Fuel sensitivity analyses for active drag reduction systems

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ABSTRACT

Active drag reduction systems, such as hybrid laminar flow control (HLFC), have the potential for significant fuel savings; however, this is at the expense of an increase in aircraft weight and engine power off-take. A computer program – capable of accurately determining the trip fuel for a given mission profile – has been developed. The program was validated against manufacturer's payload-range data, and then modified to emulate the installation of an active drag reduction system, by incorporating changes to the drag polars, specific fuel consumption (SFC) data and operating empty weight (OEW). Results of sensitivity studies are presented that enable the reduction in trip fuel to be determined for given changes in C_D, SFC and OEW. The underlying assumption of linear independence of the three parameters is explored. The linearised method was observed to underestimate the fuel savings of the HLFC aircraft by approximately 0·6% compared to an analysis which took into account the coupling between the parameters. A mathematical relationship has been established to estimate the impact on cruise fuel burn arising from relative changes to the aircraft's mass, lift-to-drag ratio and SFC.

NOMENCLATURE

A/C	aircraft
BRW	brake release weight
c	specific fuel consumption (SFC)
$\bar{c}$	mean specific fuel consumption
C_D	drag coefficient
C_L	lift coefficient
E	lift-to-drag ratio (L/D)
$\bar{E}$	mean lift-to-drag ratio
FL	flight level
g	gravitational acceleration
HLFC	hybrid laminar flow control
ISA	international standard atmosphere
LFC	laminar flow control
m	aircraft mass
m_1	start-of-cruise aircraft mass
m_2	end-of-cruise aircraft mass
m_f	fuel mass
MVO	multi-variate optimisation
OEW	operating empty weight
R	range
V	true airspeed (TAS)

1.0 INTRODUCTION

Laminar flow control (LFC) is 'an active boundary layer control technique employed to maintain the laminar state at chord Reynolds numbers beyond that which is normally characterised as being transitional or turbulent in the absence of control'[1]. This can be achieved by a number of principles including suction, blowing, temperature control and the use of micro-electro-mechanical systems[1,2]. Of these concepts the one that has received greatest attention is suction. Instabilities are suppressed by sucking air – at modest flow

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velocities of 0·1 to 0·3m/s – through small holes in the external skin (typically 0·05 – 0·10mm in diameter). The air is conveyed through a network of pipes to a pump and then exhausted. Hybrid laminar flow control (HLFC) is a hybrid of full-chord LFC and natural laminar flow, where a correctly profiled contour is used to maintain a laminar boundary layer aft of the suction area (see Refs 1,3 and 4, for example).

The design of a HLFC system for the wing, empennage or nacelle of an airliner is a multi-disciplinary task, for which a number of design solutions are possible. The development of an 'optimum' design is a non-trivial task, due to the high degree of inter-dependence that exists between the structural, aerodynamic and systems design parameters. Consider, for example, candidate design solutions for a HLFC engine nacelle. Design modifications would include replacing a portion of the external skin with a robust, perforated structure and the installation of a suction system, which would be driven by power off-take from the engines. The performance penalties associated with the increased weight and poorer specific fuel consumption (SFC) (due to the increased engine power off-take) negate some of the drag reduction benefit. A design solution optimised solely for drag reduction could maintain laminar flow to well beyond 50% of the chord; however, the structural and systems implications become greater the further back the laminar flow is maintained. In an effort to extend the laminar flow along the nacelle chord, a point is reached where the penalties outweigh the benefits. Multi-variate optimisation (MVO) of this problem offers the opportunity to evaluate candidate designs. Crucial inputs to such optimisation are the relationships that link the design parameters. An aspect of this inter-relationship is explored herein. Sensitivity studies have been performed to evaluate the impact on fuel burn, due to changes to the operating empty weight (OEW), SFC and drag coefficient (C_D) of an aeroplane.

2.0 OBJECTIVE AND METHODOLOGY

The objective was to investigate the impact on fuel burn due to the incorporation of an active drag reduction system that would simultaneously reduce the aircraft's drag, while increasing the OEW and SFC. Two complementary approaches are presented.

