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Future Aircraft Fuel Efficiencies - Final Report

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Executive Summary

The UK Department for Transport (DfT) have produced forecasts of UK air traffic for a number of years to inform long term strategic aviation policy. In response to the increasing global focus on climate change, aviation carbon dioxide (CO_2) emissions have been added to these forecasts.

These forecasts of aviation CO_2 comprise forecasts of demand for UK aviation which are input to a DfT UK fleet mix model. This model projects the base year movements by aircraft type using the change in demand by seat class to produce future year movements by aircraft type. In the current approach, the fuel consumption by each aircraft type is calculated using the CORINAIR Emissions Methodology Guidebook. To account for new aircraft types, assumptions are made on the likely introduction date of new types and their fuel efficiency.

The DfT have requested a review of the current forecast method and updates to the assumptions related to the fuel efficiency of current and new aircraft types.

The assessment has covered the mapping of aircraft types to those in CORINAIR, the accuracy of the CORINAIR data (by comparison with data from the AERO2k greenhouse gas model) and the accuracy of the curve fits used when applying the CORINAIR fuel burn data. The supply pool assumptions, defining which aircraft types are introduced into the fleet when existing aircraft retire, have also been assessed.

From this assessment, a number of observations on the modelling of CO_2 emissions from aircraft have been made and recommendations provided for enhancing the accuracy of these calculations. These have included factors to be applied to the fuel burn for existing CORINAIR types and approaches to generating data for additional types not in the CORINAIR guidebook.

A review of technologies for future aircraft, based on information previously submitted to the Committee on Climate Change, has also been provided. From this review, recommendations have been made for defining fuel burn data for generic aircraft types to be introduced beyond the year 2030.

The report also describes some alternatives to the central case, including the drivers for them and the likely effect on the future fleet.

The three alternative scenarios considered are:

- Scenario 1: High and low projections of oil price
- Scenario 2: Lower end of a plausible range of fuel efficiency improvements
- Scenario 3: Upper end of a plausible range of fuel efficiency improvements

The high oil price scenario is expected to lead to an acceleration in the development of new aircraft technology, with an associated reduction in the retirement age of the existing types and a more rapid penetration of the supply pool by the new types. The low oil price scenario is expected to lead to slower development of new technology with an increase in the retirement ages of existing types.

The drivers which could cause future fuel efficiency improvements to be at the lower end of the likely range include ongoing global economic difficulties and either

noise or emissions of nitrogen oxides (NOx) being the dominant environmental concern.

The drivers which could lead to future technology achieving the upper bound of the likely range include a strong global economy together with high carbon costs and a commitment to significant reductions in CO_2 emissions.

Recommendations for adjustments in the modelling of future aircraft types have been made for these scenarios.

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1 Introduction

The UK Department for Transport (DfT) have produced forecasts of UK air traffic for a number of years to inform long term strategic aviation policy. In response to the increasing global focus on climate change, aviation carbon dioxide (CO_2) emissions have been added to these forecasts [1].

These forecasts of aviation CO_2 comprise forecasts of demand for UK aviation which are input to a DfT UK fleet mix model. This model projects the base year movements by aircraft type using the change in demand by seat class to produce future year movements by aircraft type. In the current approach, the fuel consumption by each aircraft type is calculated using the CORINAIR Emissions Methodology Guidebook [2]. To account for new aircraft types, assumptions are made on the likely introduction date of new types and their fuel efficiency.

The DfT have requested a review of the current forecast method and updates to the assumptions related to the fuel efficiency of current and new aircraft types. The stated objectives for the project are:

- review the DfT's assumptions regarding the fuel efficiency of aircraft available for use at UK airports between now and 2050;
- assess the continuing suitability of the CORINAIR guidebook methodology for future fuel burn forecasts and suggest possible modifications;
- assess whether current DfT fuel efficiency assumptions are a reasonable representation of a 'central case'; and if not, propose alternative assumptions that could be used to inform a central case projection of CO_2 emissions from aircraft using UK airports;
- use evidence on the key drivers of efficiency for various aircraft types to develop a number of scenarios to demonstrate the range of uncertainty in the path of fuel efficiency of aircraft available for use at UK airports to 2050.

Specifically excluded from the study are any consideration of operational efficiency improvements, load factors, air transport management and any fleet-related assumptions used in the fleet modelling (other than aircraft retirement ages).

This report includes the assessment of the effect of a number of alternative scenarios relating to the aircraft technologies and efficiencies that could be in the fleet operating from UK airports to 2050.

Section 2 of this report describes the current approach to the forecasting of fuel burn from UK air traffic. Some validation work on the techniques and models used in the current approach is described in Section 3. Recommendations for the modelling of known future types are given in Section 4. A review of future aircraft technologies is given in Section 5 with recommended updates to the forecast method for the central case summarised in Section 6.

As a prelude to the discussion of alternative scenarios, Section 7 reviews the assumptions behind the central case. The alternative scenarios themselves are then assessed in Section 8 with recommendations for implementing these scenarios in the CO_2 forecasts given in Section 9. Conclusions are then given in Section 10.

2 Current Method

Although the aim of the current programme is to review the assumptions regarding the fuel efficiency of future aircraft, this section provides a summary of the current DfT methodology for forecasting CO_2 emissions from UK air movements, including demand and fleet growth/replacement issues, to provide context. A full description can be found in DfT's *UK Air Passenger demand and CO2 Forecasts* (January 2009) [1].

The process begins with the National Air Passenger Demand Model, which forecasts unconstrained passenger demand (i.e. a demand for travel which is not constrained by airport capacity). The 'NAPAIM' model then converts the national unconstrained passenger demand forecasts into forecasts of passenger and air traffic movement (ATM) throughput (constrained by airport capacity) for each UK airport, by route (or group of routes), aircraft 'seat band', and carrier type (scheduled, charter, or Low Cost / No Frills Carrier). At this stage, the fleet mix information is therefore fairly limited, representing aircraft type simply by size, using six seat band categories.

To produce CO_2 forecasts, it is necessary to expand the seat band dimension of this ATM throughput forecast data into specific aircraft types (e.g. Boeing 747-400, Airbus A340-300, etc). This is undertaken by the DfT Fleet Mix Model (FMM).

The Fleet Mix Model starts with a set of base year (currently 2008) data showing the number of ATMs split by aircraft type, aircraft age (in years), carrier type (i.e. scheduled, charter, or No-Frills Carrier (NFC)) and NAPAIM seat band (derived from calibrated graphed relationships between demand, load factor and aircraft size for groups of routes);

There is considerable overlap between aircraft in the seat band categories because of the variability between cabin seating configurations between different airlines and carrier types. For example: bmi tend to operate their A320s at 156 seats (seat band 3) while BA tend to operate at 149 seats (seat band 2); easyJet generally operate their A319s at 151 seats (seat band 3) while BA tend to operate at 123 seats; and Boeing 747s may be configured with anything between 290 and 450 seats.

For the first forecast year (2009), the FMM calculates the number of ATMs by seat band and carrier class from aircraft that have reached retirement age. This involves 'aging' the base year distribution of ATMs (by age, aircraft type, carrier type and seat band) by one year. This, combined with user assumptions about the retirement age of each aircraft type, defines the number of ATMs (by aircraft type, carrier type, and seat band) that are performed by aircraft at their retirement age and need to be re-allocated to new aircraft.

The reallocation of these ATMs between aircraft types is governed by user input assumptions about the 'supply pool'. This details for each forecast year (and carrier type and seat band) how 'retiring ATMs' from an aircraft type would be replaced by ATMs from available 'in-production' aircraft types for that year. For example, if the FMM identified that 100 ATMs were to be performed by 22 year old A340-300s, then it would identify these as due to retire[1], and reallocate their ATMs to a mixture of aircraft types (which could include new A340-300s).

[1] 22 years is the assumed retirement age for this aircraft type.

The first forecast year's number of ATMs by each aircraft type is then calculated as: base year ATMs – retired ATMs + replacement ATMs.

Subsequent forecast year fleet mixes are then calculated by the same process set out above, taking the previous forecast year as the base year.

The data thus generated are then used to assign specific aircraft types to the forecasts of ATMs.

The CO_2 forecasting model takes the resulting forecasts of ATMs at each airport, by route, aircraft type and carrier type. The distance flown on each route is then calculated from the great circle distance between the departure and arrival airports, factored to account for the deviation from great circle trajectories. Based on international estimates, an extra 9% of distance is added due to this "inefficiency". To calculate the fuel burn on each flight, the aircraft type is mapped to one of the types in the CORINAIR guidebook [2] and the fuel burn calculated from the tables of fuel burn vs. flight distance. To simplify the process of calculating the fuel burn, a cubic curve is fitted to the CORINAIR data and the fuel burn calculated algebraically. In the event that the flight distance exceeds the highest range of the CORINAIR data, the fuel burn is calculated by a linear extension to the CORINAIR data. An additional factor is then applied, based on the expected load factor of the aircraft (the CORINAIR data assume a load factor of 65%, which is quite low by today's standards and significantly low compared to the expected levels in future years). The CO_2 emitted from each flight is then calculated by applying a factor of 3.15 to the fuel burn.

The aircraft types for which data are available in CORINAIR are shown in Table 1 below.

Table 1 List of aircraft types in CORINAIR

Turbofan types	**Turboprop types**
Airbus A310	Swearingen Metro III
Airbus A320	Shorts SC7
Airbus A330	Shorts 360-300
Airbus A340	Shorts 330
BAC 1-11	Saab 340B
BAe146	Saab 2000
Boeing 727	Reims F406 Caravan II
Boeing 737-100	Lockheed P-3B Orion
Boeing 737-400	Lockheed C130 Hercules
Boeing 747-100/200/300	Fokker F50
Boeing 747-400	Fokker F27
Boeing 757	Embraer 110
Boeing 767-300ER	Dornier 328
Boeing 777	De Havilland DHC-3 Turbo Otter
Douglas DC9	De Havilland Dash 7

Douglas DC10	De Havilland Dash 8 Q400
Fokker F28	Cessna 208 Caravan
Fokker F100	Beech Super King Air 350
McDonnell Douglas MD81-88	Beech Super King Air 200B
	Beech 1900C
	BAe Jetstream 41
	BAe Jetstream 31
	ATR 72-200
	ATR 42-320
	Antonov 26

For the forecasting of future year operations, there is a need to include models of aircraft types which are not in service (or were not available when the CORINAIR data were generated) and for whom a direct map to an existing aircraft is not appropriate. At present, these additional aircraft include the Airbus A350 and Boeing 787 (both are modelled using the same aircraft model) and the Airbus A380. Another future aircraft, the Bombardier C_Series is mapped to a BAe146. The Airbus A380 data are derived from those for the Boeing 747-400, but with an improvement of 20% in fuel burn per seat-kilometre (seat-km) flown. Similarly, the Airbus A350 and Boeing 787 data are derived from those for the Boeing 767-300ER with an improvement of 20% in fuel burn per seat-km.

The Advisory Council for Aeronautics Research in Europe (ACARE) have published their vision for 2020 [3], in which there is a target of a 50% reduction in CO_2 emissions per seat-km by 2020, relative to a base year of 2000. Of this 50%, 40% is attributed to aircraft-level improvements, while 10% comes from operational improvements. Therefore, the current DfT methodology assumes that a new generation of ACARE 2020-compliant aircraft start entering the fleet, in all seat classes, from 2020. In the initial year of introduction, it is assumed that these aircraft form 5% of the supply pool, which rises to 25% by 2030. The aircraft definitions for these ACARE-compliant types are given in the following table.

Table 2 Definitions of fuel burn data for ACARE-compliant aircraft types

ACARE-compliant aircraft type	Definition of fuel burn
1-70 seats	ATR42-300 – 40%
71-150 seats	Boeing 737-400 – 40%
151-250 seats	Boeing 757-200 – 40%
251-350 seats	Boeing 777-200 – 40%
351-500 seats, twin-engined	Average of (Boeing 777, Airbus A340) – 40%
351-500 seats, four-engined	Boeing 747-400 – 40%

This detailed level of forecasting is applied to passenger ATMs flying between the 31 domestic airports and 48 international zones included in NAPAIM. Other ATMs, including freight, use generic CO_2 emission rates.

3 Validation of method

A range of comparisons have been made to investigate (and, where possible, validate) the current approach, concentrating on the aircraft mapping and performance aspects.

3.1 Aircraft mapping table

The aircraft mapping table, "NETCEN AC Type", used by the DfT to map individual aircraft types to those available in CORINAIR, is based on data in the 2004 report from NETCEN/AEAT to Defra [4]. This mapping table has been assessed. This produced the following observations.

- There is no Airbus A300 aircraft type in CORINAIR, so all A300 variants are mapped to the A310.
- There is no Airbus A318 aircraft in the mapping table.
- The Airbus A319, A320 and A321 aircraft are all mapped to the A320.
- The Airbus A340-600 aircraft is mapped to the A340-300, even though it is a longer range aircraft with significantly larger engines.
- There is no Airbus A340-500 aircraft in the mapping table.
- The Boeing 737-800 and -900 ("Next Generation") aircraft are mapped to the A320.
- The Boeing 737-600, 700 ("Next Generation") aircraft are mapped to the 737-400 ("Classic").
- The Boeing 737-300 aircraft is mapped to the 737-100, even though it was fitted with the CFM56 engine (as fitted to the 737-400) rather than the JT8D (as fitted to the 737-100 and -200).
- There are no Boeing 777-200LR or Boeing 777-300ER aircraft (the variants of the 777 fitted with the GE90-110B and -115B engines) in the mapping table.

The Airbus A380 aircraft is not in the mapping table, but it is modelled as a modification to the Boeing 747-400 data. Similarly, the future Airbus A350 and Boeing 787 aircraft are modelled by a modification to the Boeing 767 data. The Boeing 747-8, also not in the mapping table, is modelled as a 747-400. The Bombardier C Series is modelled as a BAe146.

Looking at the current analysis for the year 2030, it is possible to extract the distance flown and CO_2 produced by each aircraft type. The results for the top 18 aircraft types, in terms of total distance flown and CO_2 emissions, are shown in the following two tables, respectively.

The aircraft types in Table 3 cover over 90% of the total distance flown, while those in Table 4 cover over 93% of the CO_2 produced (and fuel burnt).

From these tables, it can be seen that the aircraft which are not in the mapping table but modelled through additional models (the Airbus A380, Boeing 747-8 [referred to as 747-800 in the tables], the Boeing 787 and Airbus A350) are all significant aircraft in the future year analyses. Additionally, the Airbus A340-600, Boeing 737-700 and -800, Airbus A319 and A321, and the Boeing 777-300ER are also significant aircraft types. Further discussions of the modelling of these aircraft types is covered in the following sections.

Table 3 Table of distance flown by top aircraft types in 2030

Aircraft Type	Distance Flown (km)	Percentage of Total
Boeing 737-800	690,599,845	11.3%
Boeing 787 all passenger (pax) models	689,317,844	11.3%
Airbus A320-100/200	506,729,825	8.3%
Boeing 737-700	404,761,244	6.6%
ACARE Next-Gen CL3	374,894,221	6.1%
Airbus A380 pax	367,046,382	6.0%
Airbus A319	355,116,808	5.8%
Airbus A321	330,901,770	5.4%
Boeing 747-800	281,081,577	4.6%
Airbus A340-600	253,407,441	4.1%
Airbus A350-900	241,190,518	3.9%
Boeing 777-300	168,706,851	2.8%
Bombardier C Series	152,805,934	2.5%
Airbus A350-800	147,146,628	2.4%
Boeing 777-300 (ER)	146,906,777	2.4%
Bombardier DHC-8 Q400	141,099,301	2.3%
ACARE Next-Gen CL4	140,478,135	2.3%
Boeing 777-200	137,188,817	2.2%

Table 4 Table of CO_2 produced by top aircraft types in 2030

Aircraft Type	CO_2 produced (Tonnes)	Percentage of Total
Airbus A380 pax	7,475,396	16.0%
Boeing 747-800	4,587,038	9.8%
Boeing 787 all pax models	4,545,608	9.7%
Boeing 737-800	3,650,318	7.8%
Airbus A340-600	2,700,461	5.8%
Airbus A320-100/200	2,656,469	5.7%
Boeing 737-700	2,361,454	5.0%
Boeing 777-300	1,969,645	4.2%
Airbus A319	1,936,277	4.1%
ACARE Next-Gen CL3	1,787,062	3.8%
Boeing 777-300 (ER)	1,703,715	3.6%
Airbus A321	1,697,905	3.6%
Boeing 777-200	1,591,732	3.4%
Airbus A350-900	1,554,685	3.3%
Airbus A350-800	1,012,158	2.2%
ACARE Next-Gen CL4	977,464	2.1%
Bombardier C Series	806,726	1.7%
Embraer 170	534,831	1.1%

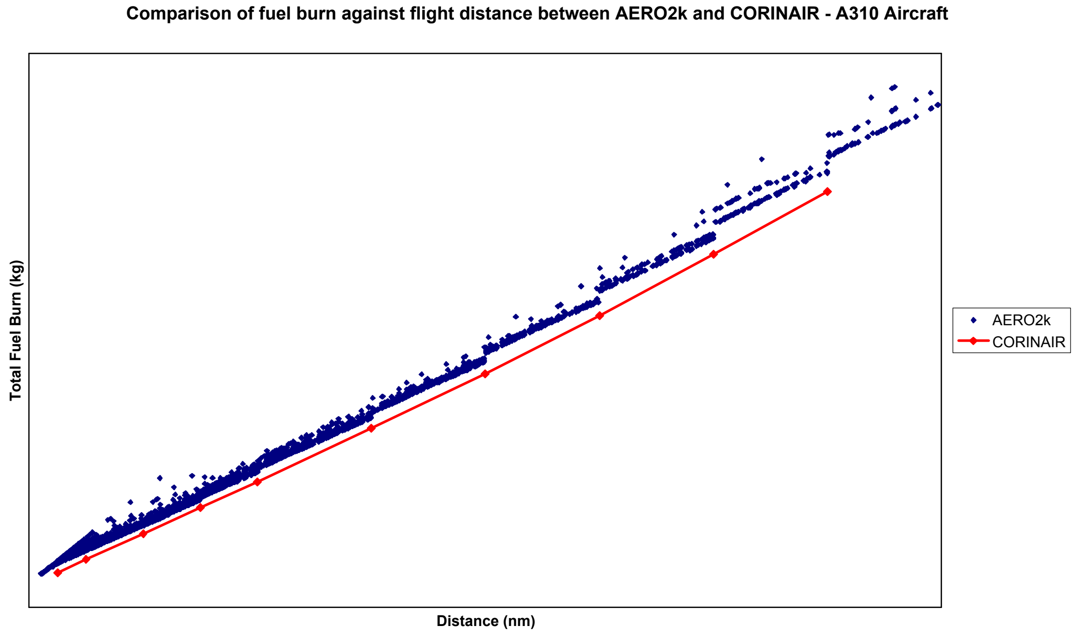
3.2 CORINAIR fuel burn tables

The fuel burn data in the CORINAIR tables were derived using the PIANO [5] aircraft design and performance model, which is itself in widespread use for such modelling. The data used in the QinetiQ AERO2k [6] model, one of the models approved for the Committee for Aviation Environmental Protection (CAEP) greenhouse gas modelling, were also derived using PIANO, though a more recent version than that used for generating the CORINAIR data[2]. As part of the CAEP/8 NOx Stringency and Goals analyses, the results from AERO2k were compared with those from the other greenhouse gas models involved in the analyses [7]; good agreement was found on fuel burn between the various models. It is, therefore, useful to compare the results obtained using the two models and update the CORINAIR data where applicable.

The data for AERO2k were extracted from the results of the analyses performed over the past two years for the CAEP/8 NOx Stringency and Goals analyses. For these analyses, AERO2k was used to compute the fuel burn and emissions for a very large number of flights by a large number of aircraft types. In common with CORINAIR, AERO2k uses a limited number of aircraft models and maps the actual aircraft types to these models. For comparisons with CORINAIR, the data have been extracted (as fuel burn against flight distance) for the relevant representative aircraft, where there is a good match between the representative aircraft in the two models.

The comparisons between the two models are presented as plots of fuel burn against flight distance. The terms under which QinetiQ has access to the PIANO tool restrict detailed data release at an aircraft type level, so the scales on the plots have been removed for this report.

Figure 1 Fuel burn vs. distance for A310 aircraft



[2] Two of the four greenhouse gas models used in the recent CAEP/8 NOx Stringency and Goals modelling programme employed PIANO for their aircraft performance modelling.

Figure 2 Fuel burn vs. distance for A319, A320 and A321 aircraft, compared to CORINAIR data for A320

