together with noise estimation and a conceptual design model enables new aircraft designs to be optimised for minimum noise levels.

The two applications presented illustrate the variety of possible scenarios that may be assessed with the model. Results from the second scenario suggest that alternative approach procedures offer great potential for noise mitigation. Initially it is likely that the main interest will lie with reducing noise levels for existing aircraft designs. However, it is possible in future decades that industry may be required to more fully account for social costs incurred through aircraft operations. As such costs rise, in part from greater public awareness, it may then be necessary to design aircraft for minimum total social cost.

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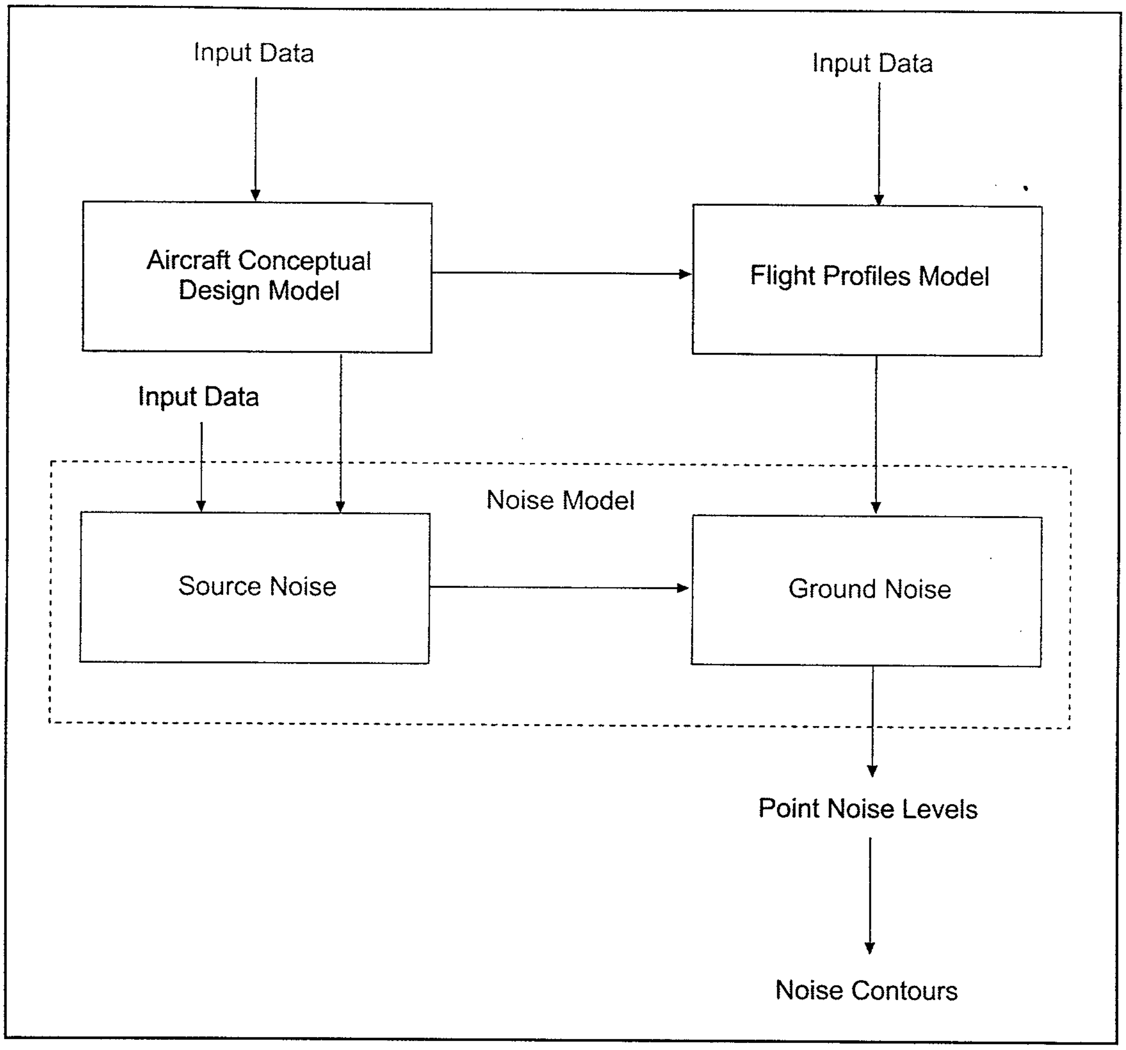