1. A computer model (see Section 3) has been used to evaluate the sensitivity of trip fuel due to individual, and combined, changes to the input parameters (Section 5).
2. An approximate mathematical method, based on the assumption that the variables can be considered as linear and independent, is presented for the cruise segment of the mission (Section 4).

3.0 COMPUTER PERFORMANCE MODEL

A computer performance program, capable of accurately determining the fuel required for a specified mission, has been developed. Two aircraft types, i.e. the B757-200 and the A330-200, were selected as reference vehicles, representative of modern medium- to long-range airliners. For each leg of the mission (Fig. 1) the fuel required, distance covered and time lapsed, was calculated and then summed. The climb, cruise and descent legs were divided into a number of segments to increase accuracy. The results of the program were compared against appropriate aircraft operations manuals and manufacturer's payload-range information. Details regarding the program are presented in Refs 5 and 6. As the performance characteristics of the aircraft models would not comply in all respects with those of the reference aircraft, a distinction is made herein, and the computer models are referred to as the B757-200 class aircraft and A330-200 class aircraft.

The concept involved:

1. modelling the en route performance of these two aircraft,
2. validating the models by cross-checking performance predictions against manufacturer's data, and
3. adapting the models to take into account the virtual installation of a HLFC system.

The modifications involved a decrease in drag and a corresponding increase in SFC during the part of the mission where the HLFC system would be operational (Fig. 1), and an increase in the OEW resulting from the installation of the system. All other design parameters were unchanged, including the wing planform and powerplant characteristics.

4.0 THEORETICAL EVALUATION OF TRIP FUEL SENSITIVITY

4.1 Numerical expression for small changes

In this section an approximate method is presented for studying the impact on fuel burn during cruise, due to changes to the aircraft's OEW, drag and SFC. If it is assumed that during the cruise that m_2 (end-of-cruise mass), $\bar{E}$ (mean lift-to-drag ratio) and $\bar{c}$ (mean SFC) are independent, then a linear expression for small changes of these variables may be formulated, i.e.

$$\frac{\delta m_f}{m_2} = \left(\frac{\partial m_f}{\partial m_2}\right)\frac{\delta m_2}{m_2} + \left(\frac{\partial m_f}{\partial \bar{c}}\right)\frac{\delta \bar{c}}{m_2} + \left(\frac{\partial m_f}{\partial \bar{E}}\right)\frac{\delta \bar{E}}{m_2} \qquad \ldots (1)$$

where m_f is the fuel used in the cruise and $\frac{\delta m_f}{m_2}$ represents a relative change in the fuel burn due to small changes in the variables m_2, SFC and L/D. To determine expressions for the partial derivatives $\left(\frac{\partial m_f}{\partial m_2}\right)$, $\left(\frac{\partial m_f}{\partial \bar{c}}\right)$ and $\left(\frac{\partial m_f}{\partial \bar{E}}\right)$, the following equation was used.

$$R = -\int_{m_1}^{m_2} \frac{V E}{c g m}\, \mathrm{d}m \qquad \ldots (2)$$

where R is the cruise range, V is the true airspeed, E is the lift-to-drag ratio, c is the SFC and m is the aircraft mass. If $\bar{E}$ and $\bar{c}$ are defined by

$$\bar{E} = -\frac{1}{m_f}\int_{m_1}^{m_2} E\, \mathrm{d}m \quad \text{and} \quad \bar{c} = -\frac{1}{m_f}\int_{m_1}^{m_2} c\, \mathrm{d}m$$

respectively, then the integral expression (2) may be written as:

$$R = \frac{V\bar{E}}{\bar{c}\, g}\ln\left(\frac{m_1}{m_2}\right) \qquad \ldots (3)$$

which is, of course, a form of the Breguet range equation. For this application it was required that m_f be expressed in terms of R. It is possible to derive this as a function of either m_1 or m_2. The result for the latter case is:

$$m_f = \left(e^{\frac{R\bar{c}g}{V\bar{E}}} - 1\right) m_2 \qquad \ldots (4)$$

Partial derivatives of Equation (4) were determined with respect to: m_2, $\bar{E}$ and $\bar{c}$, and substituted into Equation (1), to yield the following expression:

$$\frac{\delta m_f}{m_2} = \left(e^{\frac{R\bar{c}g}{V\bar{E}}} - 1\right)\frac{\delta m_2}{m_2} + \left(e^{\frac{R\bar{c}g}{V\bar{E}}}\,\frac{R\bar{c}g}{V\bar{E}}\right)\frac{\delta \bar{c}}{\bar{c}} - \left(e^{\frac{R\bar{c}g}{V\bar{E}}}\,\frac{R\bar{c}g}{V\bar{E}}\right)\frac{\delta \bar{E}}{\bar{E}} \qquad \ldots (5)$$

It is noted that the change in fuel burn due to a fixed change in aircraft mass, i.e. the first partial derivative in Equation (5), is the same as that presented by Shustrov[7]. Similar sensitivity relationships are given in Ref. 8, attributed to Le Claire[9]; however, they are not in the same form, nor derived in the manner presented here. Equation (5) is very convenient, as the changes to m_2, $\bar{E}$ and $\bar{c}$ are expressed in non-dimensional terms. The impact on fuel burn can thus be determined from relative changes to m_2, $\bar{E}$ and $\bar{c}$.

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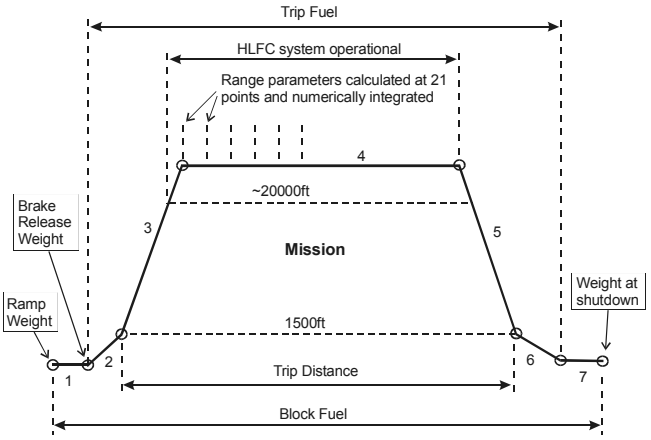


Figure 1. Flight profile for fuel planning of HLFC aircraft.

4.2 Method of validation

To explore the accuracy of Equation (5), use was made of the computer program described in Section 3 above, with the B757-200 class aircraft data. The cruise segment was considered in isolation and used to evaluate the fuel required to cover a fixed distance of 2,350nm at Mach 0·80 at 35,000ft (ISA conditions). The end-of-cruise mass (m_2) was used as a control parameter and set equal to 90,996kg. For each computer run, mean values of *L*/*D* and SFC were required. The numerical integration of the range equation (i.e. Equation (2)), performed within the computer program, required data to be evaluated at 21 evenly spaced locations during the cruise (Fig. 1). The $\bar{c}$ and $\bar{E}$ values were taken as the numerical averages of the SFC and *L*/*D* values calculated at these locations.

The following approach was adopted.

- Method 1 – The relative change in fuel mass $\frac{\delta m_f}{m_2}$ was determined directly, using the cruise subroutine of the computer program, for small changes to the governing parameters.
- Method 2 –The program was used to determine input data for use with Equation (5) and the relative change to the fuel mass $\frac{\delta m_f}{m_2}$ calculated.
- The results were compared.