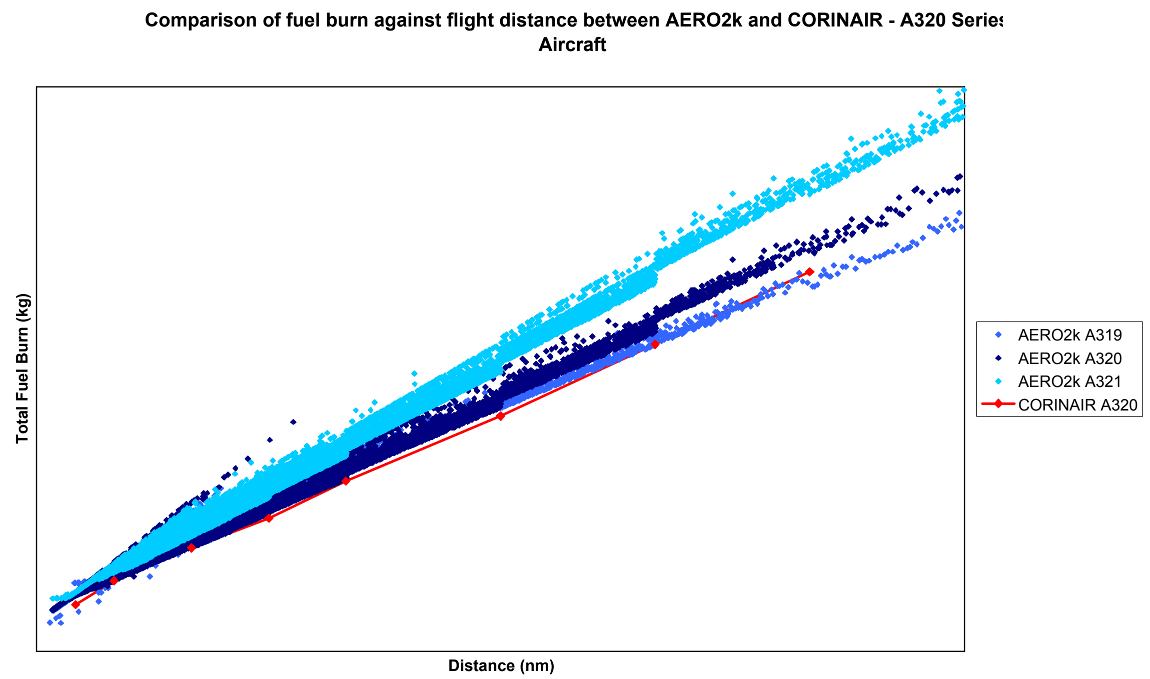


Figure 3 Fuel burn vs. distance for A330 aircraft

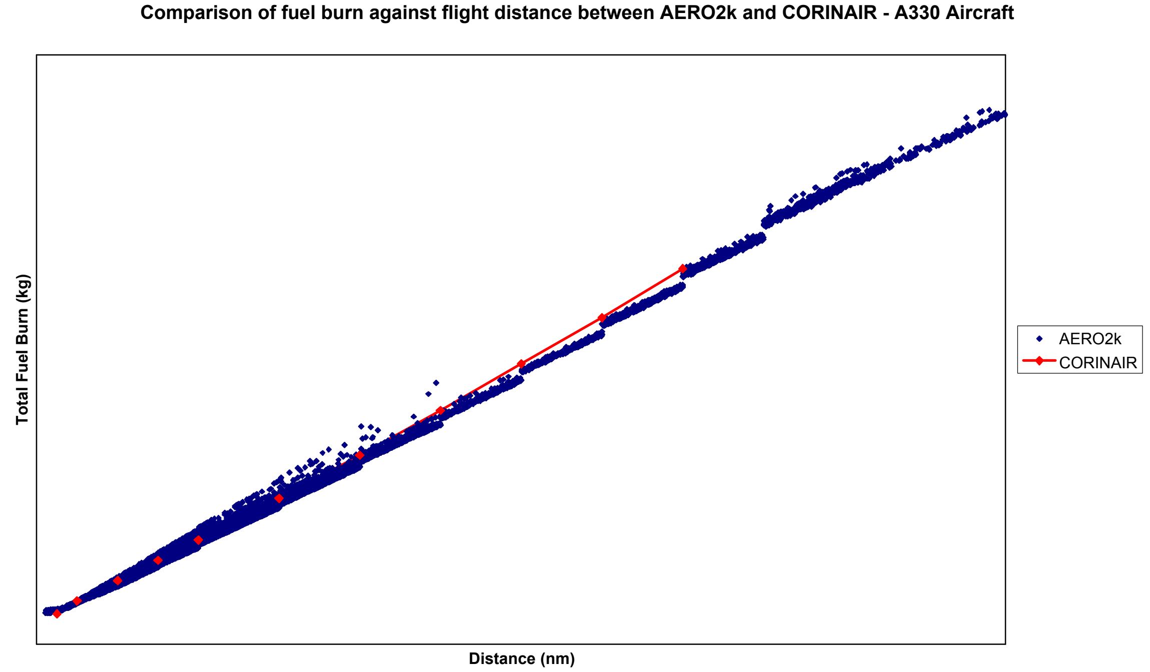


Figure 4 Fuel burn vs. distance for A340 aircraft

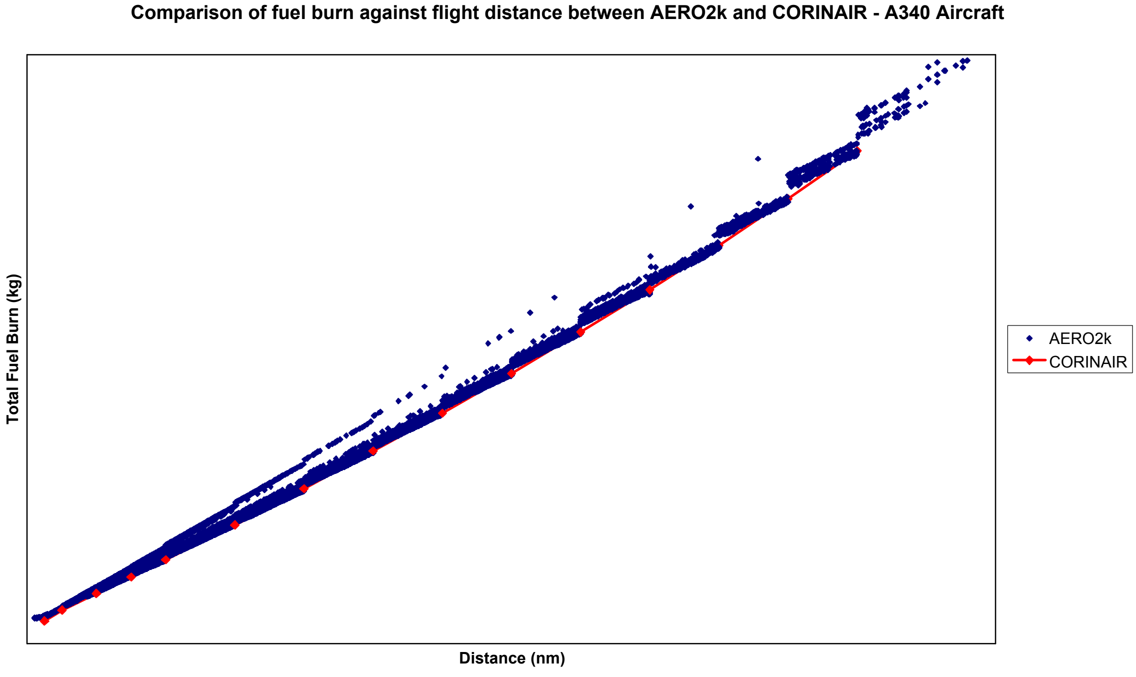


Figure 5 Fuel burn vs distance for Boeing 737-100/200 aircraft

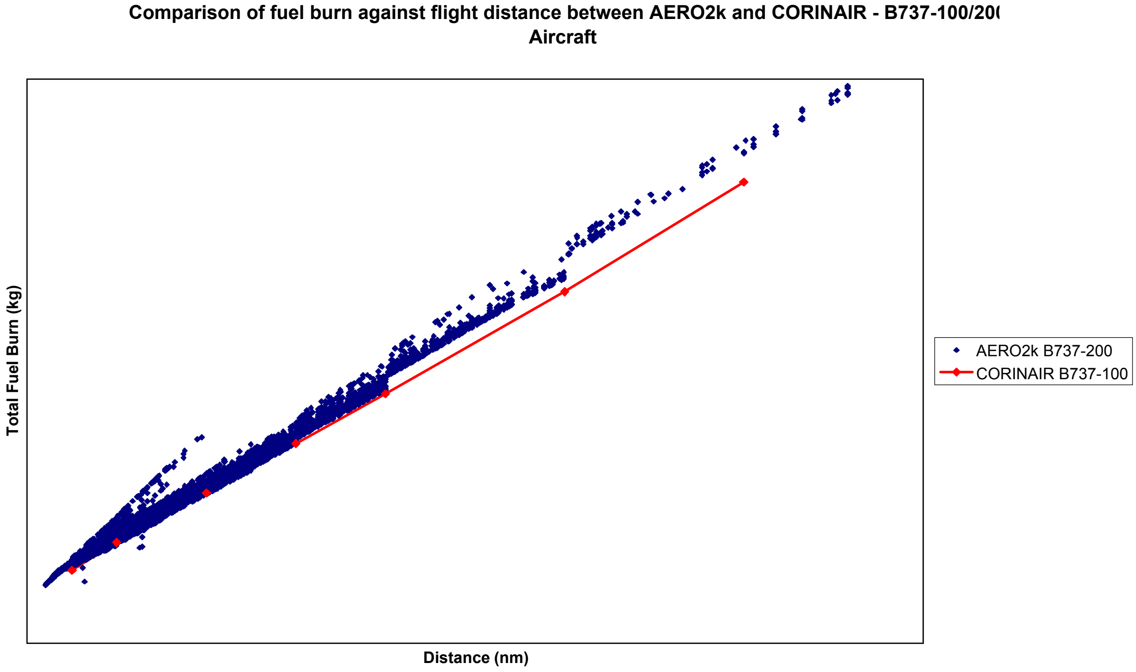


Figure 6 Fuel burn vs. distance for Boeing 737-400 aircraft

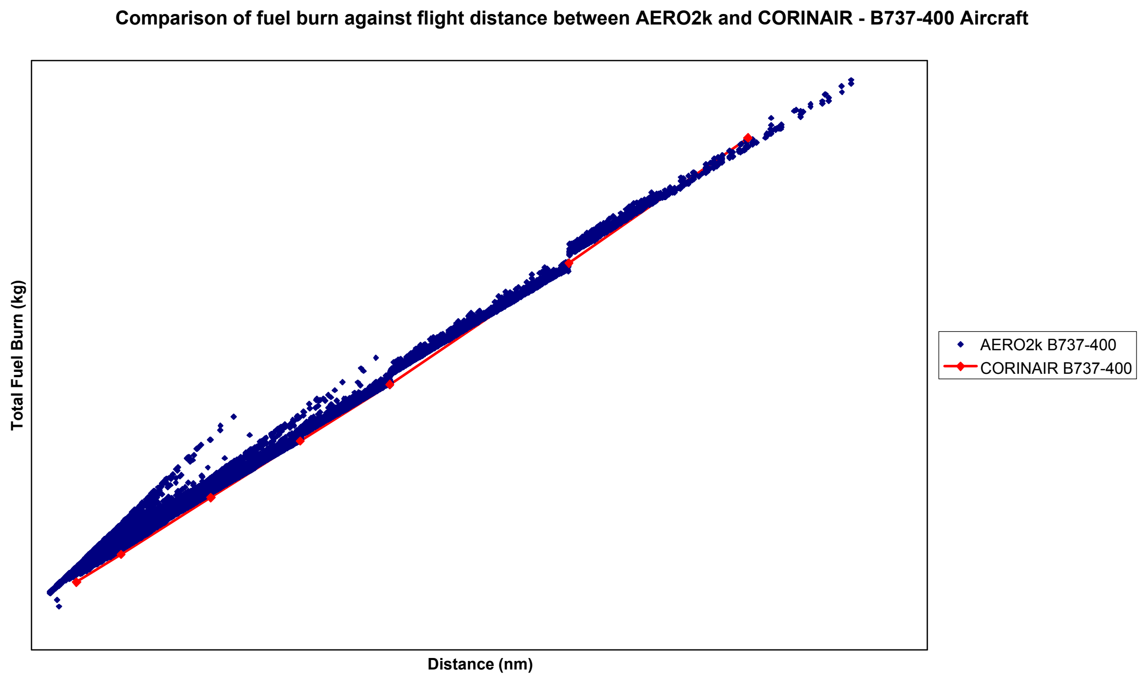


Figure 7 Fuel burn vs. distance for Boeing 737-600 and Boeing 737-400, compared to CORINAIR data for Boeing 737-400

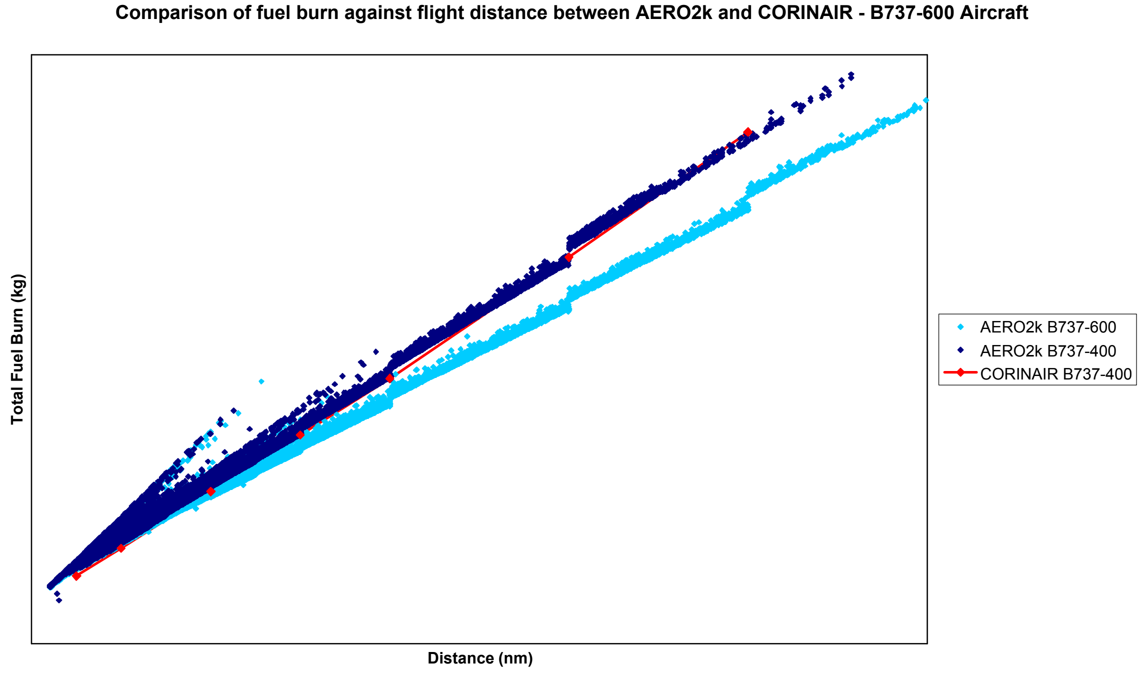


Figure 8 Fuel burn vs. distance for Boeing 737-800, compared to CORINAIR data for A320

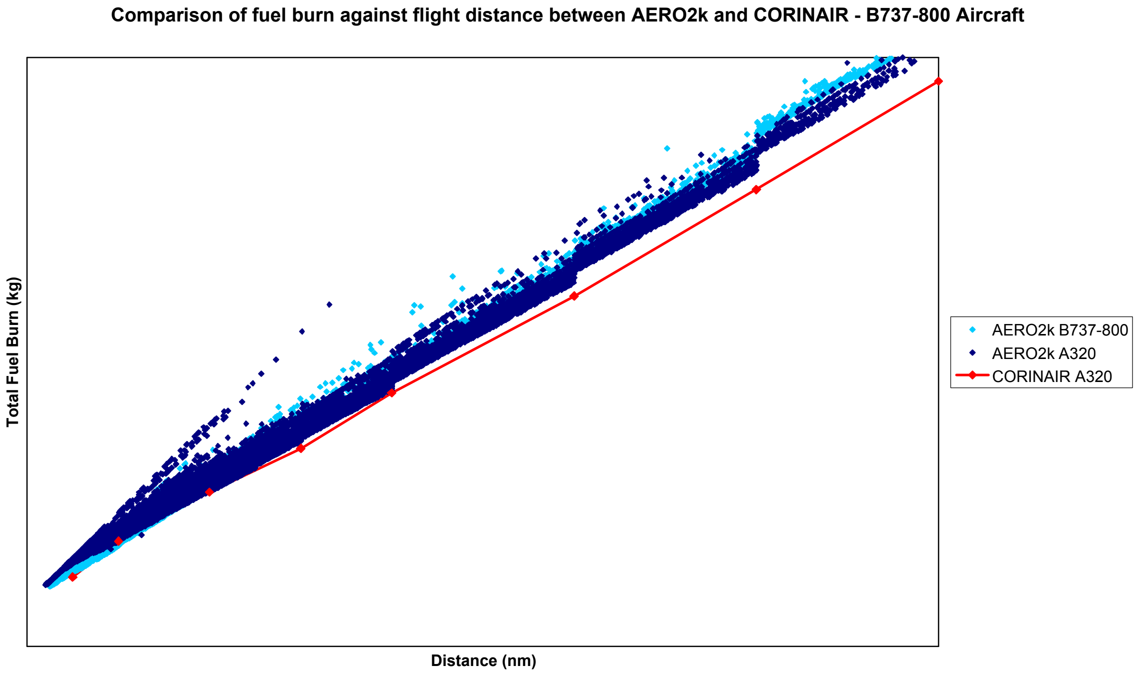


Figure 9 Fuel burn vs distance for Boeing 747-400 aircraft

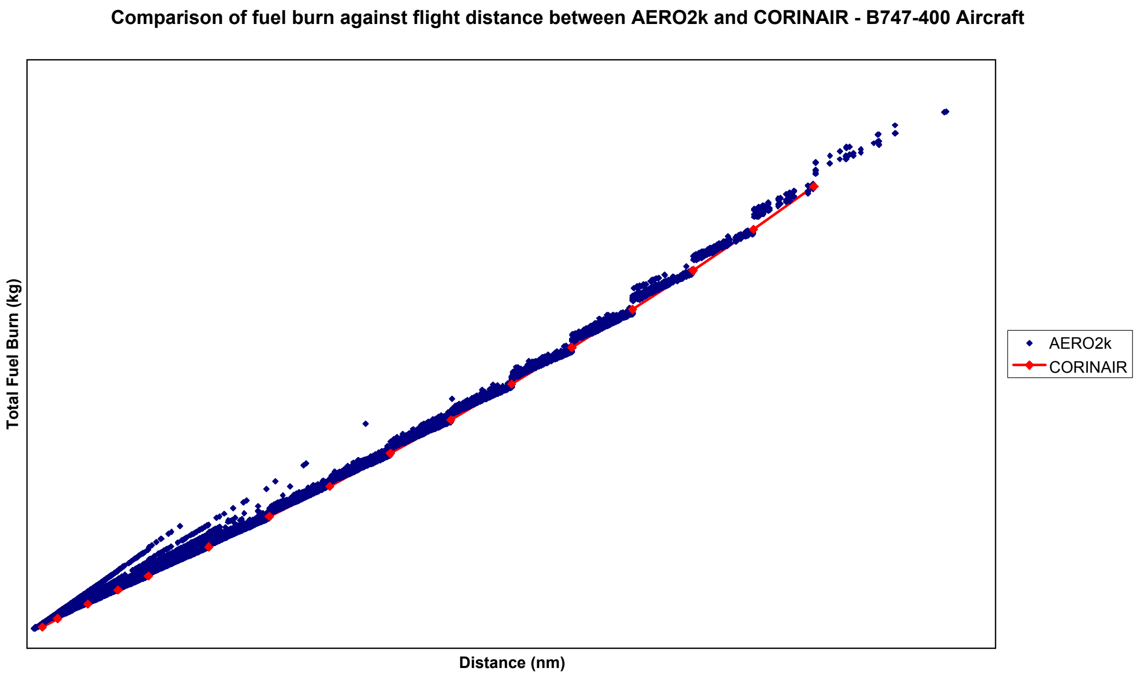


Figure 10 Fuel burn vs. distance for Boeing 767-300 aircraft

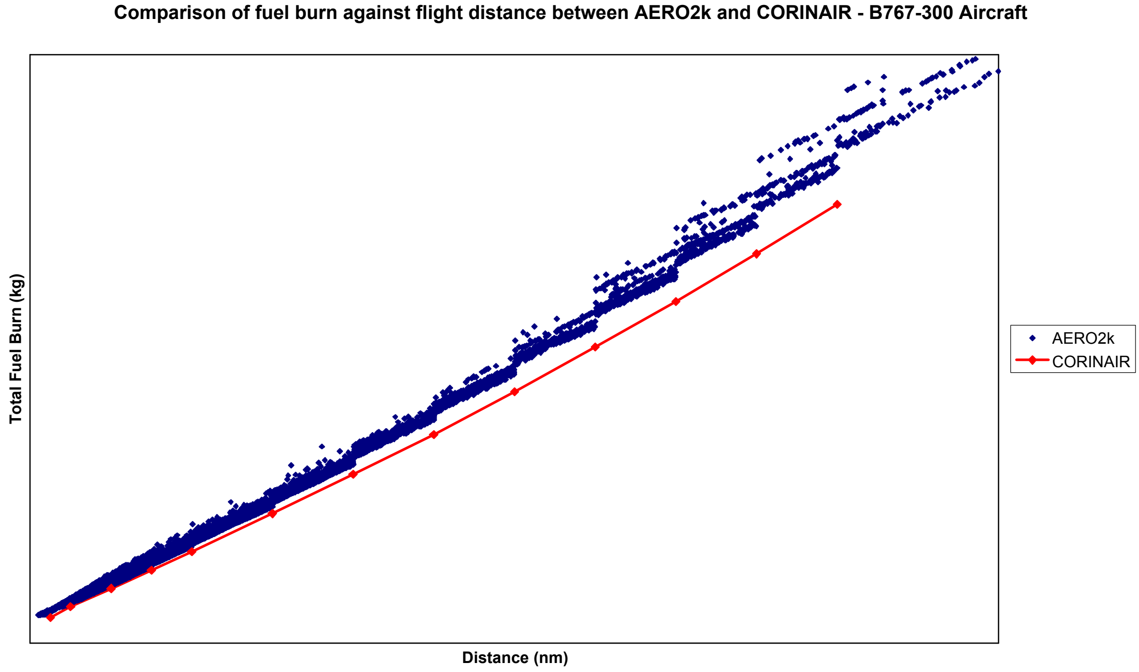


Figure 11 Fuel burn vs. distance for Boeing 777 aircraft

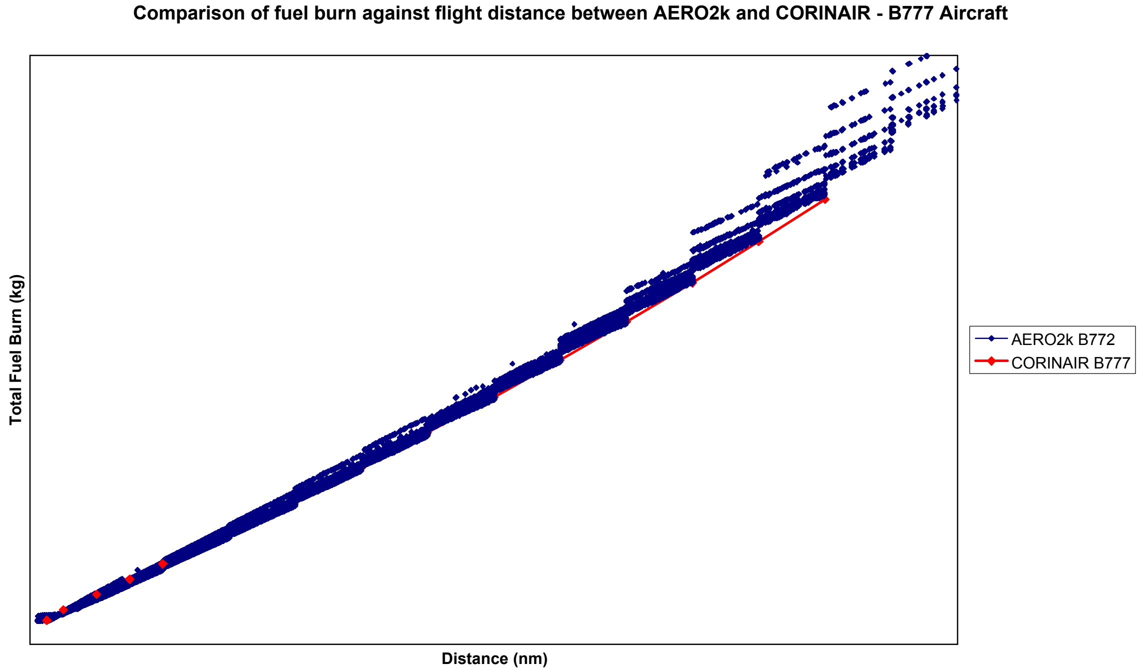


Figure 12 Fuel burn vs distance for BAe 146 aircraft

Comparison of fuel burn against flight distance between AERO2k and CORINAIR - BAe146 Aircraft

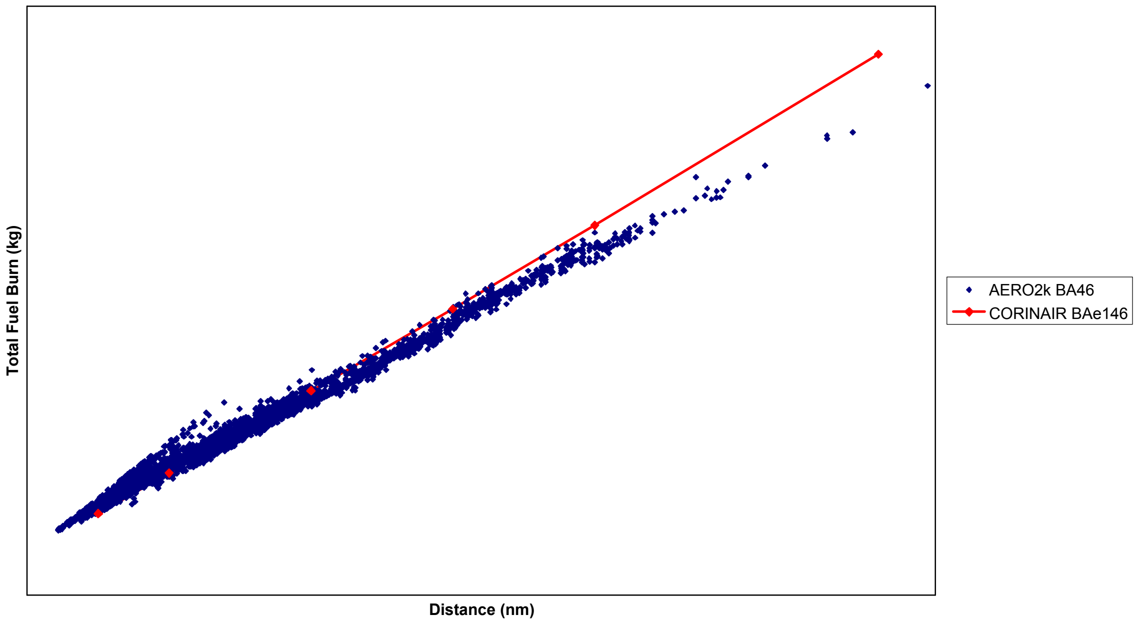


Figure 13 Fuel burn vs. distance for MD80 Series aircraft

Comparison of fuel burn against flight distance between AERO2k and CORINAIR - MD80 Series Aircraft