Figure 1: Global Noise Model

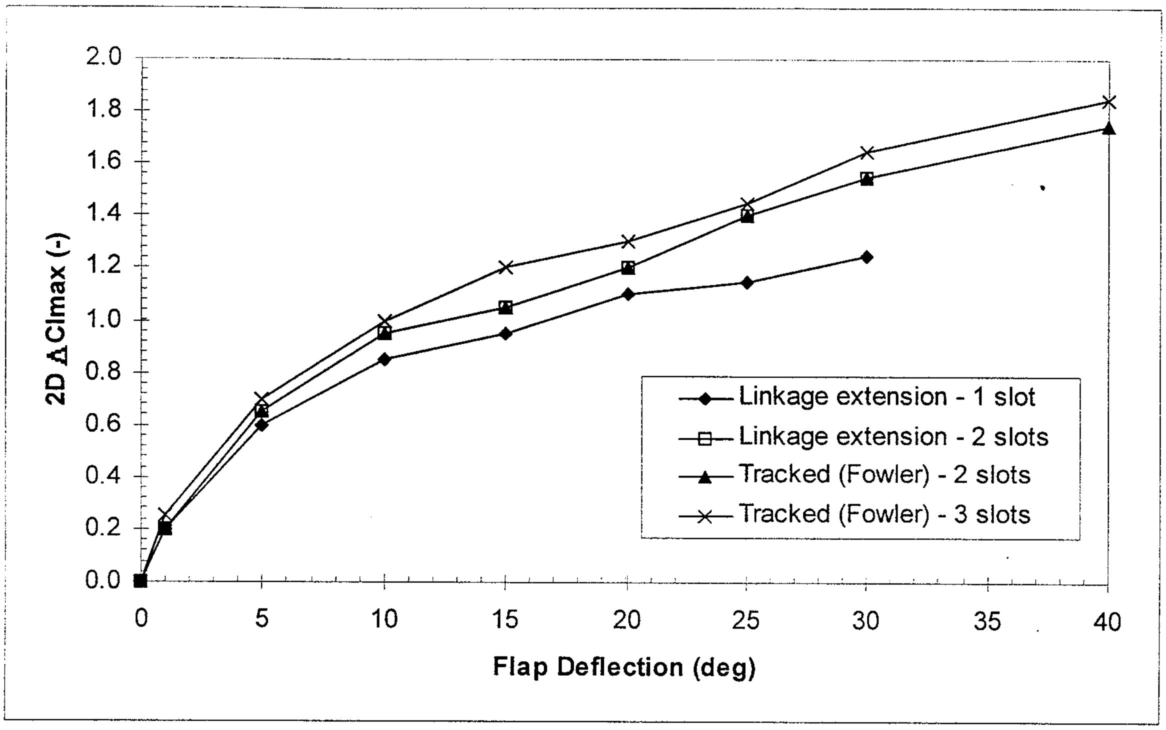

FIGURE 2: 2D Lift increment for different trailing edge flaps