Table 1
Impact of small change to end-of-cruise mass (m_2)

Computer run:	1	2	3	4	5	6
$\bar{c}$ change	0·00%	-0·01%	-0·01%	0·00%	0·03%	0·08%
$\bar{E}$ change	0·00%	–0·14%	–0·31%	–0·50%	–0·72%	–0·97%
m_1 (kg)	109,914	111,036	112,168	113,309	114,460	115,621
m_2 (kg)	90,996	91,906	92,816	93,726	94,636	95,545
m_2 change	0·00%	1·00%	2·00%	3·00%	4·00%	5·00%
$\frac{\Delta m_f}{m_2}$	0·00%	0·233%	0·477%	0·731%	0·995%	1·27%
Results from Equation (5):						
$\frac{\Delta m_f}{m_2}$	0·00%	0·208%	0·416%	0·624%	0·832%	1·04%

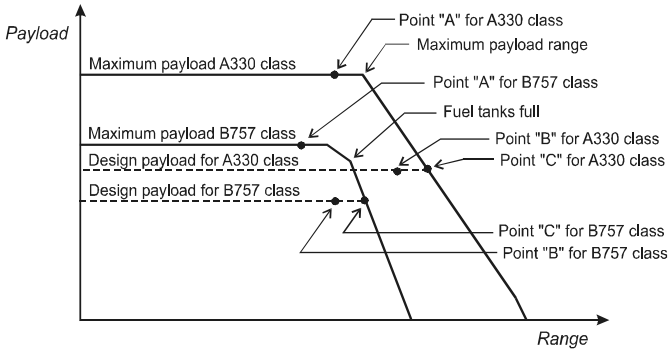


Figure 2. Payload-range graph indicating points of interest.

4.3 Method 1 – Results from computer model

The results of the three sets of calculations are given in Tables 1, 2 and 3. In each case only one governing parameter was changed, whilst the other two were kept nominally constant. The end-of-cruise weight (m_2) could be changed directly in the computer program and the impact on the cruise fuel burnt (m_f) assessed. The results given in Table 1 are for six computer runs, with run number one corresponding to the turbulent baseline vehicle, and runs two to six corresponding to a progressive increase in m_2. Each time the change in m_f was calculated as a ratio of the baseline value of m_2.

For the SFC sensitivity study the fuel flow was factored within the program database, as the SFC could not be directly controlled. (Fuel burn calculations were based on the use of fuel flow *versus* thrust tables in the program.) The fuel flow was increased in steps of 1%, from 0 to 5%. As the range did not change, the start-of-cruise mass (m_1) increased by a small amount representing the increased onboard fuel. This meant that the thrust also increased a little in the cruise to compensate for the increased drag. The mean SFC for each computer run was calculated and compared to the baseline condition (i.e. run number one). The percentage increases in $\bar{c}$, as expected, closely followed the percentage increases in fuel flow; however, as shown in Table 2, there was a minor difference in the third significant figure (e.g. a 5% increase in fuel flow resulted in a 5·01% increase in $\bar{c}$).

For the last set of calculations (Table 3) the drag coefficient was reduced within the program database in equal steps. The mean lift-to-drag ratio during cruise was calculated, and the percentage change determined with respect to the baseline condition (i.e. run number one). These percentage changes in $\bar{E}$ could then be compared to the resulting change in fuel.

Table 2
Impact of small change to SFC

Computer run:	1	2	3	4	5	6
$\bar{c}$ change	0·00%	1·00%	2·00%	3·01%	4·01%	5·01%
$\bar{E}$ change	0·00%	–0·02%	–0·04%	–0·06%	–0·09%	–0·11%
m_1 (kg)	109,914	110,126	110,339	110,552	110,766	110,981
m_2 (kg)	90996	90996	90996	90996	90996	90996
m_2 change	0·00%	0·00%	0·00%	0·00%	0·00%	0·00%
$\frac{\Delta m_f}{m_2}$	0·00%	0·233%	0·466%	0·701%	0·936%	1·17%
Results from Equation (5):						
$\frac{\Delta m_f}{m_2}$	0·00%	0·229%	0·458%	0·687%	0·916%	1·15%

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Table 3
Impact of small change to *L/D*