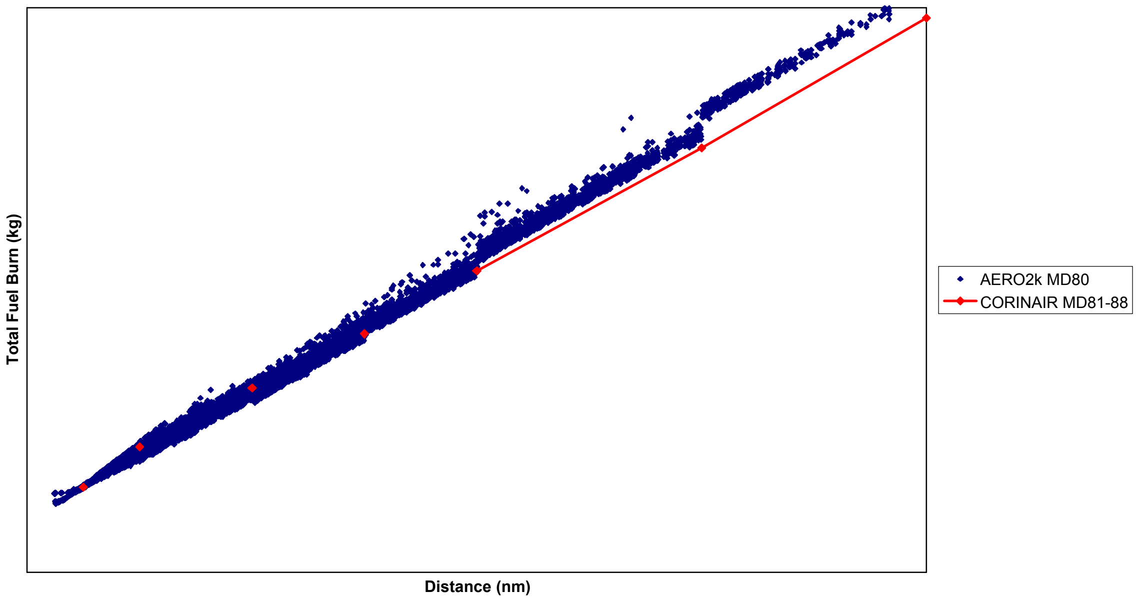


Figure 14 Fuel burn vs. distance for Saab 340B aircraft

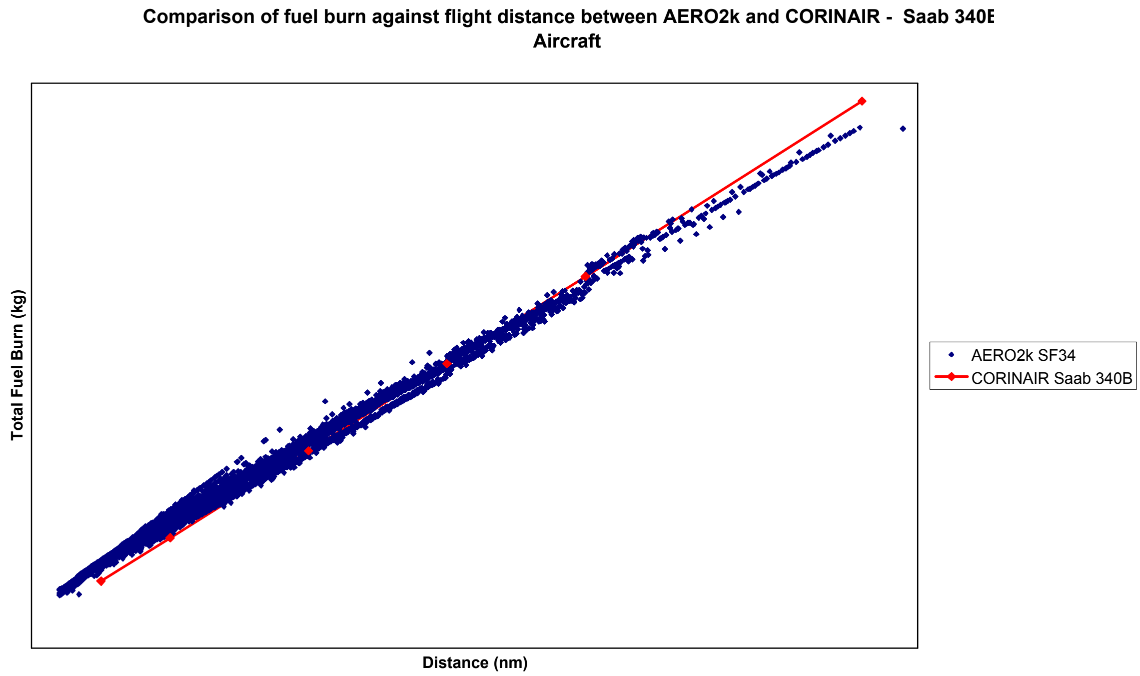


Figure 15 Fuel burn vs. distance for Fokker F50 aircraft

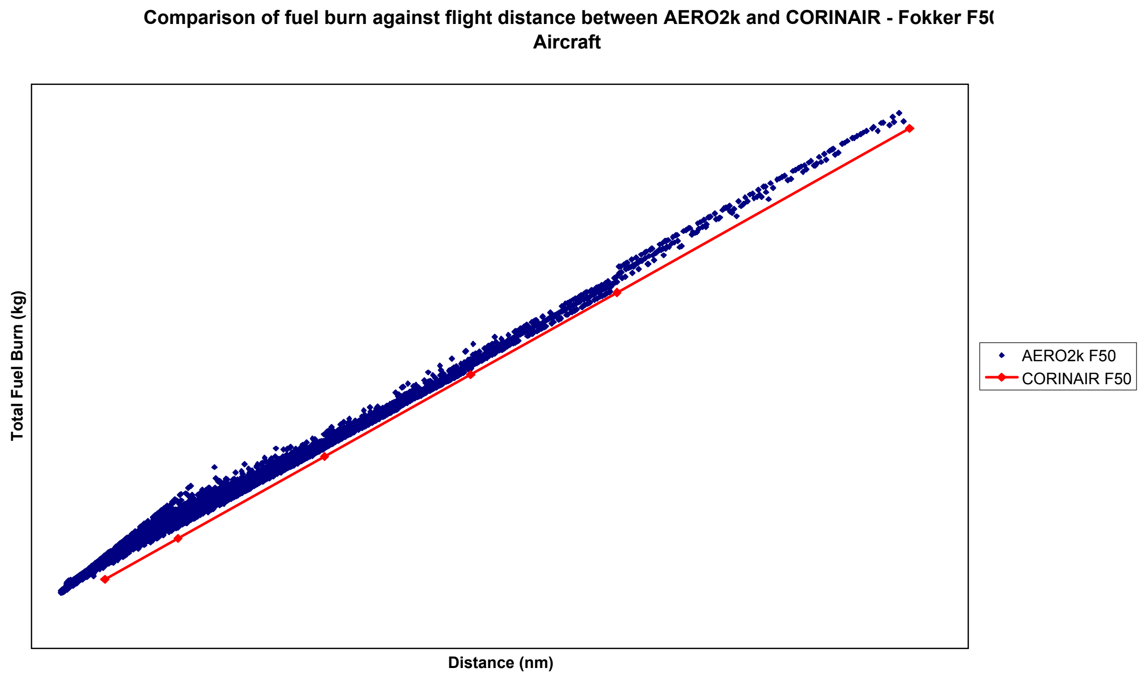
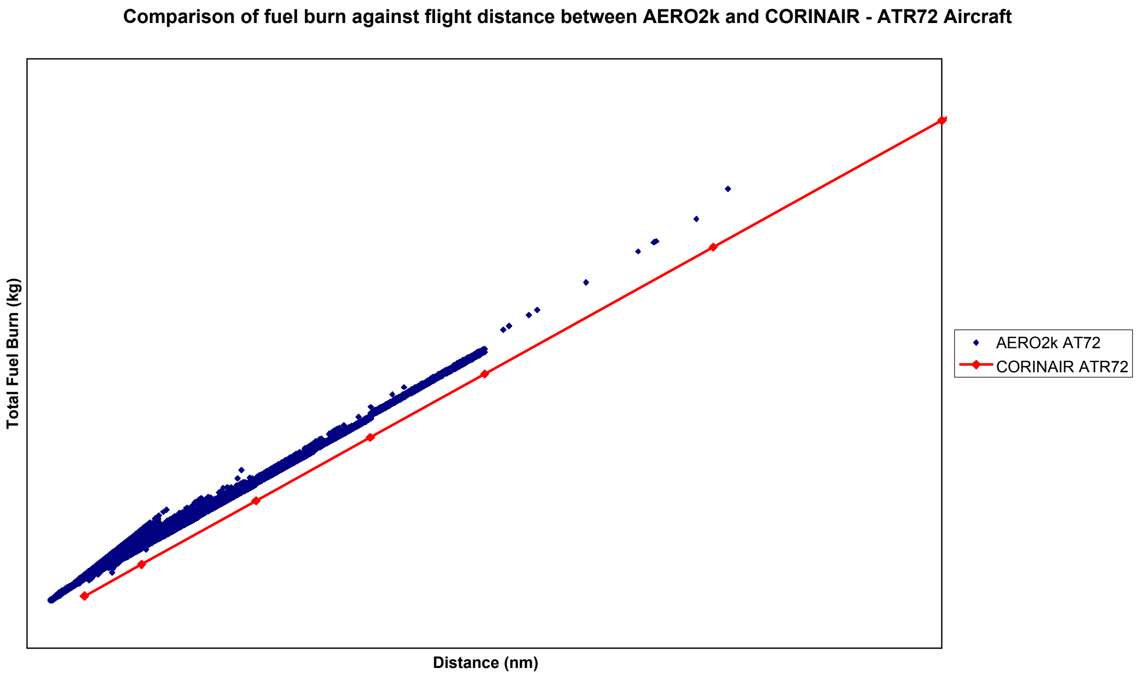


Figure 16 Fuel burn vs. distance for ATR72 aircraft



As can be seen, the AERO2k results cover a spread of fuel burns for a given distance. This results from the use of a range of trajectories for the flights, some of which are non-optimal, particularly as regards to the altitude variation. The CORINAIR data were calculated assuming optimum flight trajectories, so the comparisons between the models should be made using the lowest points on the AERO2k data. The sawtooth nature of the lower edge of the AERO2k data occurs because of a limited number of take-off weights employed in the model. When the take-off weight is increased (due to the need to carry more fuel for the increased flight distance), the fuel burn increases suddenly (because of the need to carry that additional fuel weight). As the flight distance increases towards the next step, the take-off weight remains constant, so the rate of increase of fuel burn against distance is lower. In actual operations, the amount of fuel loaded is carefully calculated based on the distance of a particular flight, so the variation of fuel burn against distance would be smoother. For AERO2k, a limited number of take-off weights were implemented for each aircraft type (considerably more than employed for other, similar models, however), to ease the calculation of a very large number of flights by employing look-up tables.

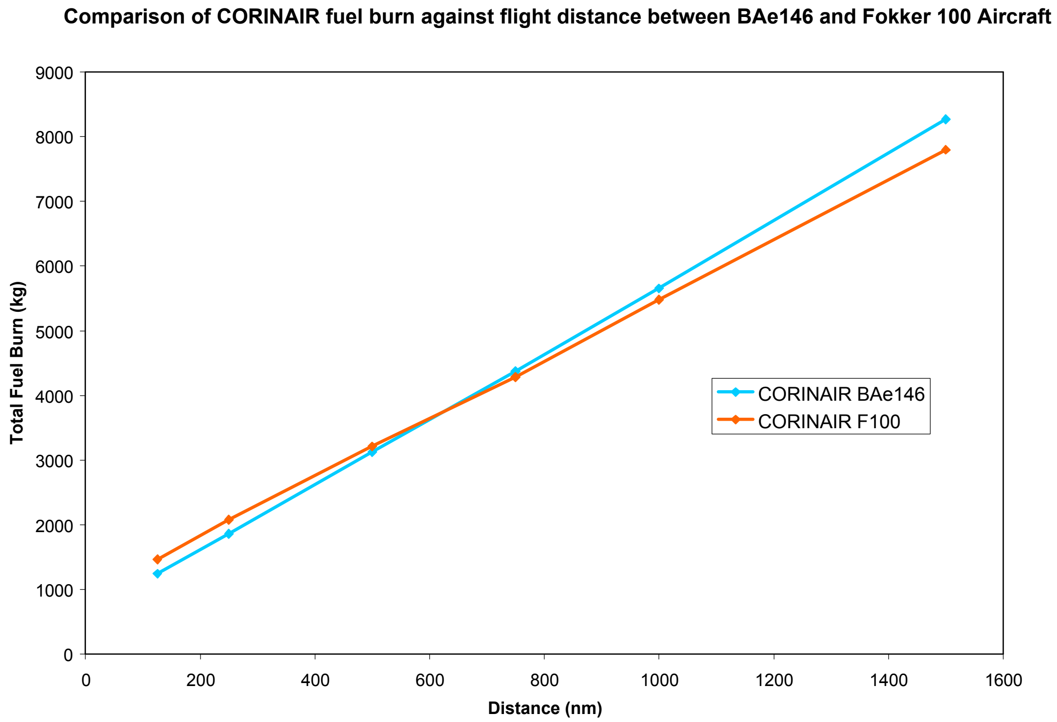
In general, there is good agreement between the lower edge of the AERO2k results and the CORINAIR data. It is noticeable that, in some cases, the AERO2k fuel burn increases more rapidly with distance than CORINAIR, leading to an observable difference in the fuel burn at the upper limit of the CORINAIR range. Particular examples of this include the Airbus A310 (Figure 1), the A320 (the middle set of data on Figure 2), the Boeing 737-100/200 (Figure 5), the Boeing 767 (Figure 10) and the MD80 Series (Figure 13). Of these, the A320 is the more important aircraft in terms of distance flown and CO_2 produced. Additionally, the Boeing 767 aircraft assumes particular importance for these analyses as it is the basis for the Boeing 787 model in the current DfT methodology. At an average range, the AERO2k A320 burns 4.2% more fuel than the CORINAIR equivalent, while the difference for the Boeing 767 is 7.0%.

Figure 2 includes AERO2k data for the A319 and A321 aircraft as well as the A320. It can be seen that the A321 burns significantly more fuel than the A320, while the A319 burns less. At an average range, the A321 burns 15.8% more fuel than the A320, while the A319 burns 4.2% less (all based on AERO2k data). At present, the DfT methodology treats all three of these types as A320s. Over the whole country, these differences are likely to balance out but, for an individual airport, it is likely that they won't. For example, in the 2009 forecast for the year 2030, there are approximately 73,000 operations from Stansted Airport by the A319, 35,000 for the A320 and 39,000 for the A321. There is, therefore, the potential for improving the accuracy of the methodology by treating the A319 and A321 as different from the A320, using factored versions of the A320 fuel burn vs. distance data. The A320 data themselves should be factored up by 4.2% to match the AERO2k data.

As previously mentioned, there are no data in CORINAIR for the "Next Generation" Boeing 737 aircraft (the -700, -800 and -900 variants). The approach adopted to date is to model the -600 and -700 models as -400 and the -800 and -900 as Airbus A320s. Figure 7 includes AERO2k data for the 737-600 and -400 together with CORINAIR data for the -400. It can be seen that, while there is good agreement between AERO2k and CORINAIR for the -400 model, the -600 has a significantly lower fuel burn. The difference between the AERO2k data for the -600 and -400 models at an average range is 12.2% (the -600 is both a smaller and more advanced aircraft than the -400). There are no Boeing 737-700 model data in AERO2k, but it would be reasonable to assume that it has a better fuel consumption than the -400 model (it is a similar size, but more advanced), probably by about 5%. Figure 8 compares the AERO2k data for the Boeing 737-800 and the Airbus A320 with the CORINAIR A320). It can be seen that there is good agreement between the AERO2k Boeing 737-800 and A320 aircraft, so the modelling of this type using the A320 data (after modification, as described above), is supported.

Another aircraft type which has a significant input into the forecast is the Embraer ERJ190 and 195 series. For the existing forecasts, this type has been modelled as a BAe 146. However, from the point of view of number of engines, thrust and take-off mass, the Fokker 100 appears to be a more suitable aircraft to represent these types. Figure 17 shows a comparison of the CORINAIR fuel burn data for these two types.

Figure 17 Comparison of CORINAIR fuel burn data for BAe 146 and Fokker 100



As can be seen, the difference in fuel burn between the two aircraft is small for flight distances below 1000nm. Therefore, although it is recommended that the Embraer 190 and 195 are modelled using Fokker 100 data, this modification to the methodology is not a high priority.

As well as the turbofan aircraft, Figure 1 to Figure 16 show some differences between AERO2k and CORINAIR for turboprop types. However, these are not important aircraft from the distance flown or fuel burnt perspective, so there is no need to modify the modelling of these types from this perspective.

As well as plotting fuel burn against distance flown, it is possible to calculate and plot fuel burn per nautical mile for the various aircraft types. Plots of this parameter are shown for some of the more significant aircraft in Figure 18 to Figure 20. These plots show the high levels of fuel consumption that occur on short range flights (because of the influence of the taxi, take-off and initial climb elements) with much lower values at longer ranges. For the Boeing 767 aircraft, it can be seen that there is an “optimum” range (one with a minimum fuel consumption per mile), after which the fuel consumption increases again. This is a well known phenomenon and occurs because of the need to carry the extra fuel (giving a higher take-off weight) for the later portions of the flight, which increases the fuel consumption during the early portions. This phenomenon is visible in both the AERO2k and CORINAIR models showing that both include the increased take-off weights for longer ranges.

In these figures, there is some indication of CORINAIR giving a lower fuel consumption on very short range flights than AERO2k. However, the total fuel burn on such a flight is itself low, and the frequency of such flights would be expected to be low, so this difference is not considered to be important.

Figure 18 Fuel burn per nautical mile vs. distance for A320 Series aircraft

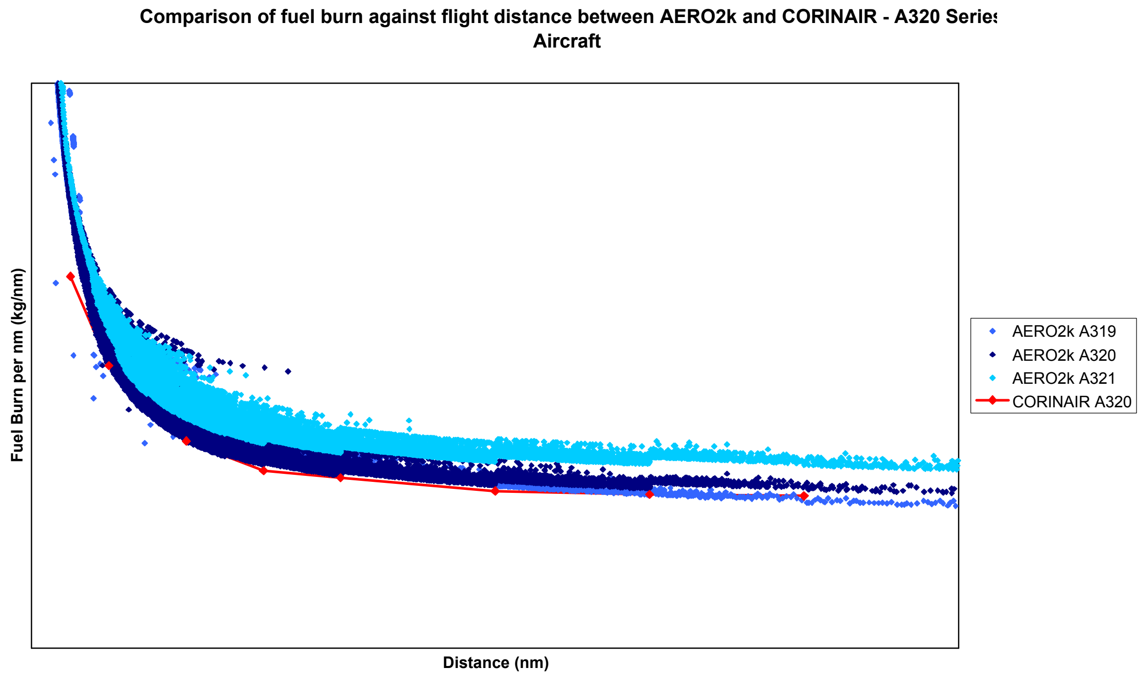


Figure 19 Fuel burn per nautical mile vs. distance for Boeing 737-600 and 737-400 aircraft

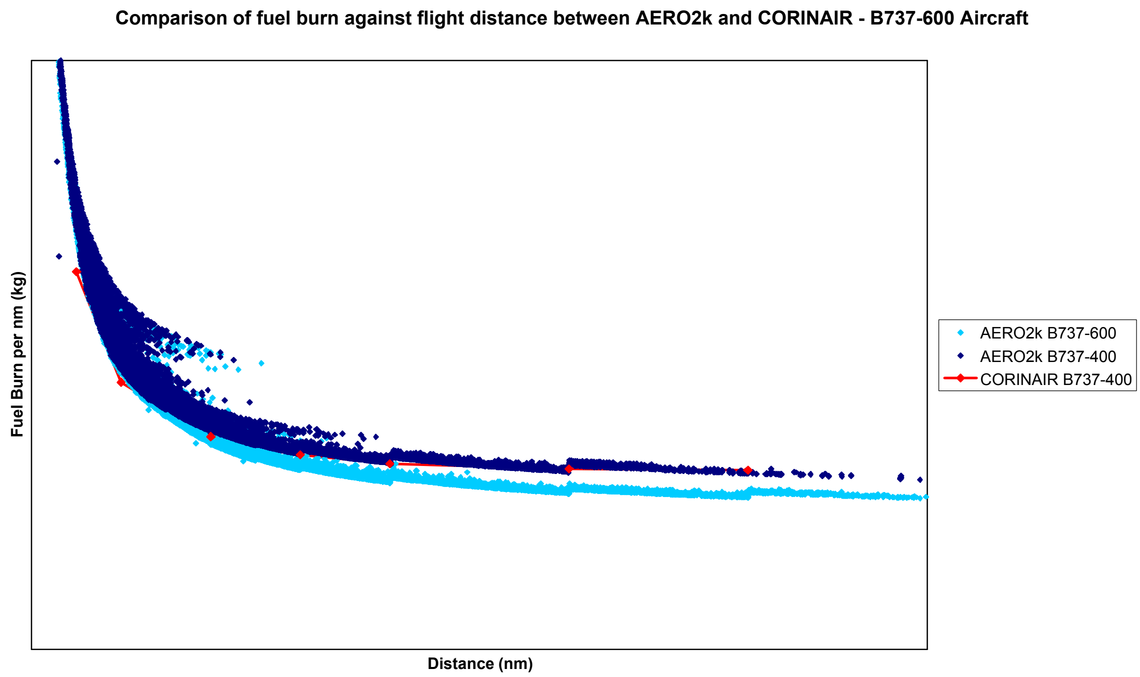
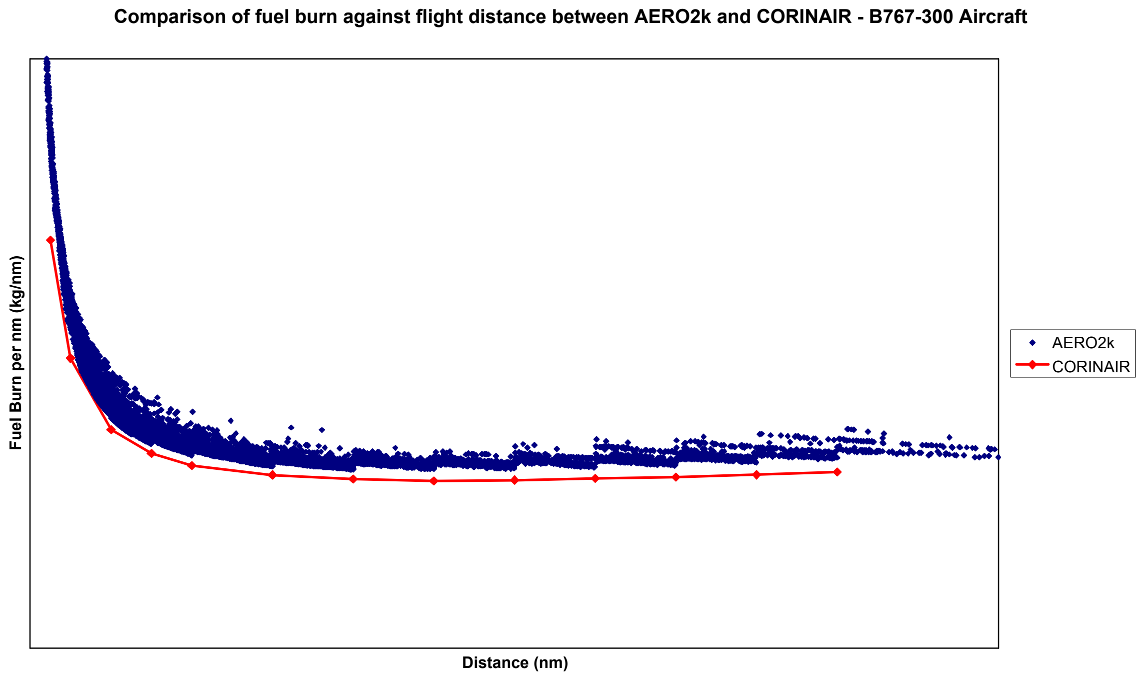


Figure 20 Fuel burn per nautical mile for Boeing 767 aircraft



3.3 Curve fits

As described in Section 2, the current approach uses a cubic curve fitted to the CORINAIR data to simplify the calculation of the fuel burn on individual flights. This curve fitting technique is applied to the fuel consumption data in the form of kilometre per kilogramme of fuel, as a function of distance. These curve fits have been assessed by comparing the curves against the same parameters calculated directly from the CORINAIR data and against newly generated cubic curve fits to the CORINAIR data. These comparisons are shown in the following figures. In each case the values calculated directly from the CORINAIR data are indicated by the red symbols, the curve fits used by DfT are shown by the light blue curves while the newly generated curve fits are indicated by the darker blue lines. As will be seen, there is generally very good agreement between the two sets of curve fits (as expected). There are slight differences apparent in some of the plots which are due to small differences in the manner in which the curve fits were generated; however, the differences would have no significant effect on the calculations using the model.