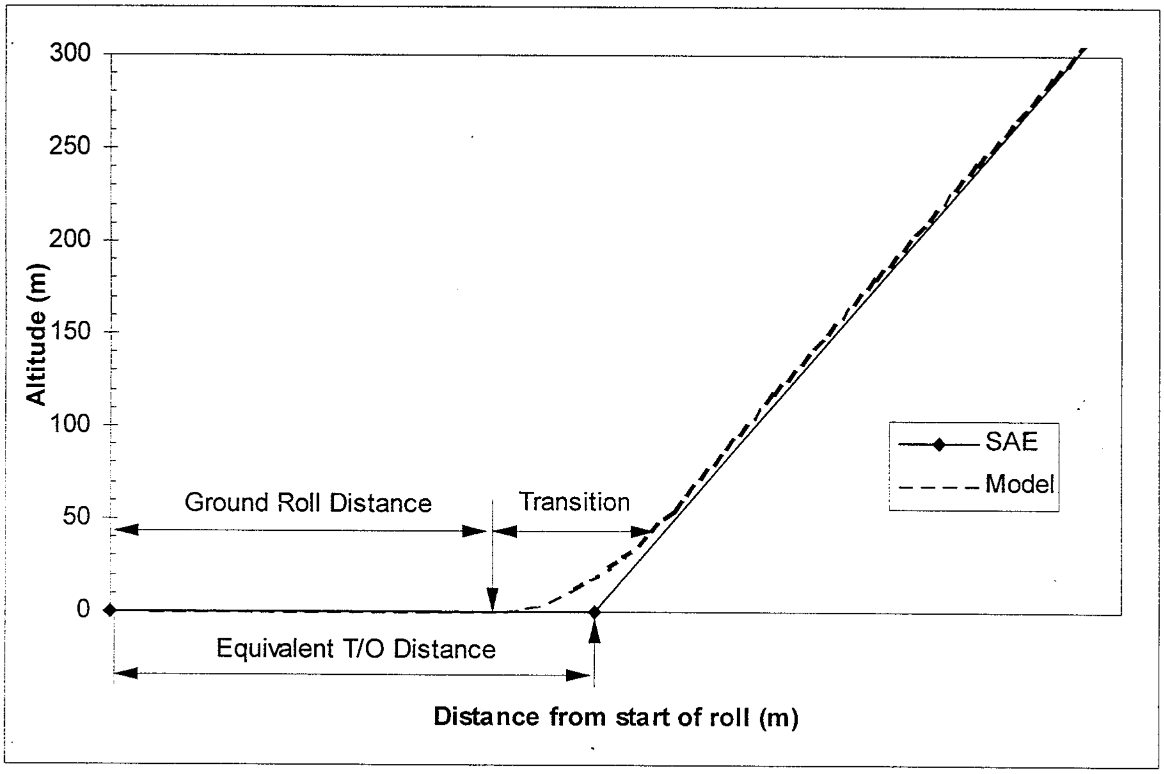

FIGURE 3: Takeoff Flight Path Construction

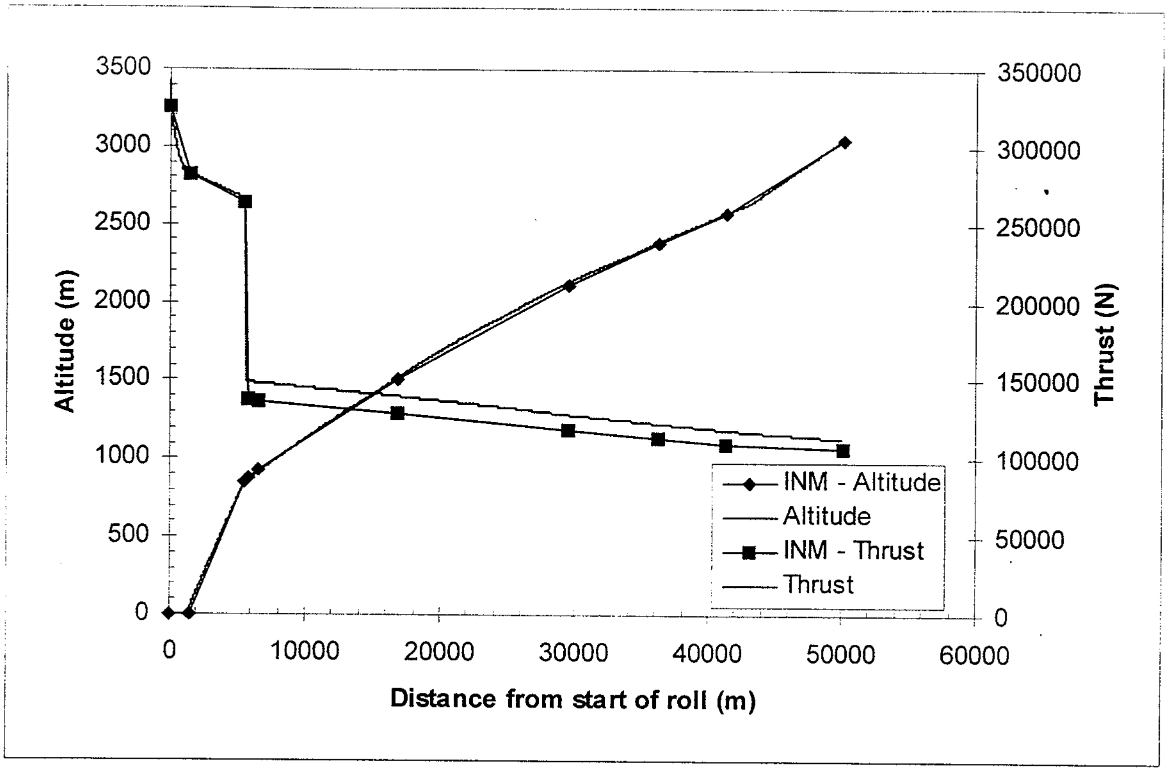