Computer run:	1	2	3	4	5	6
$\bar{c}$ change	0·00%	0·14%	0·38%	0·73%	1·21%	1·79%
$\bar{E}$ change	0·00%	3·16%	6·58%	10·20%	14·14%	18·34%
m_1 (kg)	109,914	109,311	108,717	108,149	107,593	107,054
m_2 (kg)	90,996	90,996	90,996	90,996	90,996	90,996
m_2 change	0·00%	0·00%	0·00%	0·00%	0·00%	0·00%
$\frac{\Delta m_f}{m_2}$	0·00%	–0·663%	–1·32%	–1·94%	–2·55%	–3·14%
Results from Equation (5):						
$\frac{\Delta m_f}{m_2}$	0·00%	–0·722%	–1·50%	–2·33%	–3·23%	–4·19%

Table 4
Data for reference condition (B757-200 class aircraft)

Range	TAS	$\bar{c}$	$\bar{E}$	m_1	m_2	m_f
2,350nm (4,355km)	461·1kt (237·4ms^{-1})	17·74mg/N/s (0·626lb/lb/hr)	16·89	109,914kg	90,996kg	18,919kg

Table 5
Matrix of sensitivity studies undertaken

Case	Aircraft Type	Range (nm)	Payload (kg)	OEW changed SFC & C_D unchanged	SFC changed OEW & C_D unchanged	C_D changed OEW & SFC unchanged	Results given in
1A	B757-200 class A/C	2,603	26,886	√	√	√	Fig. 3
1B	B757-200 class A/C	3,272	19,147	√	√	√	Fig. 4
2A	A330-200 class A/C	3,745	49,500	√	√	√	Fig. 5
2B	A330-200 class A/C	5,980	24,035	√	√	√	Fig. 6

Table 6
Ground rules for sensitivity studies for B757-200 class aircraft

Weights: The basic OEW is 58,394kg. Point A (Fig. 2) represents the maximum structural payload of 26,886kg and ~90% of the max. range at the max. BRW. Point B represents the 'baseline' payload of 19,147kg, based on 201 passengers plus baggage, at a passenger 'allowance weight' of 95·3kg and ~90% of the max. range at the max. fuel limit.

Mission: Climb / descent at 250kt (below FL 100) / 290kt / Mach 0·80; Cruise at Mach 0·80, FL 350; ISA + 0ºC, zero wind.

Drag reduction: The drag reduction was based on a percentage of the mean drag determined for the cruise for the turbulent baseline aircraft for the distance and weight of interest, i.e. as a percent of $C_D = 0{\cdot}03015$ for case 1A and $C_D = 0{\cdot}02841$ for case 1B.

4.4 Method 2 – Results from small change equation

The values of $\bar{c}$ and $\bar{E}$ given in Table 4 are the numerical averages of the SFC and *L/D* values calculated at the 21 cruise locations for the baseline turbulent aircraft, for a 2,350nm, Mach 0·80 cruise at 35,000ft. Using these results it follows from Equation (5) that:

$$\frac{\delta m_f}{m_2} = 0{\cdot}20807\ \frac{\delta m_2}{m_2} + 0{\cdot}22836\frac{\delta \bar{c}}{\bar{c}} - 0{\cdot}22836\ \frac{\delta \bar{E}}{\bar{E}} \qquad \ldots (6)$$

Relative changes to the fuel mass $\frac{\delta m_f}{m_2}$ were calculated, by considering, individually, small changes to m_2, $\bar{c}$ and $\bar{E}$. For each set of calculations performed using Equation (6), only one parameter was incrementally changed and the other two were held constant. The results are given in the last rows of Table 1 (where m_2 varied from 0 to 5%), Table 2 (where $\bar{c}$ varied from 0 to 5·01%) and Table 3 (where $\bar{E}$ varied from 0 to 18·34%).