Figure 21 Curve fits to Airbus A310 data

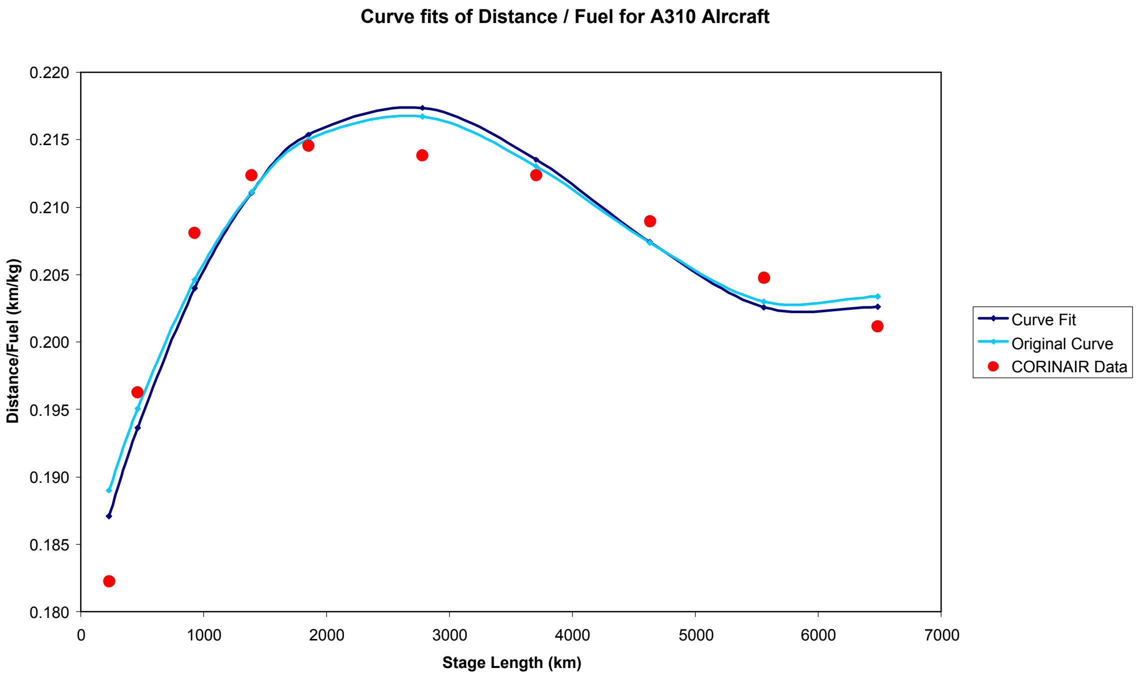


Figure 22 Curve fits to Airbus A320 data

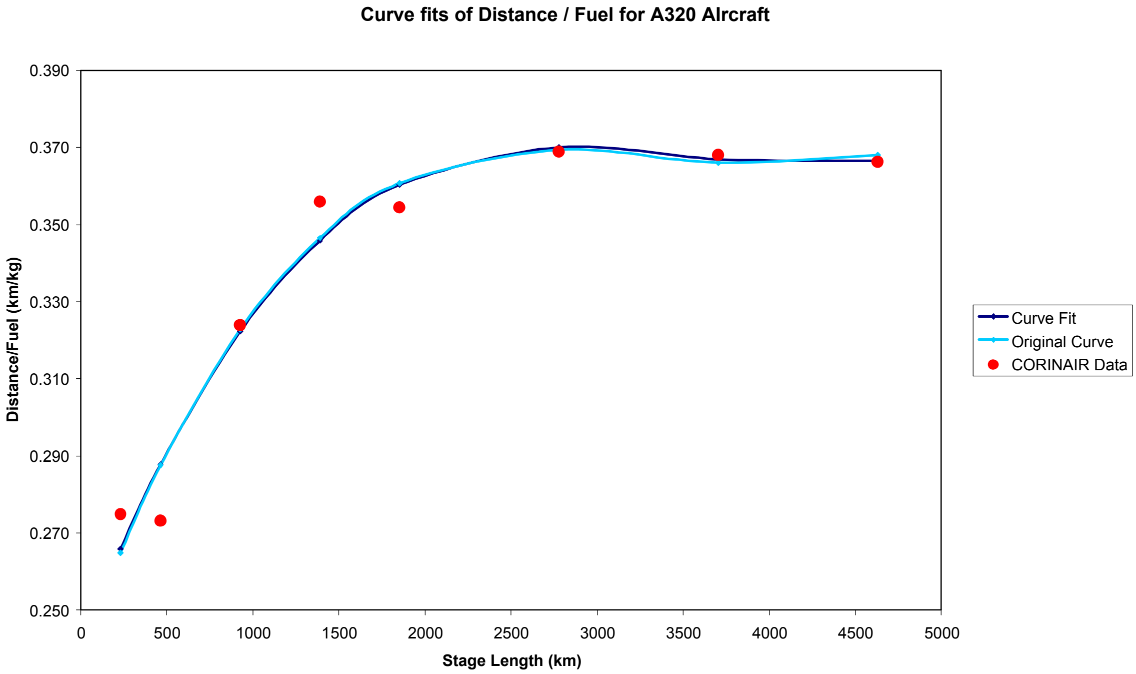


Figure 23 Curve fits to Airbus A330 data

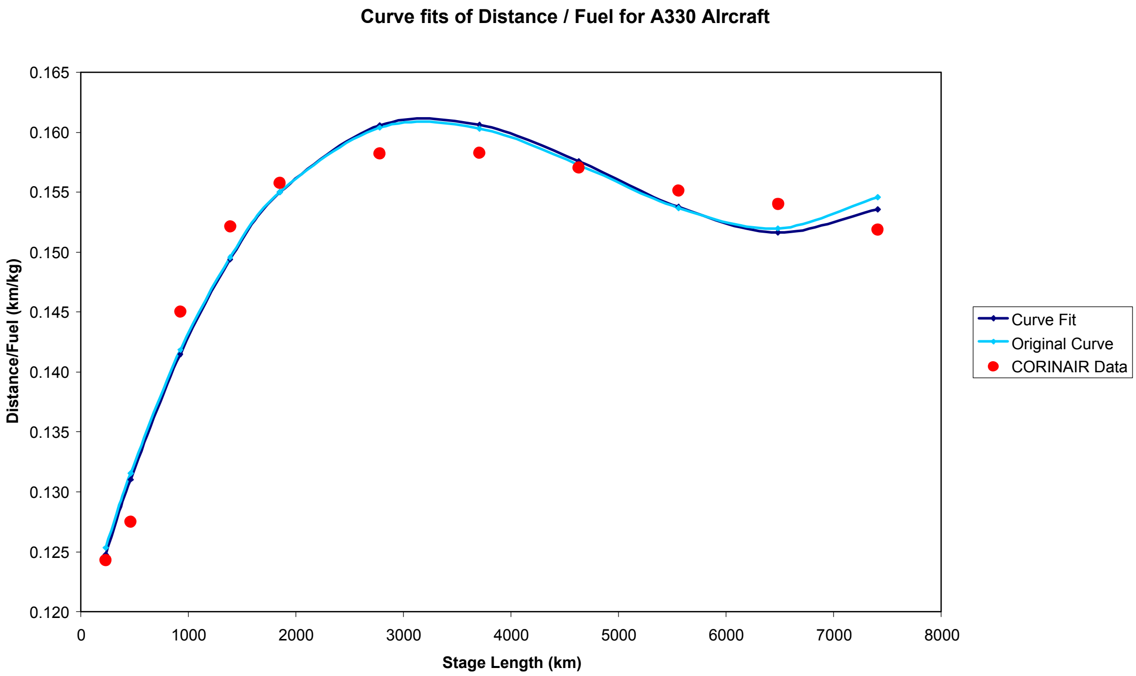


Figure 24 Curve fits to Airbus A340 data

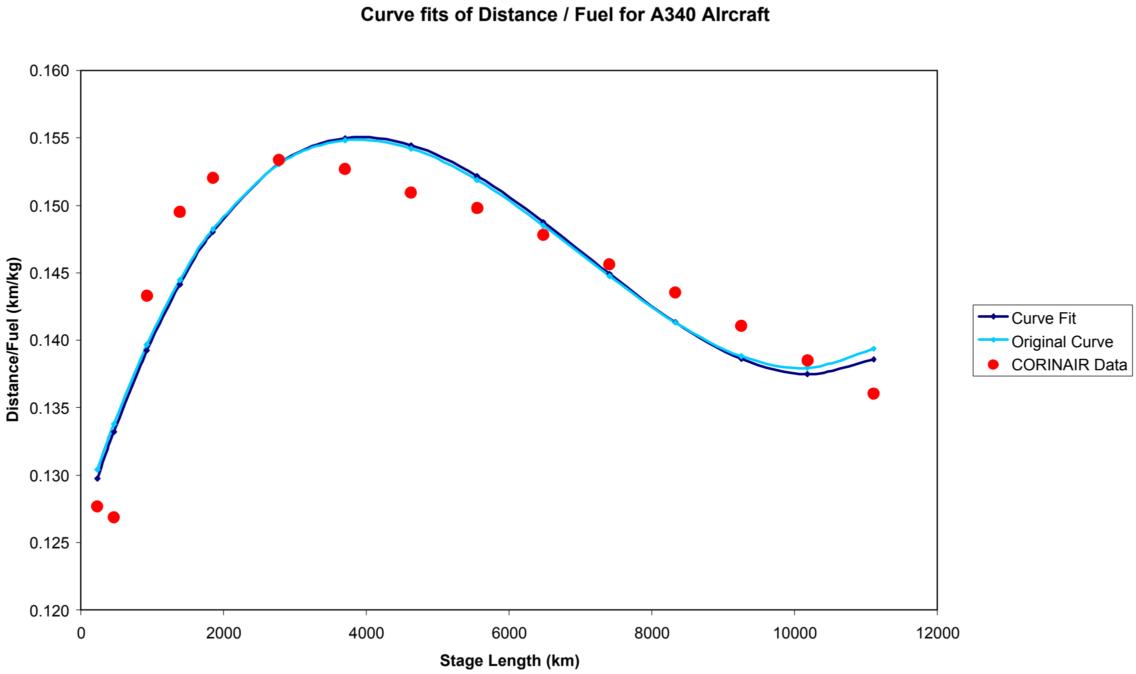


Figure 25 Curve fits to BAe 146 data

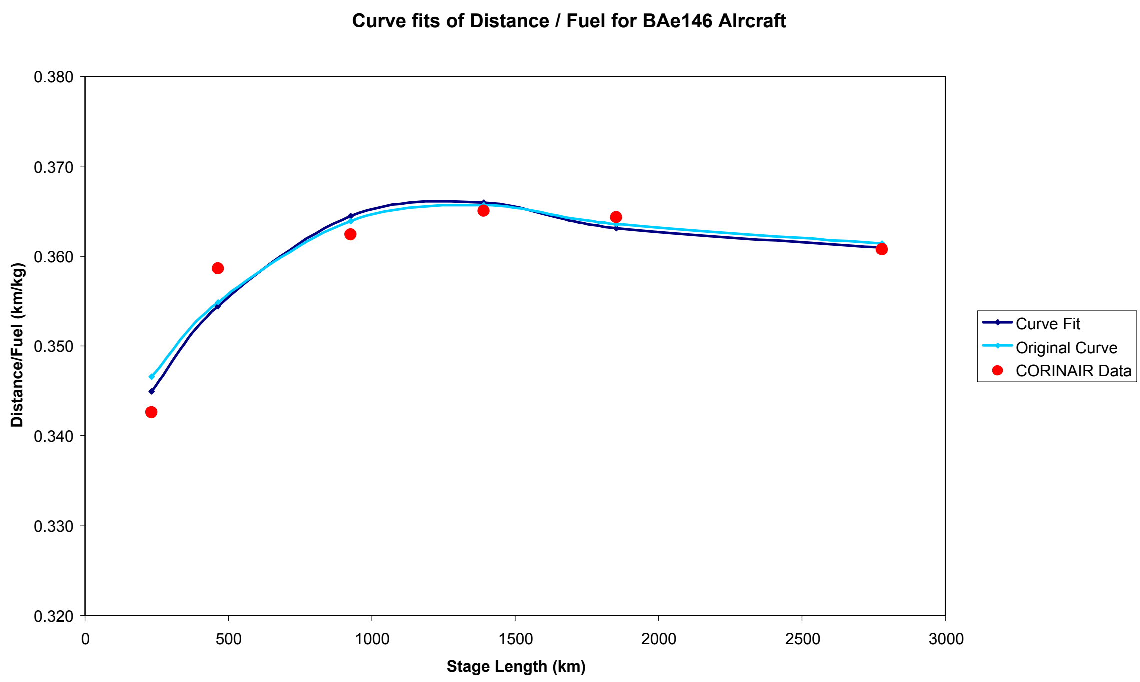


Figure 26 Curve fits to Boeing 737-200 data

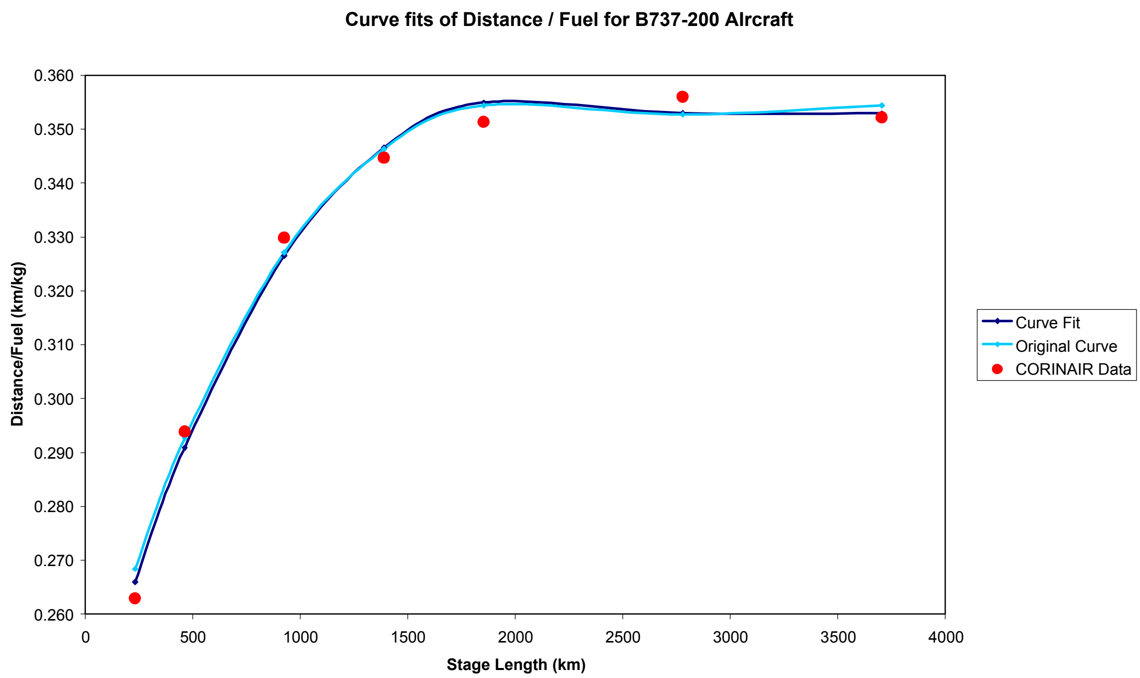


Figure 27 Curve fits to Boeing 737-400 data

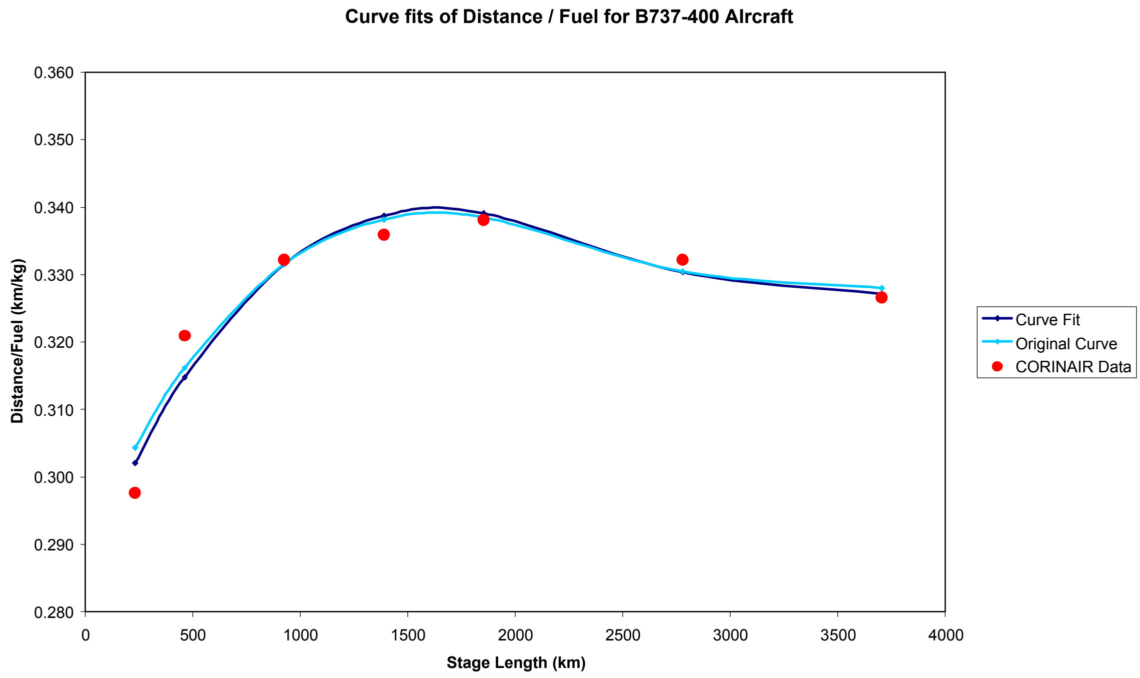


Figure 28 Curve fits to Boeing 747-200 data

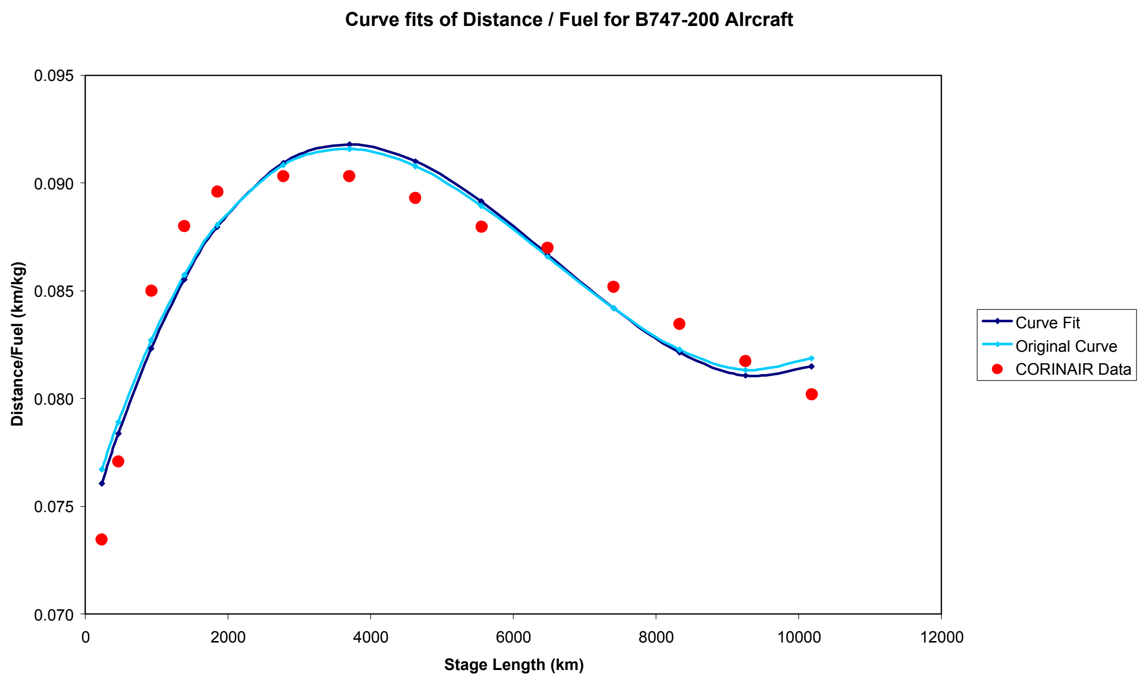


Figure 29 Curve fits to Boeing 747-400 data

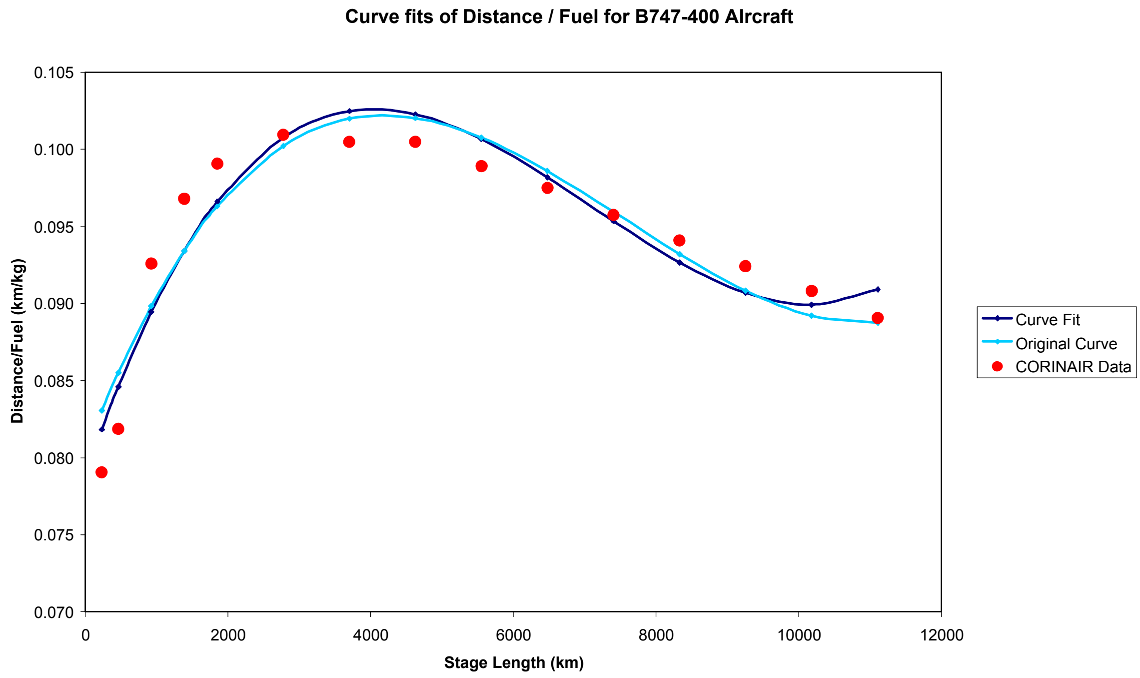


Figure 30 Curve fits to Boeing 757 data

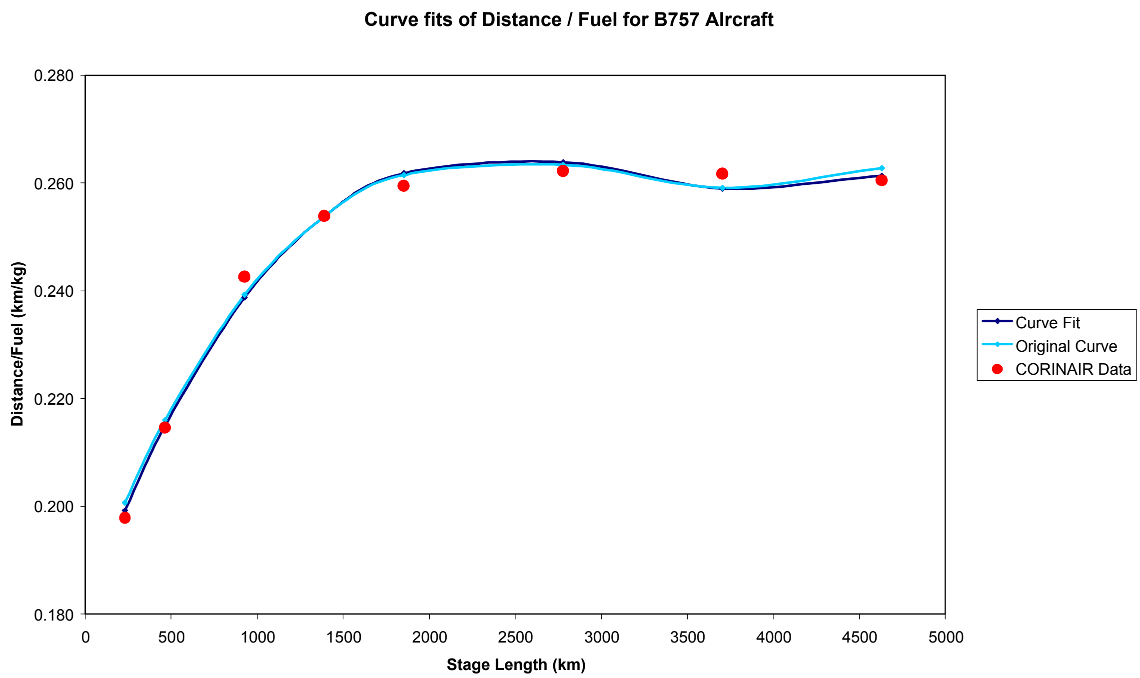


Figure 31 Curve fits to Boeing 767 data

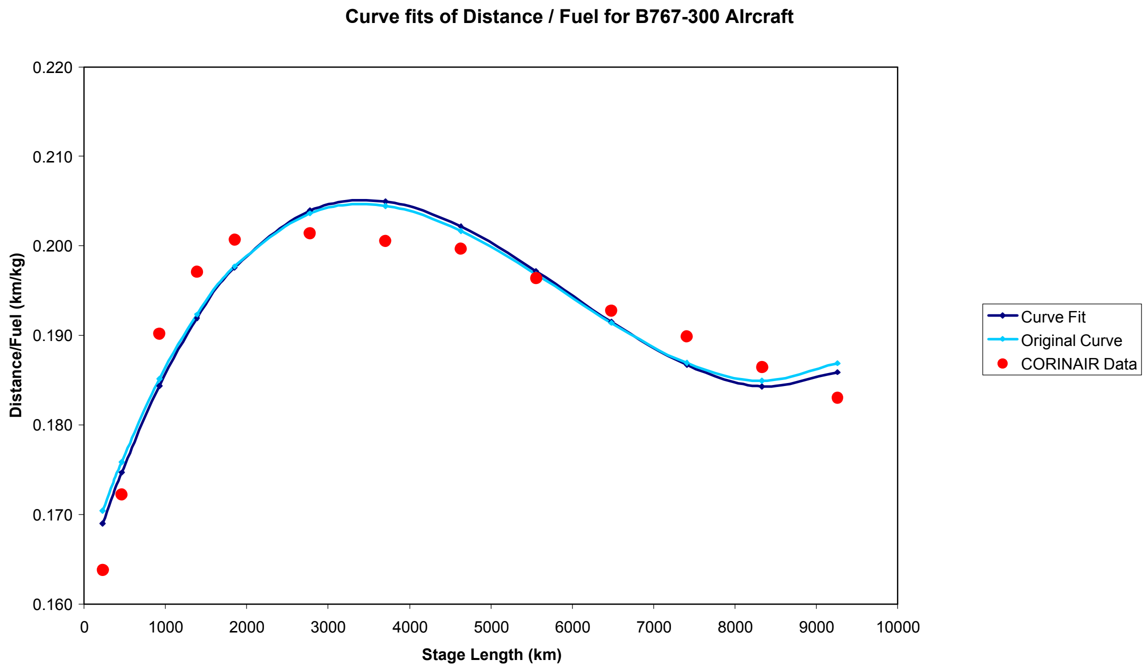


Figure 32 Curve fits to Boeing 777 data

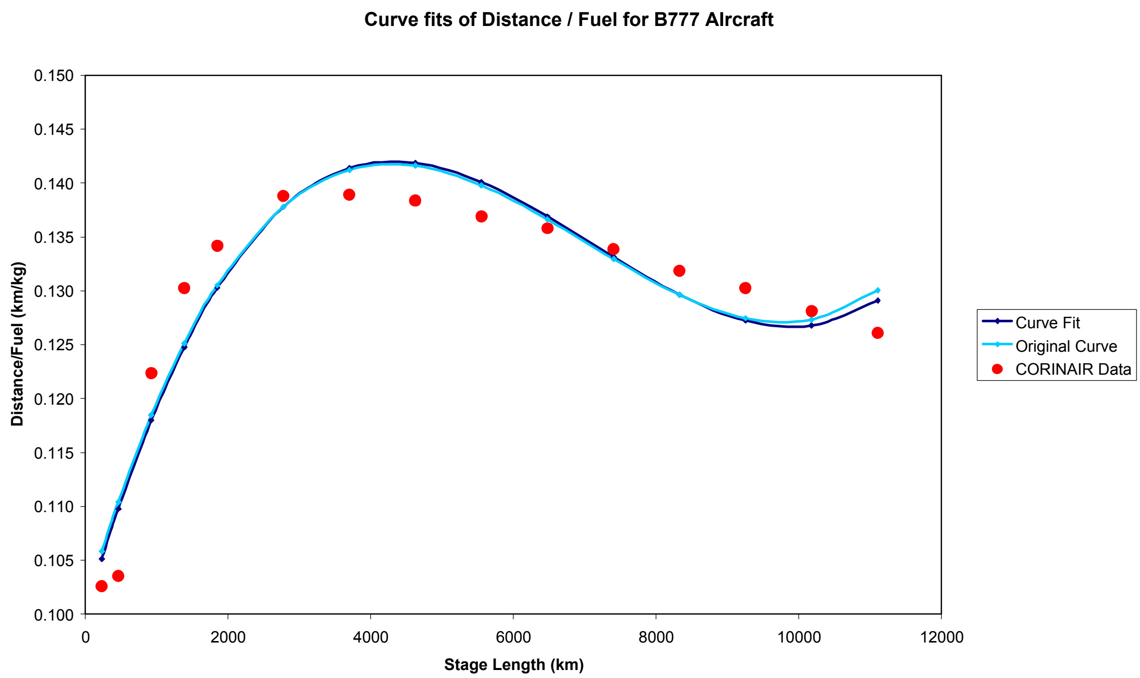


Figure 33 Curve fits to Fokker F28 data

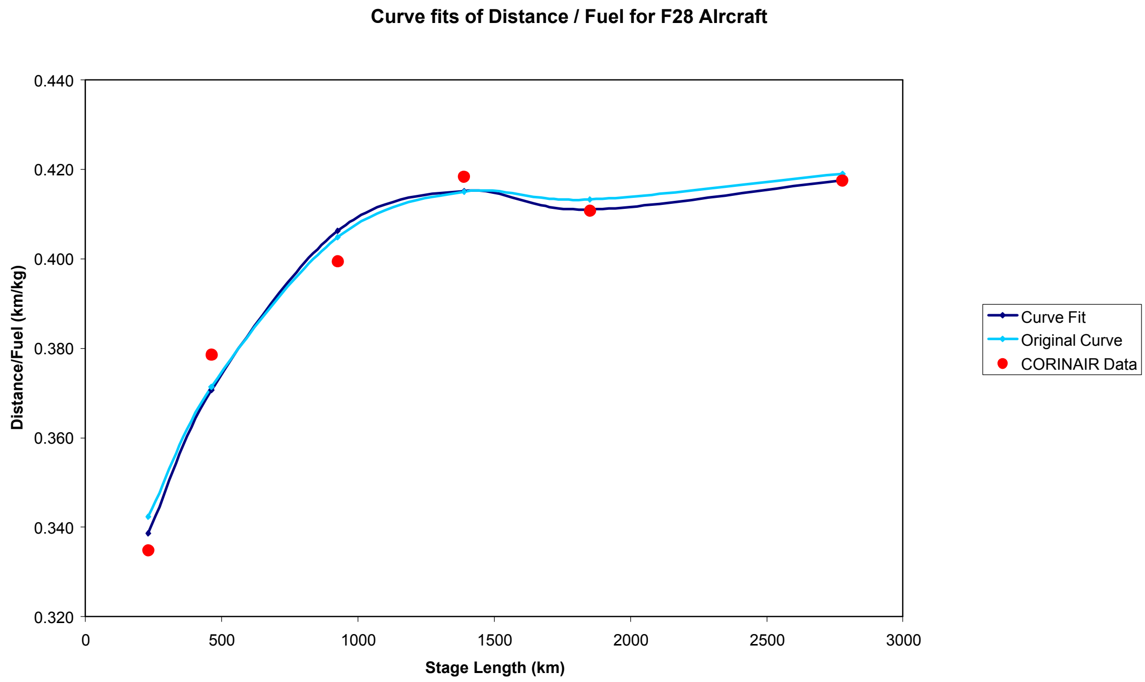


Figure 34 Curve fits to Fokker 100 data

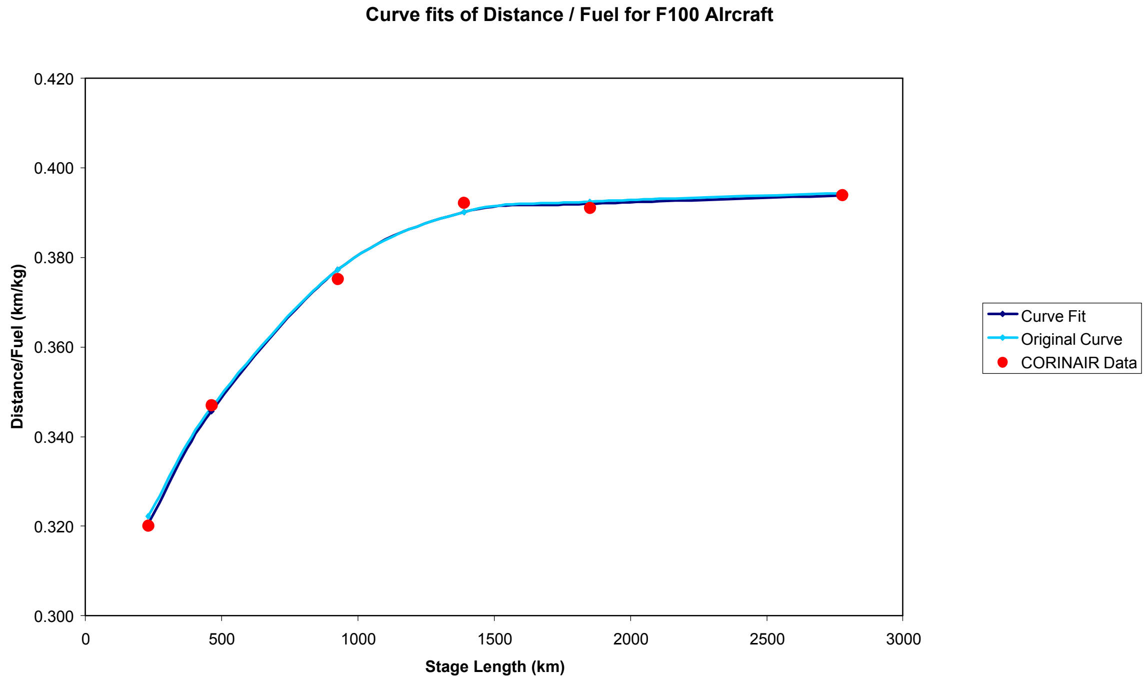


Figure 35 Curve fits to McDonnell Douglas MD82 data

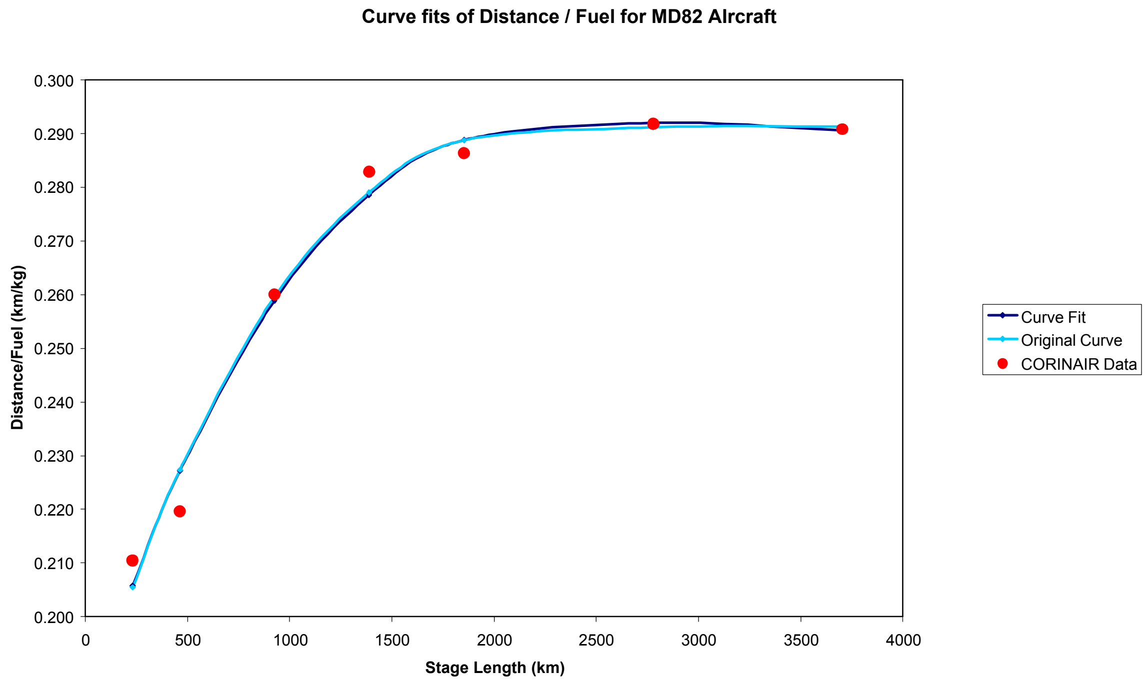


Figure 36 Curve fits to Saab 340B data

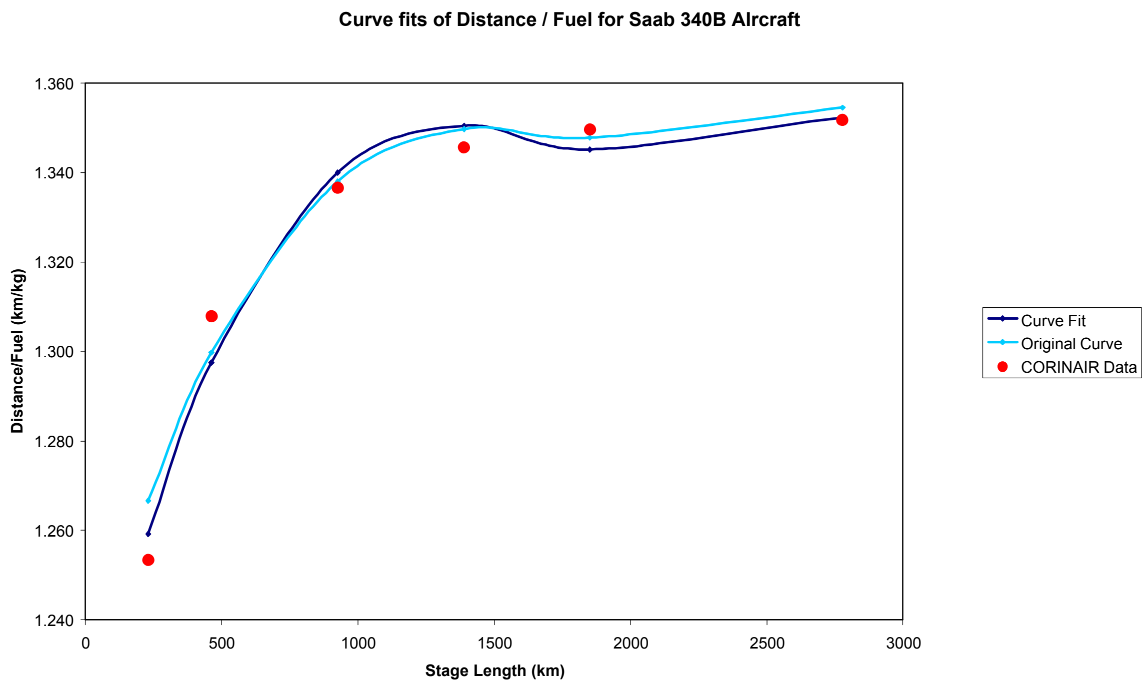


Figure 37 Curve fits to Saab 2000 data

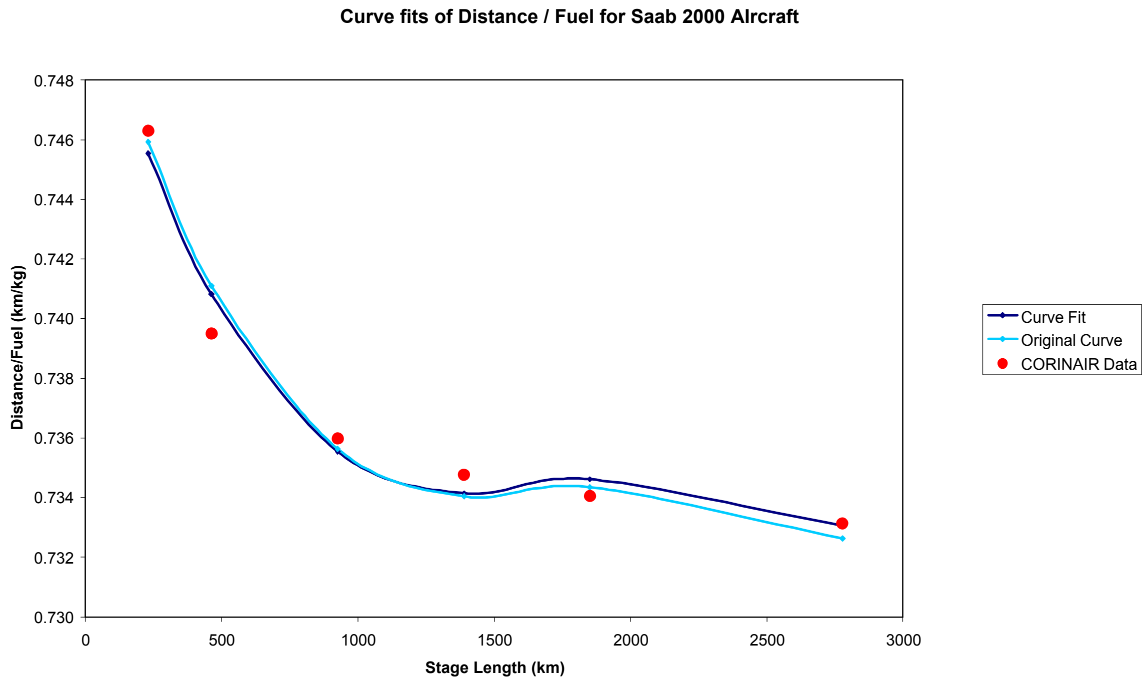


Figure 38 Curve fits to Fokker F50 data

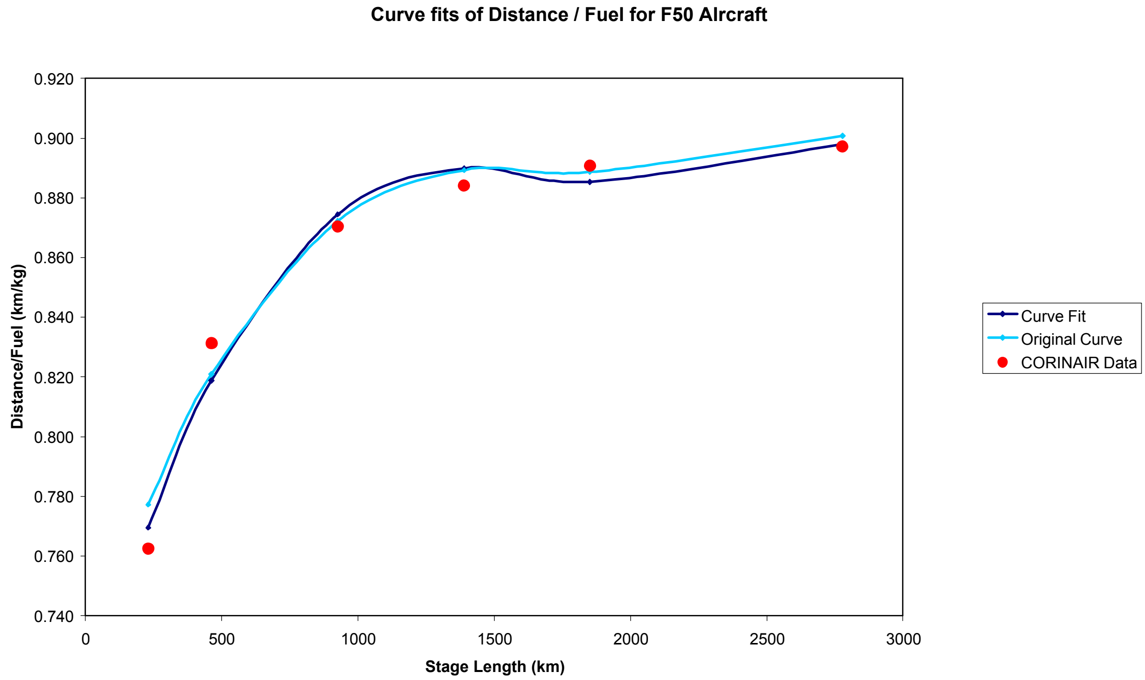


Figure 39 Curve fits to De Havilland Dash 8 data

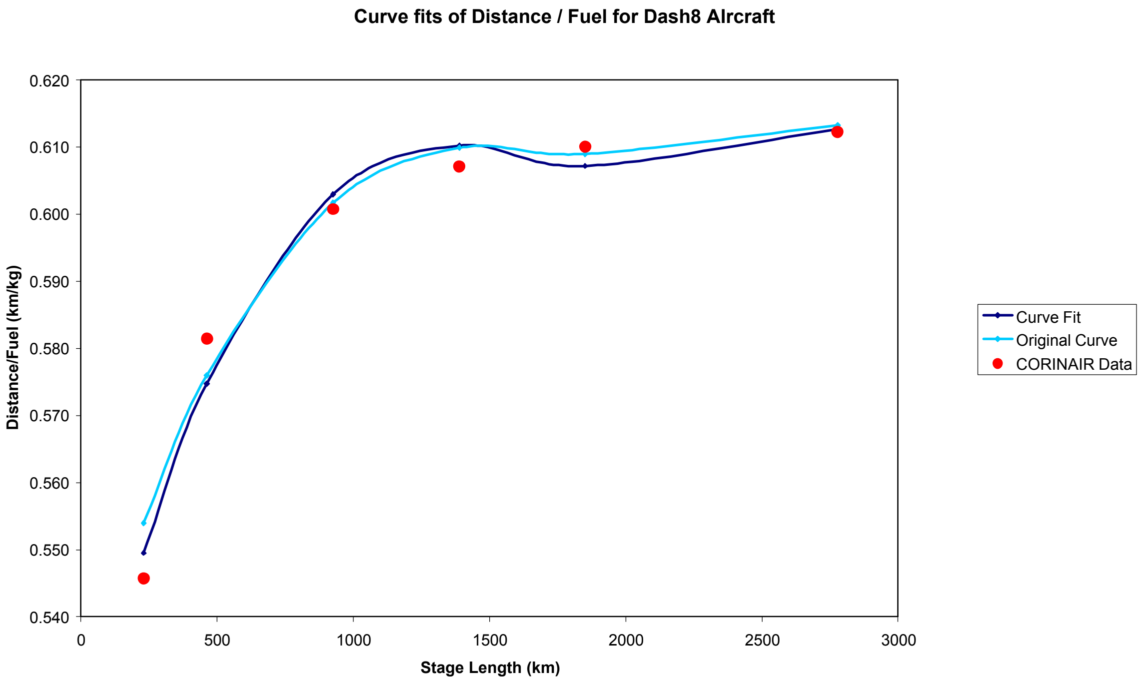
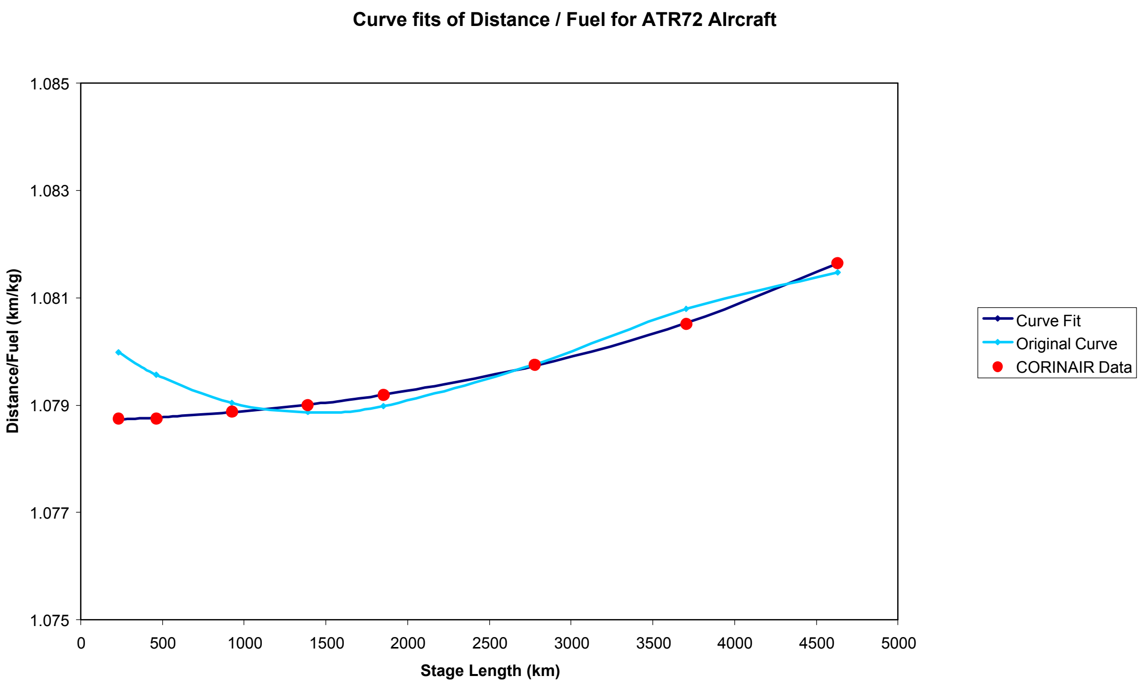


Figure 40 Curve fits to ATR 72 data



In the above figures, there are a number of cases where the fit of the cubic curve to the CORINAIR data does not appear to be very good. For the more significant of these aircraft, attempts have been made to improve the fit by trying an alternative fifth order polynomial. The plots including these new fits are shown in the figures below.

Figure 41 Curve fits, including fifth order, for Airbus A330

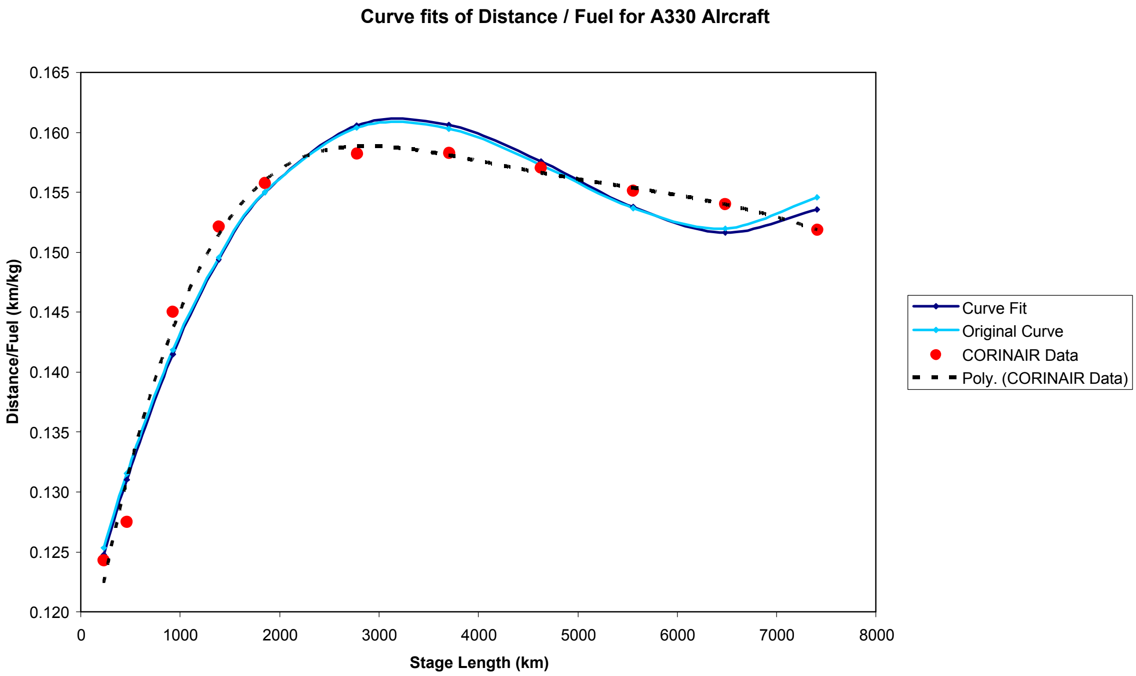


Figure 42 Curve fits, including fifth order, for Airbus A340

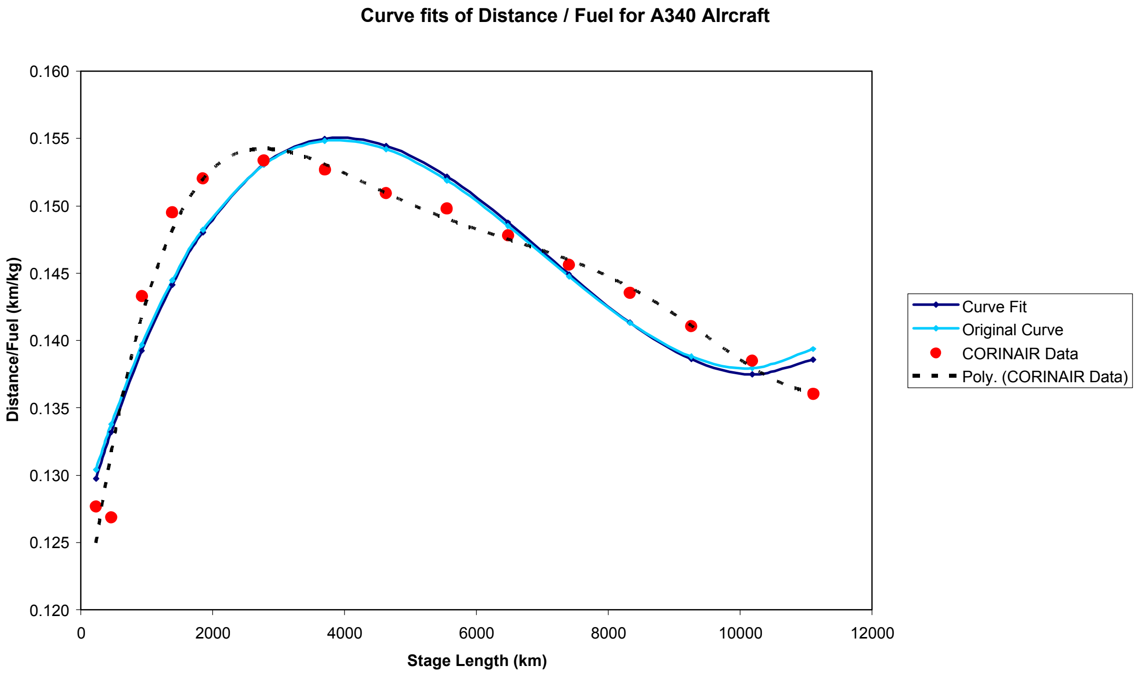


Figure 43 Curve fits, including fifth order, for Boeing 747-400

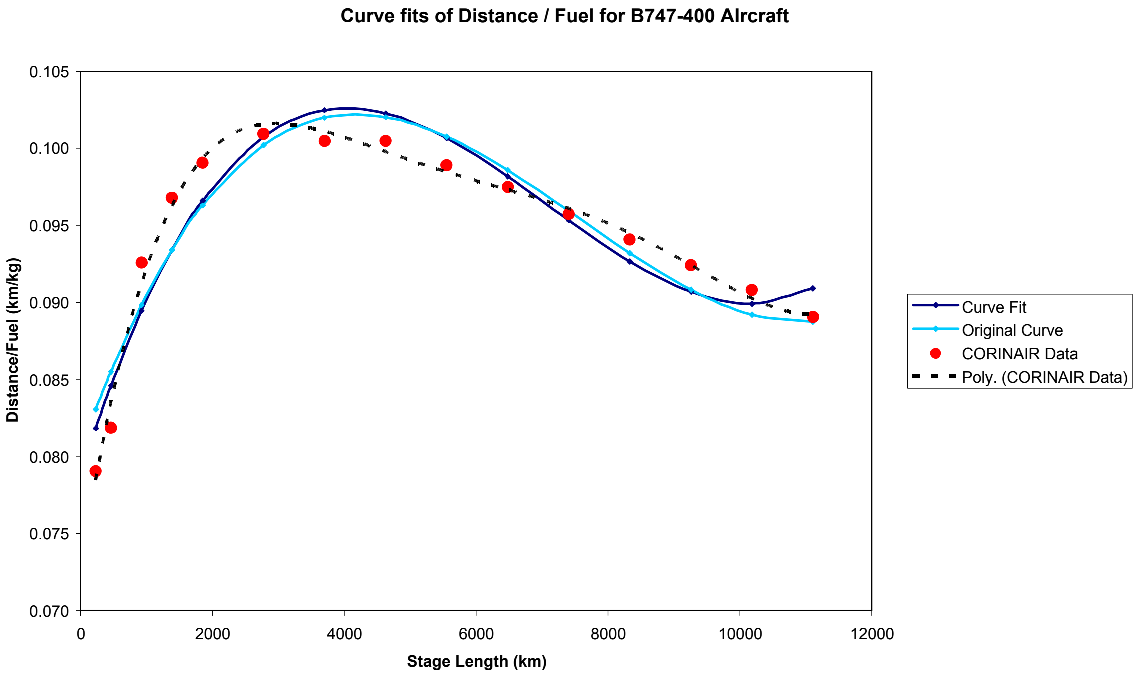


Figure 44 Curve fits, including fifth order, for Boeing 767

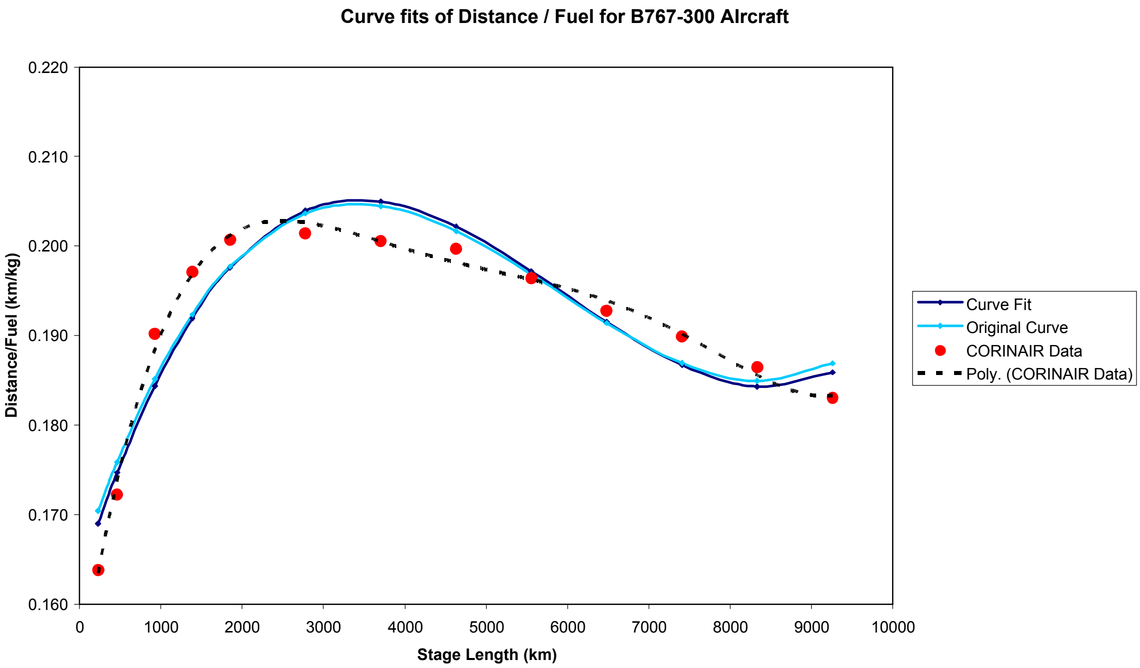
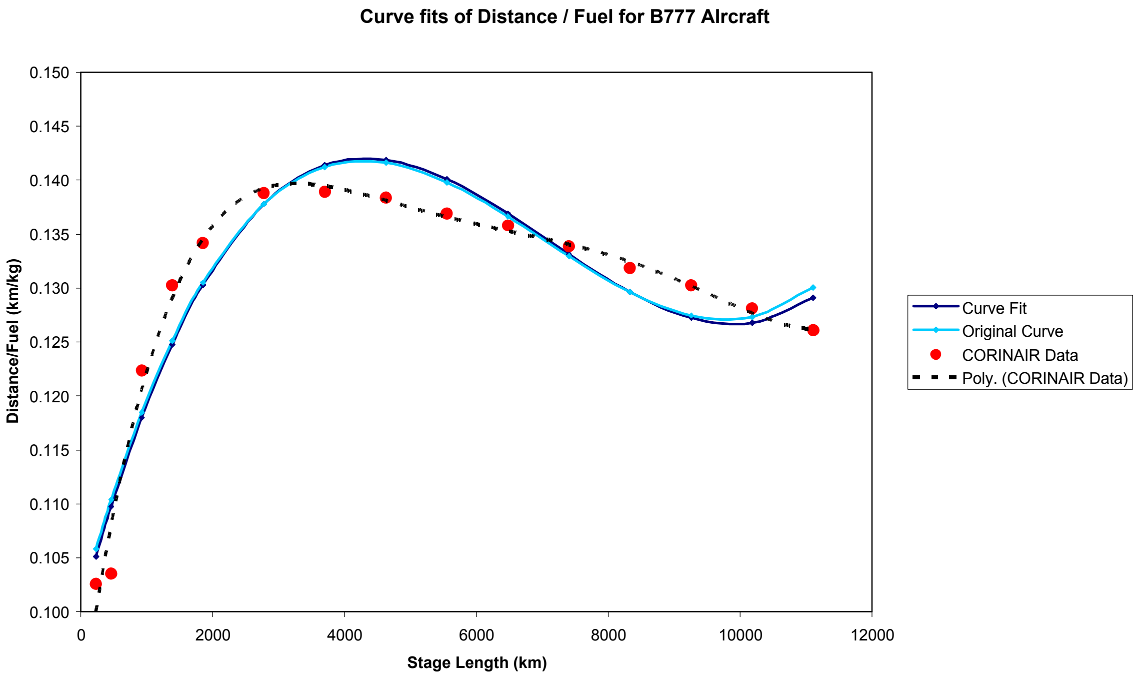


Figure 45 Curve fits, including fifth order, for Boeing 777



For these five aircraft types, the quality of the curve fit is improved considerably by using a fifth order fit. It was noted above that some of the cubic curves show a rising distance/fuel towards the top end of the stage length scale. The five quintic curves above do not exhibit this trend. Nonetheless, it is considered that the linear extension data (for routes at or beyond the upper limit of the CORINAIR stage length data) should be revisited to ensure that they exhibit a reducing distance/fuel characteristic. One of the existing extensions, that for the Boeing 767, has been checked and found to show a very slowly rising value of distance/fuel.