Figure 4: Boeing 757-200 Departure Flight Profile

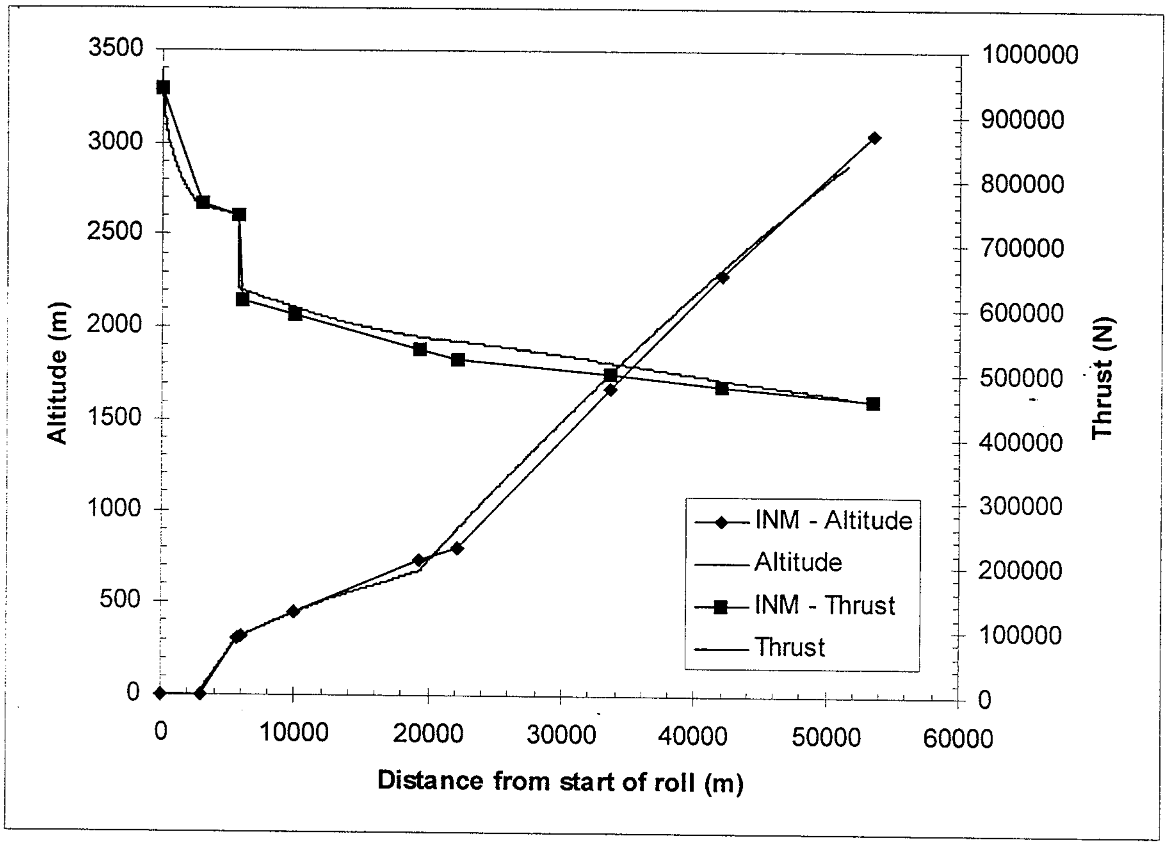

Figure 5: Boeing 747-400 Departure Flight Profile