4.5 Discussion of results

The results of the formulation given by Equation (5) were compared to the results obtained from the computer model, which took into account the coupling between the variables m_2, $\bar{c}$ and $\bar{E}$. The following was noted:

1. For a 5% increase in m_2 Equation (5) yielded a 1·04% increase in

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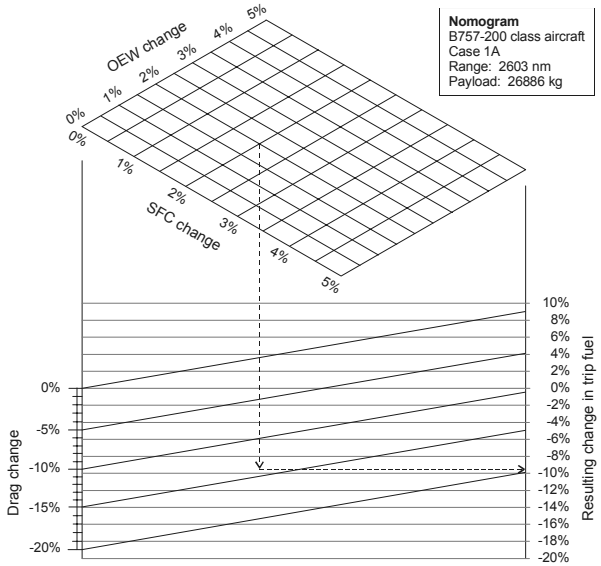


Figure 3. Change in trip fuel due to changes in OEW, SFC & drag – Case 1A.

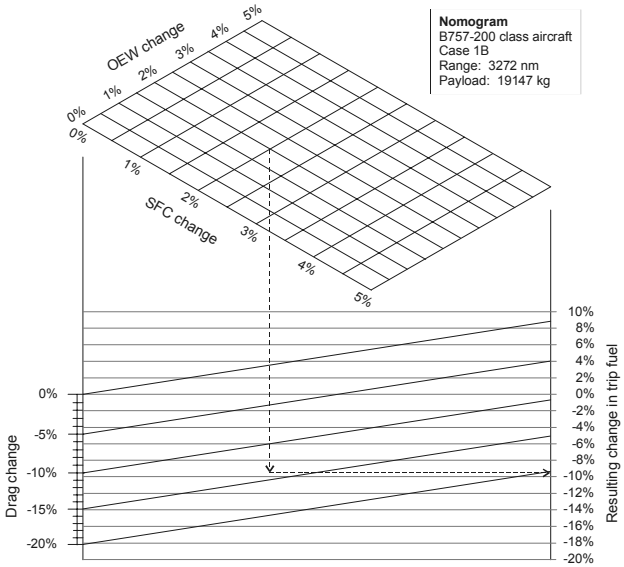


Figure 4. Change in trip fuel due to changes in OEW, SFC & drag – Case 1B.

the ratio $\frac{m_f}{m_2}$. This compared reasonably well to the 1·27% change obtained using the computer model. It is evident that as the end-of-cruise weight increases, C_L and C_D would both increase during the cruise, but not necessarily by the same amount. At the higher values the *L*/*D* ratio is seen to be a little lower for this particular cruise data; however the impact is small, as seen in Table 3. Secondly, the higher drag would require a proportionally greater thrust and this would change the SFC. The mean SFC is shown to vary, non-linearly, by a very small amount with an increasing value of m_2.

2. For a 5·01% increase in SFC, Equation (5) yielded a 1·15% increase in the ratio $\frac{m_f}{m_2}$. This compared very well to the 1·17% change obtained using the computer model. As the weight increase (due to the increased fuel requirement) is small, the mean *L*/*D* ratio does not change very much.
3. The impact of a change in *L*/*D* ratio was similarly investigated using Equation (5); however, the correlation with the computer model was not as good as that observed for the SFC change. For a 10·2% increase in *L*/*D*, Equation (5) yielded a –2·33% change in fuel mass, versus a –1·94% change obtained using the computer program. With reduced fuel load due to the lower drag, the aircraft is lighter at all times during the cruise. This will change the SFC at each point during the cruise. The mean SFC increases in this particular situation; however, due to the non-linearity of SFC changes in cruise, this result cannot be regarded as a general observation.