Mention should also be made of two other curves. The Saab 2000 curves, shown in Figure 37, appear different from the other aircraft, in that they are constantly falling rather than rising to a maximum before falling. Both curves form a good agreement with the CORINAIR data, therefore the original data have been investigated. The version of PIANO available at QinetiQ has been used to model this aircraft over the same range of flight distances. The results show a higher fuel burn (between 15% and 40% depending on distance) with a distance/fuel ratio which rises to a peak at about 1000nm. As a result, there is little confidence in the CORINAIR data for the Saab 2000.

The other aircraft to note is the ATR72. The data for this aircraft (Figure 40) are unusual in that the cubic curve fit forms an exceptionally good fit to the data (rather emphasising the difference between the new and original curve fits). The upper limit of the CORINAIR data (at almost 4,500km) far exceeds the nominal range of the aircraft. Therefore, there is also little confidence in the CORINAIR data for the ATR72.

From the above paragraphs, it can be seen that there are two turboprop aircraft, the Saab 2000 and the ATR72, for which the fuel burn data do not give confidence when plotted in this manner. For modelling these two aircraft types (or other types which are mapped to them), it is recommended that the data for the Fokker 50 are used instead (as it has a similar maximum take-off weight).

3.4 Supply pool checks

As aircraft reach their retirement age in the future year forecasts, they are replaced by aircraft drawn from the user-defined supply pool. The supply pool available for the three classes of carriers (Scheduled, Charter and No-Frills Carriers) is summarised in the following tables.

Table 5 Summary of supply pool for Scheduled Airlines

	Seat Class					
Aircraft Type	**Class 1**	**Class 2**	**Class 3**	**Class 4**	**Class 5**	**Class 6**
Airbus A318	-	2008-2030	-	-	-	-
Airbus A319	-	2008-2030	2008-2030	-	-	-
Airbus A320-100/200	-	2008-2030	2008-2030	-	-	-
Airbus A321	-	-	2008-2030	-	-	-
Airbus A330-200	-	-	2008-2015	2008-2015	-	-
Airbus A340-300	-	-	-	2008-2012	-	-
Airbus A340-600	-	-	-	2008-2030	2008-2030	-
Airbus A350-800	-	-	2013-2030	-	-	-
Airbus A350-900	-	-	-	2013-2030	-	-
Airbus A380 pax	-	-	-	-	2008-2030	2008-2030
Boeing 737-800	-	-	2008-2030	-	-	-
Boeing 747-800	-	-	-	2010-2030	2010-2030	-
Boeing 767-300	-	-	2008-2030	-	-	-
Boeing 777-200	-	-	2008-2017	2008-2030	2008-2030	-
Boeing 777-300	-	-	-	-	2008-2030	-
Boeing 787 all pax models	-	-	2008-2030	2008-2030	-	-
Boeing 737-700	-	2008-2030	-	-	-	-
Boeing 777-300 (ER)	-	-	-	2008-2030	-	-
Bombardier C Series	2008-2030	2008-2030	-	-	-	-
Bombardier DHC-8 Q400	-	2008-2030	-	-	-	-
Embraer 170	2008-2030	-	-	-	-	-
Embraer 190	-	2008-2030	-	-	-	-
Embraer 195	-	2008-2030	-	-	-	-
EMB-135	2008-2018	-	-	-	-	-
EMB-ERJ145	2008-2018	-	-	-	-	-
Executive Jet Chapter 3	2008-2030	-	-	-	-	-
ACARE Next-Gen CL5 Quad	-	-	-	-	2020-2030	-
ACARE Next-Gen CL5 Twin	-	-	-	-	2020-2030	-
ACARE Next-Gen CL1	2020-2030	-	-	-	-	-
ACARE Next-Gen CL2	-	2020-2030	-	-	-	-
ACARE Next-Gen CL3	-	-	2020-2030	-	-	-
ACARE Next-Gen CL4	-	-	-	2020-2030	-	-

Table 6 Summary of Supply Pool for Charter Airlines

	Seat Class					
Aircraft Type	**Class 1**	**Class 2**	**Class 3**	**Class 4**	**Class 5**	**Class 6**
Airbus A318	-	2008-2030	-	-	-	-
Airbus A319	-	-	-	-	-	-
Airbus A320-100/200	-	-	2008-2030	-	-	-
Airbus A321	-	-	2008-2030	-	-	-
Airbus A330-200	-	-	-	-	2008-2019	-
Airbus A330-300	-	-	-	-	2008-2030	-
Airbus A340-300	-	-	-	-	2008-2014	-
Airbus A350 pax	-	-	-	2013-2030	2015-2030	-
Airbus A380 pax	-	-	-	-	-	2008-2030
Boeing 737-800	-	-	2008-2030	-	-	-
Boeing 747-400	-	-	-	-	-	-
Boeing 747-800	-	-	-	-	2010-2030	2008-2030
Boeing 767-200	-	-	-	2008-2012	-	-
Boeing 767-300	-	-	-	2008-2010	-	-
Boeing 777-200	-	-	-	-	2008-2030	-
Boeing 787 all pax models	-	-	-	2011-2030	-	-
Boeing 737-700	-	2008-2030	-	-	-	-
Bombardier Challenger	2008-2030	-	-	-	-	-
Bombardier RJ700	-	-	-	-	-	-
Bombardier DHC-8 Q400	-	2008-2030	-	-	-	-
Embraer 190	-	2008-2030	-	-	-	-
Embraer 195	-	-	-	-	-	-
EMB-135	2008-2030	-	-	-	-	-
ACARE Next-Gen CL5 Quad	-	-	-	-	2022-2030	-
ACARE Next-Gen CL5 Twin	-	-	-	-	2022-2030	-
ACARE Next-Gen CL1	2022-2030	-	-	-	-	-
ACARE Next-Gen CL2	-	2022-2030	-	-	-	-
ACARE Next-Gen CL3	-	-	2022-2030	-	-	-
ACARE Next-Gen CL4	-	-	-	2022-2030	-	-

Table 7 Summary of Supply Pool for No-Frills Carriers

	Seat Class					
Aircraft Type	**Class 1**	**Class 2**	**Class 3**	**Class 4**	**Class 5**	**Class 6**
Airbus A318	-	2008-2022	-	-	-	-
Airbus A319	-	-	2008-2030	-	-	-
Airbus A320-100/200	-	-	2008-2030	-	-	-
Airbus A321	-	-	2008-2030	-	-	-
Boeing 737-800	-	-	2008-2030	-	-	-
Boeing 737-700	-	2008-2030	-	-	-	-
Bombardier RJ700	2008-2030	-	-	-	-	-
EMB-ERJ145	2008-2030	-	-	-	-	-
ACARE Next-Gen CL1	2022-2030	-	-	-	-	-
ACARE Next-Gen CL2	-	2020-2030	-	-	-	-
ACARE Next-Gen CL3	-	-	2020-2030	-	-	-

There are some entries in these tables which warrant consideration and possible revision. The Airbus A340-300 is available in the pool until 2012, while the A340-600 is available to 2030. The first of these is already out of production while the latter is being produced in very low numbers and it is unlikely that there will be any further deliveries after 2012. Similarly, the Boeing 777-200 and 777-300 are not being produced in significant numbers currently (the majority of current orders for the 777 series are for the long range 200LR and 300ER variants). Therefore, it is unlikely that these types will still be entering the UK fleet in 2030; a cut-off date of 2025 or even 2020 would seem more likely.