5.0 COMPUTER SENSITIVITY STUDY (TRIP FUEL)

5.1 Methodology

Whereas the cruise segment of the mission was considered in isolation in Section 4, in this part of the study the trip fuel (Fig. 1) was evaluated for both the B757-200 class and A330-200 class aircraft, using the computer performance model. Three sets of calculations to

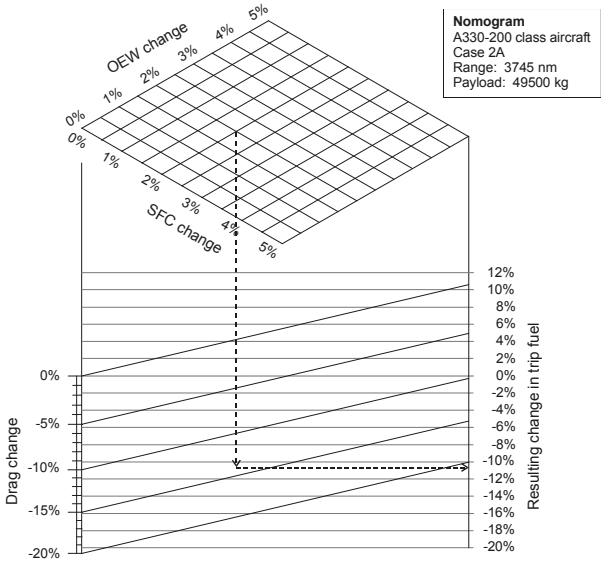


Figure 5. Change in trip fuel due to changes in OEW, SFC & drag – Case 2A.

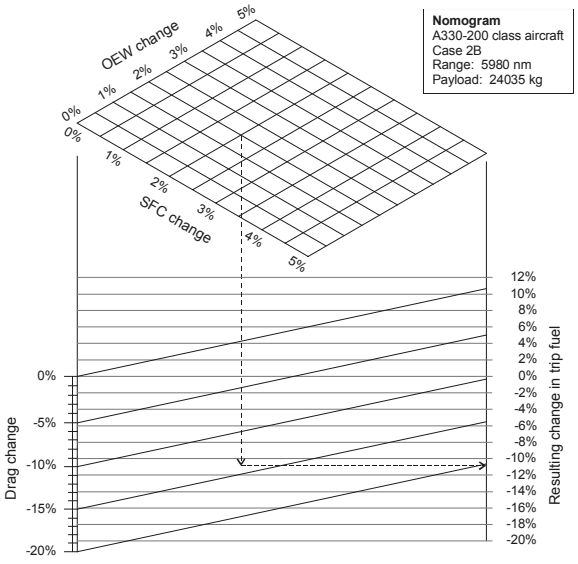


Figure 6. Change in trip fuel due to changes in OEW, SFC & drag - Case 2B.

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Table 7
Ground rules for sensitivity studies for A330-200 class aircraft

Weights:	The basic OEW was 120,500kg. Point A (Fig. 2) represents the maximum structural payload of 49,500kg and ~90% of the max. range at the max. BRW. Point B represents the 'baseline' payload of 24,035kg, based on 253 passengers plus baggage, at a passenger 'allowance' weight of 95kg and ~90% of the max. range at the max. BRW.
Mission:	Climb / descent at 250kt (below FL 100) / 300kt / Mach 0·80; Cruise at Mach 0·80, FL 370 / 410 (step climb); ISA + 0ºC, zero wind.
Drag reduction:	The drag reduction was based on a percentage of the mean drag determined for the cruise for the turbulent baseline aircraft for the distance and weight of interest, i.e. as a percent of C_D = 0·02821 for case 2A and C_D = 0·02588 for case 2B.

determine the trip fuel were performed for selected combinations of payload and range.

1. The OEW was increased in small steps, whilst the SFC and C_D were unchanged.
2. The SFC was incrementally increased, whilst the OEW and C_D were unchanged.
3. The C_D was reduced, whilst the SFC and OEW were unchanged.

The SFC and C_D changes were implemented above 20,000ft in the climb (Fig. 1); however the mass change (due to the drag reduction system), was incorporated by changing the aircraft's OEW. For each 'flight', the lowest brake release weight (BRW) was determined for the specified range, which ensured that the smallest fuel quantity was calculated each time. The resulting change in trip fuel was determined as a percentage of the fuel required for the baseline turbulent model and plotted against the variable parameter.