The A320-series aircraft are listed as being available to 2030. In production terms, it is currently expected (see, for example, [8]) that this aircraft series (in common with the Boeing 737) will receive some form of “overhaul”, with new engines and winglets amongst other changes, around 2016, and will then go out of production once the new generation single-aisle aircraft (possibly with open rotor engines) goes into production around 2024. As such, variants of the A320 and 737 series may well be entering the UK fleet in 2030, but they will probably be to a different specification to today’s aircraft.

The current table has the Boeing 787 and the Bombardier C Series entering the supply pool in 2008. It is now expected that the 787 will enter service in the 2011-2012 timeframe, while the C Series is not expected in production until 2013.

In the current tables, the Boeing 747-8 (listed as a 747-800) is expected to enter the supply pool from 2010. The entries are then expected to rise over a two year period to form 30% of deliveries in its seat class (Class 5, 351-500 seats). At the time of writing, the Boeing 747-8 has just made its first flight and Boeing are targeting an entry-into-service date of 2011. Thus far, only Lufthansa and Korean Air have ordered the passenger version of the aircraft (plus some VIP orders); the cargo version has proved more popular. As a result, it is recommended that the 747-8 appears in the supply pool from 2012, and deliveries are limited to 20% of the supply pool for the seat class.

The Bombardier DHC-8 Q400 (the “Dash 8”) is listed as being in the supply pool for Class 2 from 2008 to 2030. This aircraft is a turboprop and lies close to the bottom of the seat range for the class (Class 2 covers 71 to 150 seats; the Dash 8 has 78 seats). As such, its fuel burn remains better than even the ACARE 2020-compliant type in the same class. Therefore, it is considered that this aircraft type (or a derivative or a new turboprop type to replace it) is likely to be in production up to 2030. The continued inclusion of this type in the supply pool to 2030 is, therefore, supported.

The ACARE 2020-compliant types start being introduced to the pool for scheduled airlines in 2020 and two years later for Charter airlines. For classes 2 and 3, the No-Frills Carriers take these aircraft from 2020 as well, which is consistent with the recent practice of easyJet and Ryanair, who operate some of the youngest fleets. However, as noted above, it is now generally expected that the new generation single aisle aircraft will not be available until around 2024. Given the competition between the two major aircraft manufacturers (Boeing and Airbus), it is likely that both will offer new aircraft at about the same time. Once the aircraft enter production, it is unlikely that the production of existing types (such as upgraded A320s and 737s) will continue, so their rate of entry into the fleet will be much reduced.

For the other seat classes, it is not so clear what form the first “ACARE-compliant” aircraft will be, nor which manufacturer will build it. Therefore, the current approach of assuming a new aircraft type becoming available in 2020, with existing types continuing to be built alongside it, is sensible.

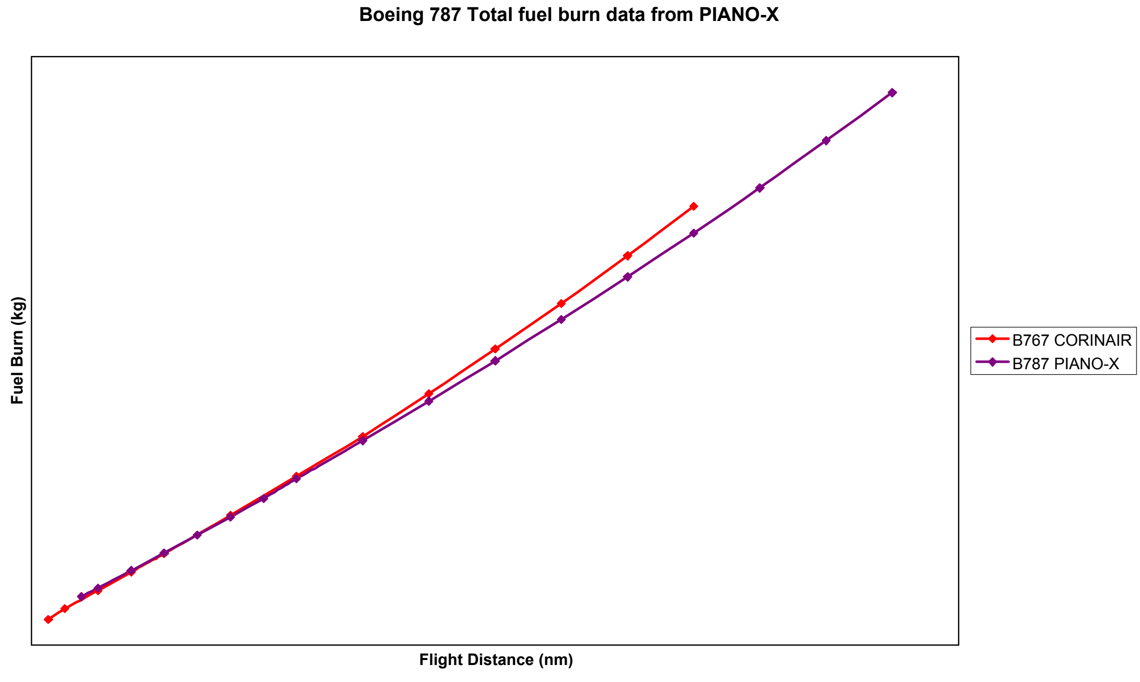
4 The modelling of known future aircraft types

It was noted above that there are some current and near-term future aircraft types in the forecast for which data do not exist in CORINAIR, in particular the Airbus A340-600 (modelled as an A340-300), the Airbus A380 (modelled as a Boeing 747-400 with a 12% reduction in fuel burn per passenger-km) and all models of the Boeing 787 and Airbus A350 (both modelled as a Boeing 767 with a 20% reduction in fuel burn per passenger-km).

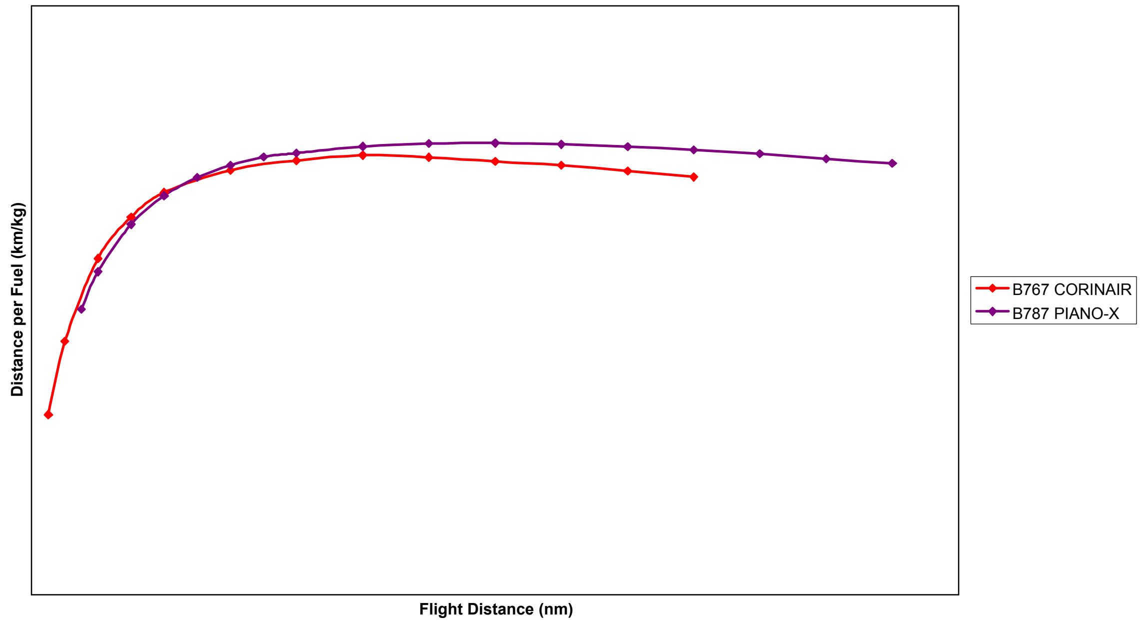
To investigate these aircraft, data have been generated for the Boeing 787-8 using the freely downloadable version of the PIANO-X program and data [5], and for the other three aircraft using the version of PIANO available at QinetiQ (for which the terms of use restrict the release of specific aircraft data), using model data which have been developed at QinetiQ.

The results for the Boeing 787-8 are shown in the following figure.

Figure 46 Total fuel burn and fuel consumption for the PIANO-X Boeing 787 compared to the CORINAIR Boeing 767



B787 Total fuel burn data from PIANO



As can be seen, the difference in fuel burn between the two sets of data is not very large, ranging from near zero at short ranges to 6% at the upper limit of the Boeing 767 range. However, it should be remembered that it was shown in Section 3.2 that the AERO2k fuel burn for the Boeing 767 was higher than the CORINAIR data by 7% for an average flight length. As a result, the above plots represent a reduction of about 13% for the Boeing 787-8 compared to the AERO2k Boeing 767. For scheduled flights, the number of seats assumed for the two aircraft are 250 for the Boeing 787-8 and 223 for the 767, which results in an approximately 25% advantage for the 787-8 in fuel burn per seat-km.

For modelling the Boeing 787 aircraft in future forecasts, therefore, it is recommended that data are derived using the PIANO-X tool, as these data are expected to give more accurate results than basing it on Boeing 767 data with corrections.

The results of calculations for the Airbus A340-600, using PIANO, have been compared to the CORINAIR data for the A340-300. At an average range, the A340-600 fuel burn was 36% higher than the CORINAIR A340 (remembering that, from Figure 4, there was good agreement between the AERO2k and CORINAIR A340 aircraft).

The PIANO data for the Airbus A380 aircraft have been compared to the CORINAIR data for the Boeing 747-400. At an average range, the A380 fuel burn was 15.5% higher than the CORINAIR Boeing 747-400. There was also good agreement between the AERO2k and CORINAIR 747-400 aircraft (Figure 9). The assumed seat numbers for scheduled operations for these two aircraft are 520 and 358 respectively, giving the A380 an advantage of 20% in fuel burn per seat-km.

The PIANO data for the A350-900 have been compared to the CORINAIR data for the Boeing 767. At an average range, the PIANO fuel burn for the A350-900 was 10% higher than the CORINAIR data for the Boeing 767. As for the Boeing 787, the CORINAIR data for the Boeing 767 should be increased by 7%, so the A350 would then be 3% higher than these modified data. The assumed seat numbers for the

A350-900 and Boeing 767 aircraft are 300 and 223 respectively, giving the A350 an advantage of 23% in terms of fuel burn per seat-km.

Both the Boeing 787 and Airbus A350 aircraft are being developed in three models (although the short range Boeing 787, the 787-3, currently has no orders and an indefinite entry-into-service date [9]). The variation of weight and range across the models may be significant. For example, the A350-800 has a maximum take-off weight (MTOW) of 248 tonnes, the A350-900 has a MTOW of 268 tonnes and the A350-1000 has a MTOW of 298 tonnes. However, given the lack of certainty in the final design and performance of the different variants, it is reasonable to use the data presented above to model each variant of the aircraft type.

There is much less information available for the Boeing 747-8 aircraft than some other future types. Based on the published information on the maximum take-off weight [10], it would appear to be approximately 10% heavier than the 747-400. The improvements in aircraft aerodynamics and engine technology would be expected to lead to a considerable improvement in the aircraft fuel efficiency, but there are no reliable data on this. Therefore, the current approach of modelling the aircraft as a Boeing 747-400 should be continued until additional data are available.

In addition to the “new” long-range types, it was noted in Section 3.4 that the majority of future deliveries of the Boeing 777 aircraft are likely to be the 777-200LR and the 777-300ER models. Data derived from PIANO modelling of the Boeing 777-300ER have been compared to the CORINAIR data for the 777-200. At an average range, the 777-300ER fuel burn was 12% higher than the CORINAIR data for the 777-200.

The Bombardier C Series is currently modelled as a BAe 146. This is presumably due to the lack of an Airbus A319 data set. From the results shown in Section 3.2, it will be possible to derive a set of A319 data by factoring the A320 data. The C Series is expected to offer 20% improvements in fuel burn over today’s equivalent aircraft, so a model for the C Series should apply a factor of 0.8 to the A319 model derived above.

It is becoming increasingly evident that the replacement for the Airbus A320 series and the Boeing 737 (the “Next Generation Single-Aisle” aircraft) will not appear until the 2024 timeframe. There is, therefore, increasing pressure from airlines on the manufacturers to provide an update to the existing designs in the middle of the coming decade. Indeed, Airbus are already discussing new winglet designs and possible re-engining of the aircraft. This might include the fitting of the Pratt & Whitney Geared Turbofan (GTF) engine (the PW1000G series), though Airbus have indicated that they would only do so through the existing International Aero Engines (IAE) route. Whatever the actual nature and designation of the new engines, it is clear that they would need to offer similar benefits in fuel burn to that of the GTF, generally stated to be 12-15% improvement in specific fuel consumption. Therefore, it is reasonable to expect that Airbus A320 and Boeing 737 series aircraft produced after 2016 to have a fuel burn some 15% lower than the current models.

The ultimate replacement for the A320 and Boeing 737 aircraft (the Next-Generation Single-Aisle aircraft) then becomes the ACARE-2020 compliant type in the relevant seat class, with an entry-into-service date of 2024.

In the existing forecast methodology, the ACARE-compliant types become available for introduction into the fleet in 2020. For the purposes of the forecasts, these ACARE-compliant types are defined as follows:

Seat Class 1	ATR42-300 less 40% fuel burn
Seat Class 2	Boeing 737-400 less 40% fuel burn
Seat Class 3	Boeing 757-200 less 40% fuel burn
Seat Class 4	Boeing 777-200 less 40% fuel burn
Seat Class 5	For twin-engined aircraft, the average of the Boeing 777-200 and Airbus A340, less 40% fuel burn For four engined aircraft, Boeing 747-400 less 40% fuel burn.

There is no ACARE-compliant aircraft defined in seat class 6 (over 500 seats).

The aircraft chosen to form the base for the ACARE-compliant types are relevant (in that they represented the state of the art in 2000) and their continued use for this purpose is supported. Seat class 1 is the only one which uses a turboprop aircraft (the ATR42) as the baseline. Although there are jet aircraft in this seat class (particularly business jets), the turboprop types are more popular because of their lower fuel consumption. Whether aircraft in this class continue to be predominately turboprops or not will be influenced by drivers such as fuel price and the market desire for speed (turboprops being slower than jets). The different fuel price scenarios and their effects on the future fleet will be examined later in this report. For the central case, as considered here, it is expected that turboprops will continue to be the main constituent of Seat Class 1.

Given the expectation for the A320/737 replacement, the ACARE-2020-compliant type in Seat Class 2 should be delayed and only appear in the supply pool from 2024.

The use of a 40% reduction in fuel burn compared to existing types (which were in service in 2005) is consistent with the ACARE target as generally stated (though there have been a number of interpretations of this target since it was first formulated).

The curve fits employed for the ACARE-compliant aircraft have been assessed in the same manner as those in Section 3.3. both distance/fuel (in km/kg) and fuel burn (in kg) have been calculated. The results are shown for all the ACARE-compliant types in the following two figures.

Figure 47 Fuel burn from curve fits for ACARE-compliant aircraft

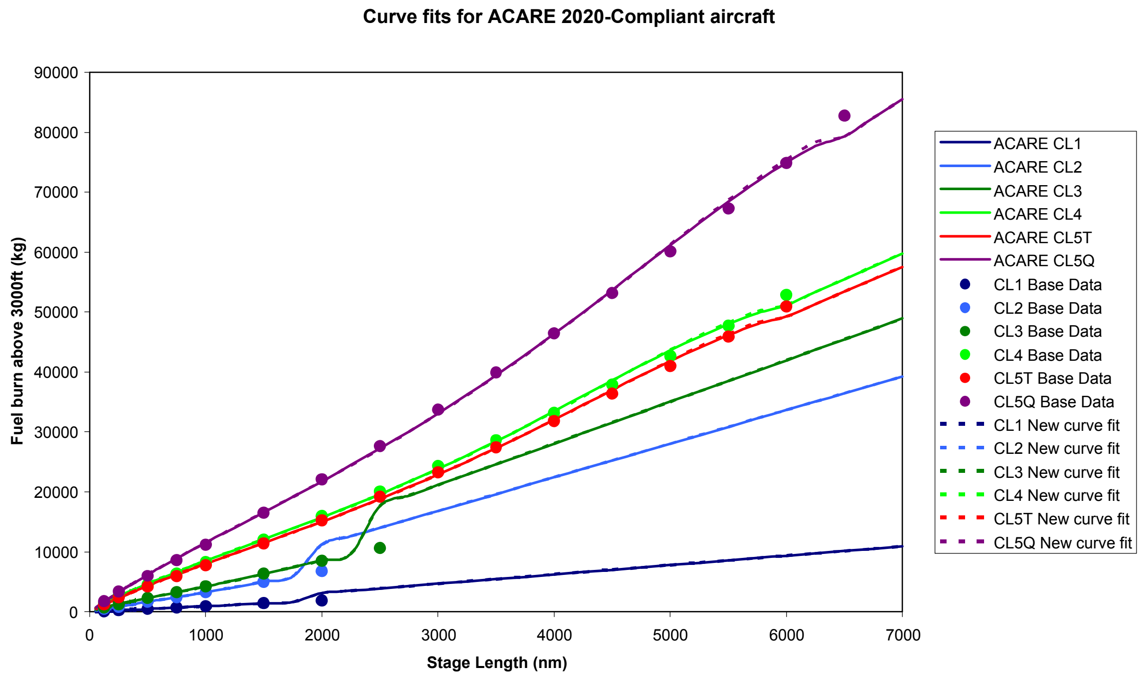
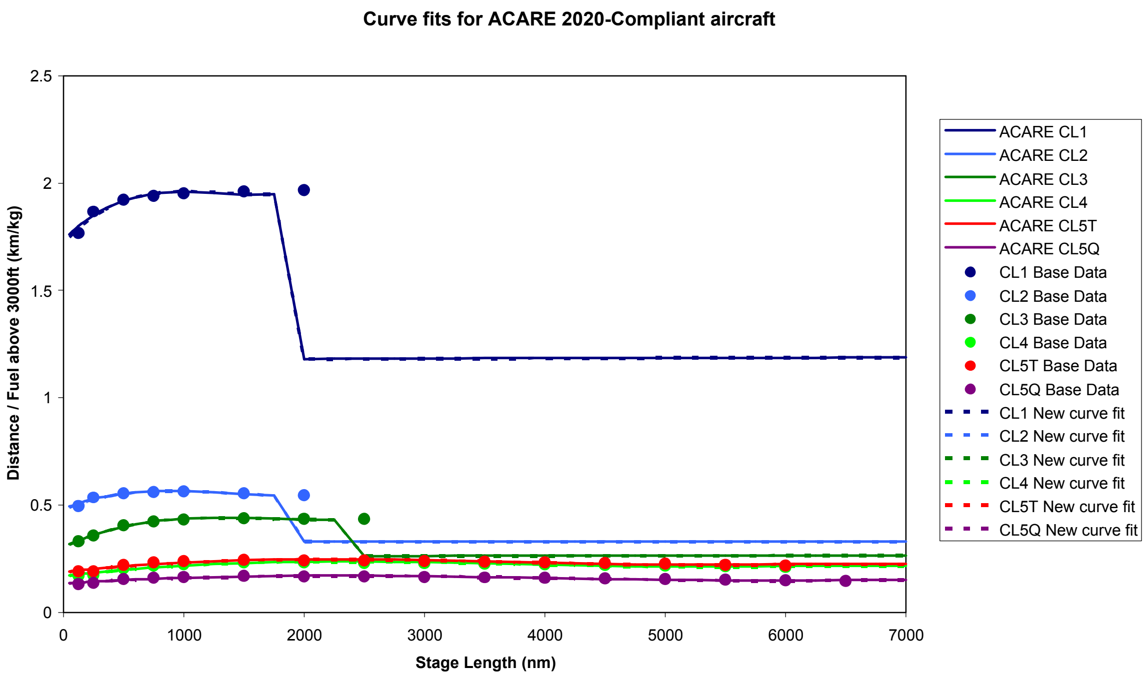


Figure 48 Distance / Fuel burn for ACARE-compliant aircraft



In the above two figures, the curves identified as “New curve fit” are new fits to the base data to confirm the accuracy of the original fits. As before, there is clearly very good agreement between the two sets of curve fits. At the scales of the above figures, there is also very good agreement between the curves and the base data.

In Figure 47 and Figure 48, the calculations of fuel burn and distance/fuel have been extended to long stage lengths for all aircraft types. It is clear that there is a problem with the linear extension part of the curve for aircraft CL1, CL2 and CL3. Examination shows that, while the linear extension data for aircraft CL4, CL5T and CL5Q have been multiplied by the 0.6 factor (for the 40% improvement in fuel efficiency), the same has not been done for the smaller aircraft. Although the linear extensions are not used for “normal” flight distances for these aircraft types (they are used for flight distances beyond 2,000nm for classes 1 and 2 and 2,500nm for class 3), it is clear that they would significantly affect the calculated fuel burn for any longer range flights by these types.

To examine the accuracy of the curve fits in greater detail, the distance/fuel data are plotted separately for the six aircraft types in the following figures.