Two points on the payload-range graph were selected for analysis for each aircraft type. The first corresponded to the maximum structural payload (point A) and the second was at a typical design payload (point B), as shown in Fig. 2. Both points were taken at about 90% of the maximum range at that payload. The points were deliberately not selected on the boundaries of the payload-range graph, to avoid encountering a weight or fuel capacity limitation, when considering either increased SFC or OEW, as this would produce an erroneous result.

In the case of the A330-200 class aircraft, the maximum range at the design payload (point C) was on the boundary where the range was restricted by maximum structural weight; whereas for the B757-200 class aircraft, it was restricted by fuel tank capacity. This combination of variables meant that 12 studies were undertaken, as illustrated in Table 5.

5.2 Results

The constraints and input variables for the studies are given in Table 6 (B757-200 class aircraft) and Table 7 (A330-200 class aircraft). Results are presented in Figs 3 and 4 (for cases 1A and 1B respectively, for the B757-200 class aircraft) and in Figs 5 and 6 (for cases 2A and 2B respectively, for the A330-200 class aircraft). The illustrative result in the nomogram corresponds to a 2% increase in OEW, a 2% SFC penalty and a 14% reduction in total drag (based on the mean drag in cruise for the turbulent baseline aircraft, for the distance and aircraft weight of interest).

5.3 Discussion of results

The approach adopted in Section 5 was to separate the effects of the three input parameters and to treat them as linear independent variables. An estimate of the trip fuel saving due to the combined effect of all three parameters can be obtained by adding the results of the three parameters, as presented in Figs 3 to 6, for the two cases considered. To explore the accuracy of this approach, for the range and payload conditions selected, the computer program was run with a simultaneous input of a 2% increase in OEW, a 2% increase in SFC and a 14% decrease in drag. The results from these 'combined' analyses are shown in Table 8, together with the results from the linear superposition method (i.e. from Figs 3 – 6). It is seen that the predicted savings in trip fuel calculated using the two methods, differ by approximately 0·6%, indicating that accurate answers can be obtained by this method.

6.0 CONCLUSIONS

1. One objective of the study was to explore the use of a simple mathematical relationship (i.e. Equation (5)) that could be used to generalise the results established for the selected aircraft types. It was concluded that the impact on cruise fuel burn can be satisfactorily estimated from relative changes to m_2 (end-of-cruise mass), $\bar{E}$ (mean lift-to-drag ratio) and $\bar{c}$ (mean SFC), using Equation (5). It was observed that this is a convenient formulation as the changes to m_2, $\bar{E}$ and $\bar{c}$ are expressed as non-dimensional terms.
2. The results of the sensitivity studies – which are presented as nomograms in Figs 3 to 6 – facilitate a rapid determination of the reduction in trip fuel for changes to the OEW, SFC and C_D. This application of these results is not restricted to laminar flow

Table 8
Results of 'spot check' to assess change in trip fuel

	B757-200 class A/C		A30-200 class A/C	
	Case 1A	**Case 1B**	**Case 2A**	**Case 2B**
Change in trip fuel due to:				
2% increase in OEW	1·42%	1·32%	1·83%	1·74%
2% increase in SFC	2·09%	2·16%	2·11%	2·46%
14% change in drag	–13·08%	–12·98%	–14·84%	–15·04%
Total	–9·56%	–9·51%	–10·90%	–10·85%
'Combined' computer run:	–10·05%	–9·98%	–11·49%	–11·53%

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control, but is valid for any active drag reduction technique. The results will be of value in MVO studies of HLFC and other active drag reduction technologies.

3. The underlying assumption of linear independence of the three parameters (i.e. SFC, OEW and C_D) was explored by comparing the results obtained by adding the individual contributions from the sensitivity studies, against those obtained by running the computer model with a simultaneous input of the parameters (Table 8). The linear superposition method was observed to underestimate the fuel savings (of the HLFC aircraft compared to the turbulent baseline aircraft) by approximately 0·6% compared to the more accurate 'combined' analysis, for the four cases considered.

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