Figure 49 Distance/Fuel curve fits for ACARE-compliant Class 1 aircraft

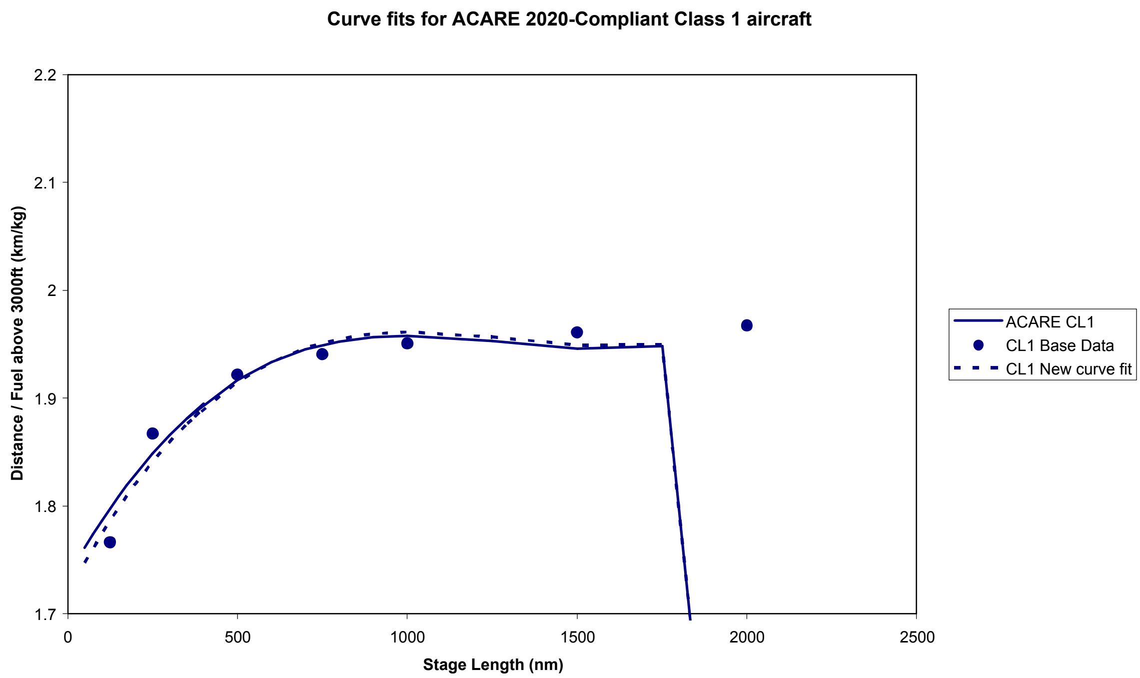


Figure 50 Distance/Fuel curve fits for ACARE-compliant Class 2 aircraft

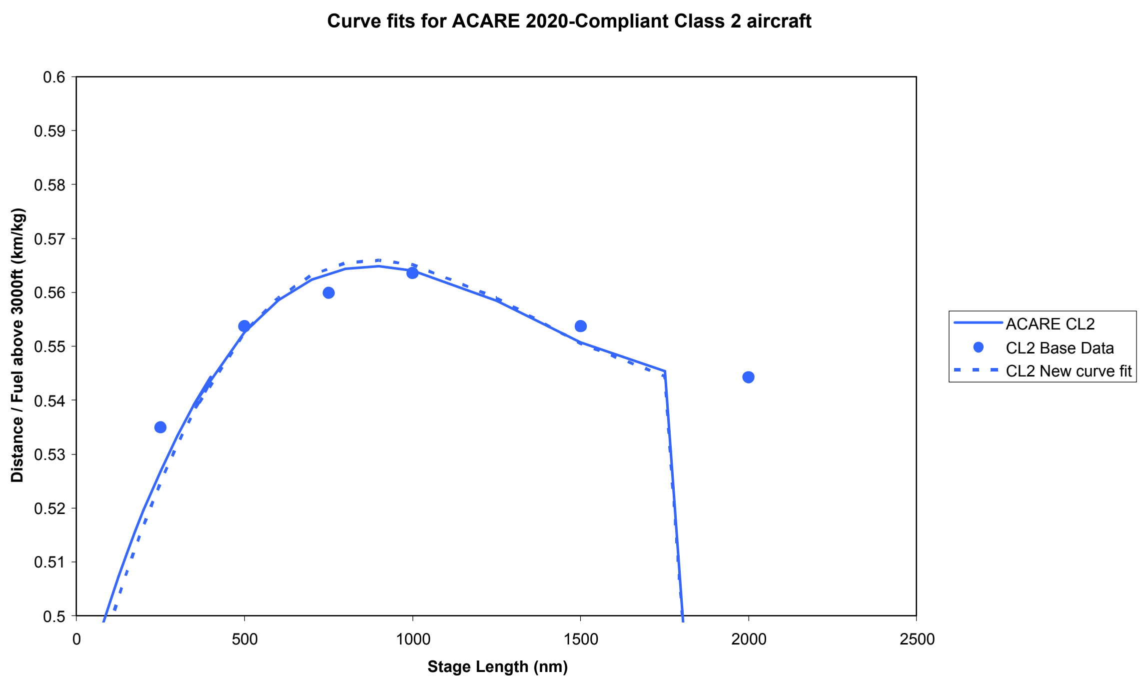


Figure 51 Distance/Fuel curve fits for ACARE-compliant Class 3 aircraft

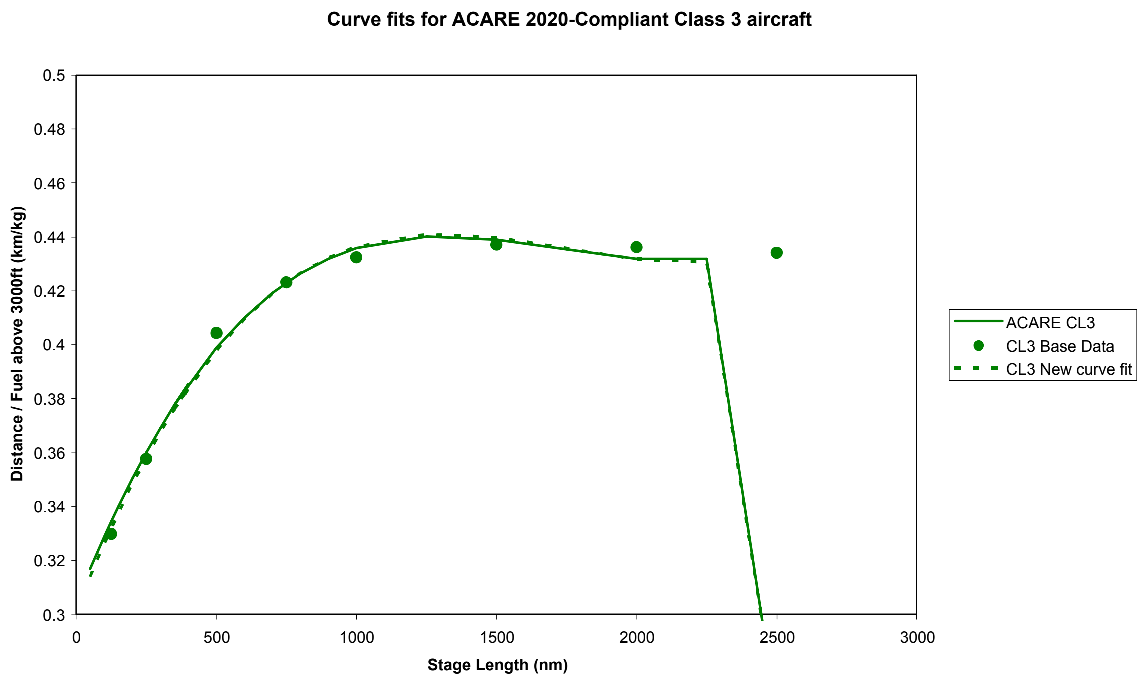


Figure 52 Distance/Fuel curve fits for ACARE-compliant Class 4 aircraft

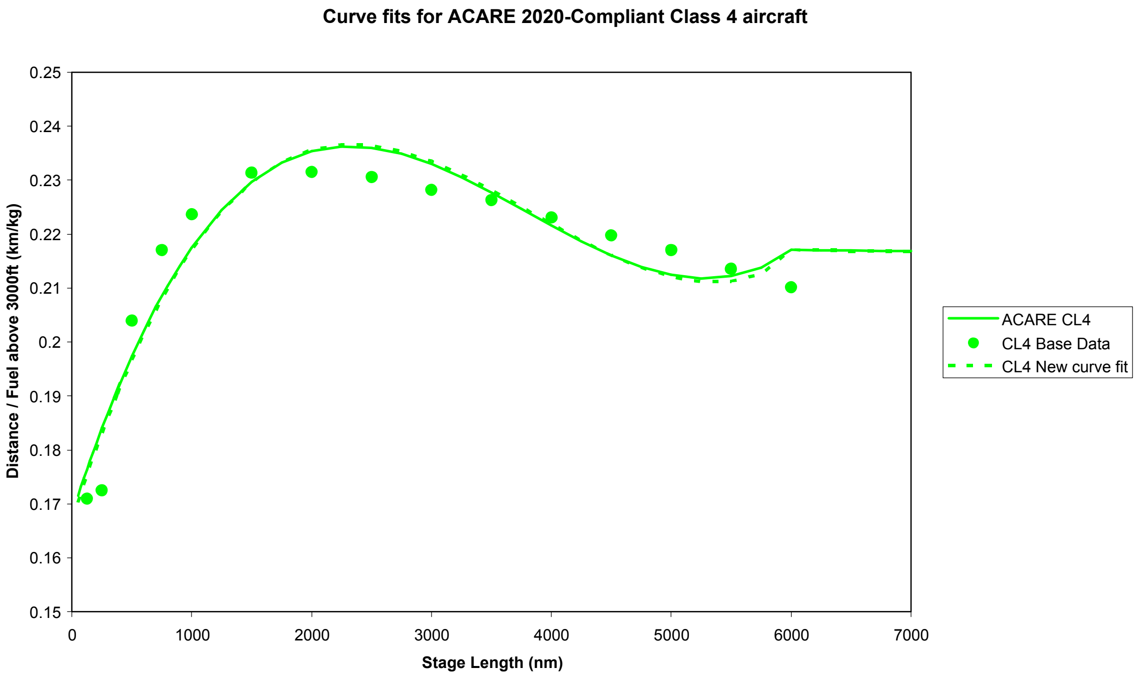


Figure 53 Distance/Fuel curve fits for ACARE-compliant Class 5 Twin-engined aircraft

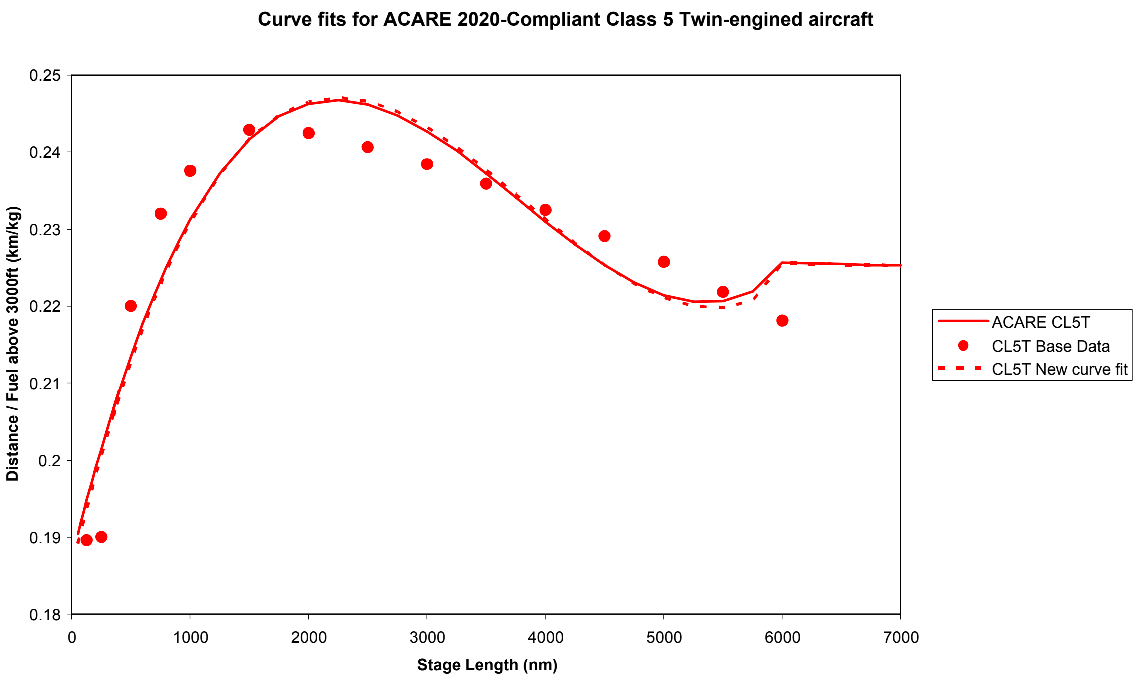
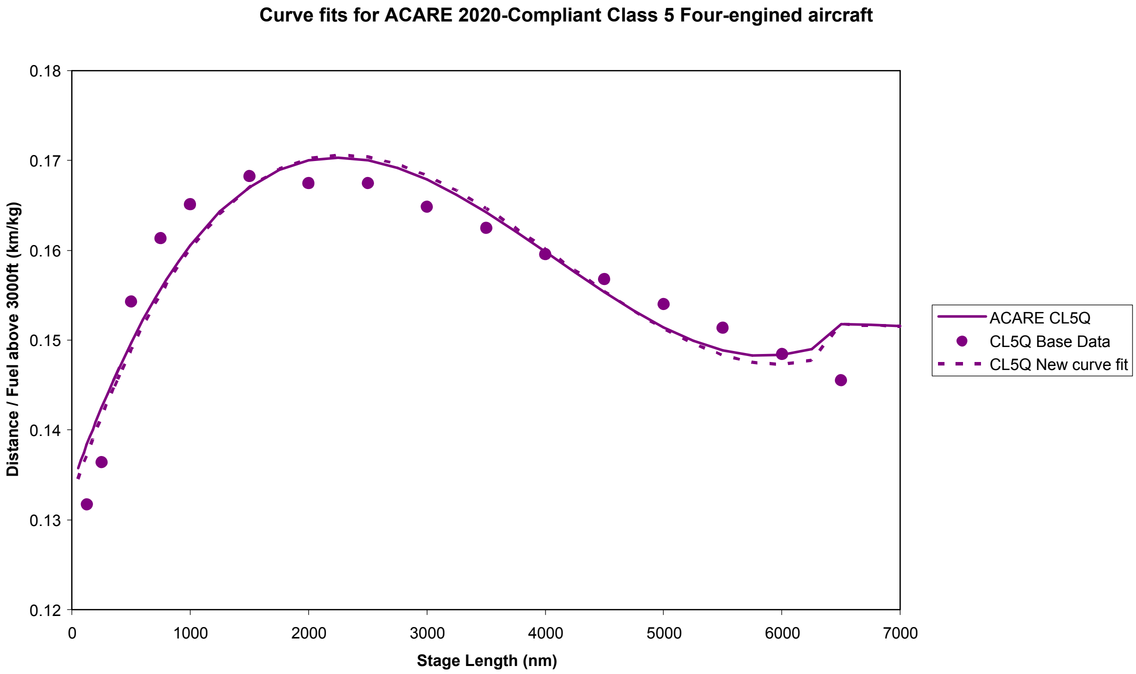


Figure 54 Distance/Fuel curve fits for ACARE-compliant Class 5 Four-engined aircraft



In the above figures, the linear extension is included as well as the cubic curve fit. Apart from the problem with the linear extension, the curves for classes 1, 2 and 3 appear to give a good fit to the base data. Classes 4 and 5 (both twin and four-engined variants) show a similar characteristic to some of the aircraft types discussed in Section 3.3, where a fifth order curve gives a better fit to the data than the cubic curve. For the class 4 and 5 ACARE-compliant aircraft, it is also clear from the above figures that the linear extension (scaled from the values used for the CORINAIR types) does not give a good match to the gradient of the base data at the high end of the stage length range, i.e. for distances close to or beyond the limit of the CORINAIR data, the model will produce an aircraft efficiency which is excessively high. A recalculation of this extension from the last few points of the base data would produce a more realistic efficiency and fuel burn (and, hence, CO_2 emission).

5 Future Aircraft Technology

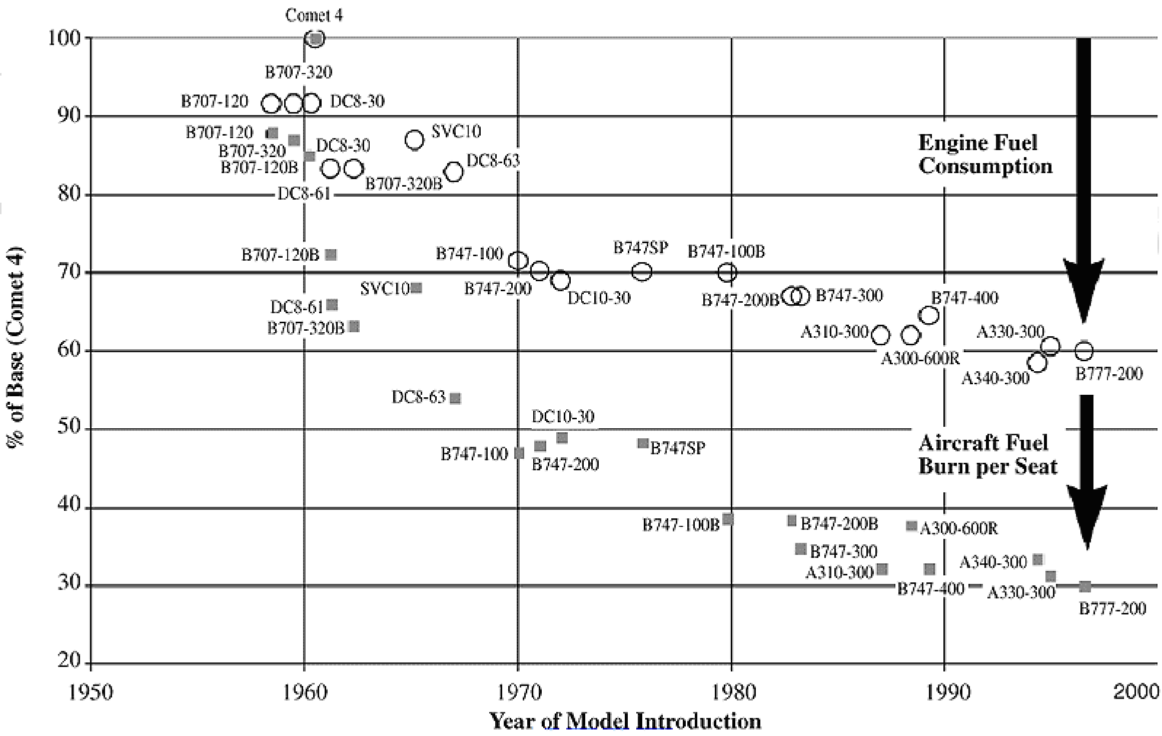
The inclusion of specific models for known future aircraft types, as described in Section 4, covers aircraft entering service up to the year 2016. The addition of "ACARE-compliant" types, starting in 2020, covers types entering service up to 2030. To cover the effect of aircraft entering service between 2030 and 2050, a more generalised approach is required, looking at the likely technologies which will be on the aircraft entering service in that timeframe, and their expected effect on the fuel consumption of the aircraft to which they are fitted. This section discusses the key technologies expected to enter service in future years, their likely dates of entry into service and their expected effect on aircraft fuel consumption.

The majority of the information in this section has been drawn from a report prepared for the Committee on Climate Change in October 2008 [11]. The first part of the section discusses evolutions of existing technologies, while the latter part discusses some, more speculative, step-changing technologies.

In broad terms, conventional technology options can be categorised as measures which will either reduce the weight of the engine or airframe, or deliver improvements in a range of engine or airframe performance metrics such as aerodynamic drag, and thermodynamic and propulsive efficiency of engines. In either case, the aim is to reduce fuel consumption while maintaining all other flight parameters constant.

The quest for reducing fuel burn per passenger kilometre (or seat-kilometre) is not new and the general trend set out in Figure 55 shows that a 70% reduction has been achieved since the first generation of jet airliners exemplified by the Comet 4.

Figure 55 - Historical Trend in Fuel Efficiency Improvement



The biggest single improvement over this period came through the introduction of high bypass ratio turbofan engines in the early 1970s. However, further progressive improvements in airframe and engine technology followed this break-through and continued the downward trend.

A number of research programmes are already in place, addressing the environmental impact of aviation through both engine and airframe innovation. As examples, the Clean Skies initiative and the propulsion technology programmes responding to the ACARE[3] Vision 2020 [3] targets provide clear evidence of commitment to the cause. However, it is equally clear that more radical solutions will need to emerge in the later decades towards 2050.

5.1 Engine Technology

5.1.1 Introduction

Around half of future aircraft fuel consumption reductions forecast for the coming decades is expected to come from improvements in engine technology, and a range of evolutionary ideas are continuously being researched and matured for incorporation into new product lines. There is a balance involved when considering emission reductions, since there is generally a trade-off between NOx emission control and fuel consumption. CO_2 emissions scale linearly with fuel consumption. Therefore controlling NOx will normally lead to a small increase in CO_2 emissions.

5.1.2 Current Technical Status and Future Development

Current high bypass ratio engines are approaching optimum fuel efficiency from present day technology. However, additional developments and modifications continue to work towards ever more efficient systems. Combustor technology has also matured to the extent that almost 100% combustion of the fuel is achieved, resulting in low emissions of carbon monoxide and hydrocarbons.

5.1.3 Future development of engine technology

The principal metrics of a defined propulsion system which influence the fuel burn, and hence CO_2 emissions are:

- Thermodynamic efficiency, for example increasing the turbine entry temperature (TET);
- Propulsive efficiency, optimisation of aerodynamic design of fan and turbine components, and minimising parasitic losses (e.g. tip clearance).
- Engine and associated systems weight.

Compared to a year 2006 baseline, thermodynamic efficiency gains of 3-5% should be achievable by 2025 through increasing the overall engine pressure ratio and improvements in materials and cooling enabling higher hot end temperatures. However, the CO_2 reduction potential may need to be traded-off against increases in other types of emission (such as NOx) and hence limit the achievement of such improvements. Further advances in the aerodynamic design of the rotating

[3] ACARE - Advisory Council for Aeronautics Research in Europe. ACARE 2020 research target for CO_2

components may also be possible over the same period, with compressor and turbine efficiencies potentially delivering a further 3-5% improvement by 2025.

5.1.4 Production Development Trends

Current trends through product development have been seen to make continual improvements in the efficiency and overall performance of engines and their associated technologies. Take for example the Rolls-Royce Trent engine. The Rolls-Royce Trent family of engines were developed from the three shaft design of the RB211. The engines have evolved from the initial Trent 600, although this was never produced, through to the Trent 1000 and other new concepts, e.g. the Trent XWB. The thrust rating and cruise Specific Fuel Consumptions for a selection of Trent engines is provided in Table 8.

Table 8 - Trent Engine Data (Source: Rolls-Royce plc & Jane's Defence Programmes)

Entry/Target date Into Service	Trent Engine	Thrust Rating (lb)	Engine Weight (lb)	Bypass Ratio[4]	SFC[5] mg/Ns (lb/h/lb)
1995	700	67,500 and 71,000	10,550	5.0	Not known
1996	800	74,600 to 95,000	13,100	5.7 to 6.2	15.86 (0.56)
2002	500	53,000 and 56,000	10,400	7.5 to 7.6	15.26 (0.539)
2007	900	70,000 and 76,500	13,842	8.5 to 8.7	14.665 (0.518)
2009	1000	53,000 to 75,000	11,924	10.4 to 11.0	14.325 (0.506)
N/A	1700	63,000 to 75,000	Not known	10.0	13.289 (0.486)
2013	XWB	75,000 to 95,000	Not known	11.0+	Not known

Technology developments through the series of Trent engines have generally resulted in quieter and more efficient engines, producing lower emissions. It is notable from the above table that the advances between the Trent 800 and Trent 1000 gave a reduction in specific fuel consumption of almost 10% in 13 years, a

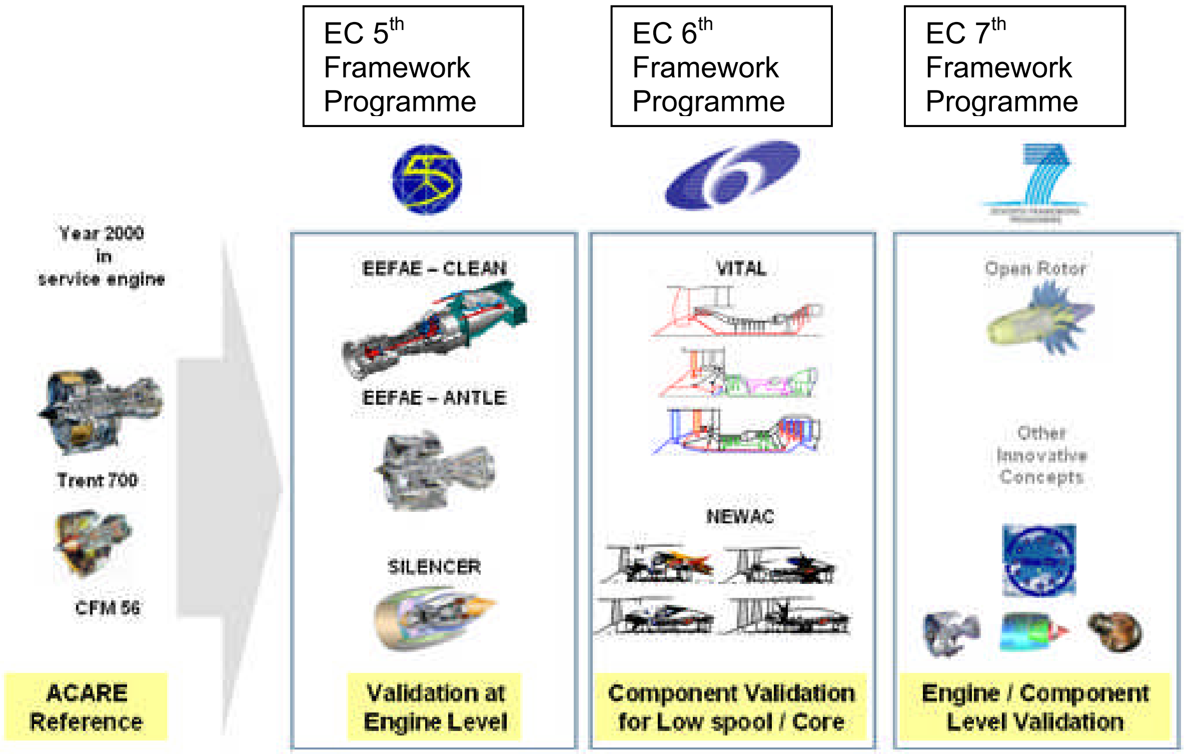
[4] The bypass ratio of a turbofan engine is the ratio of the mass flow of air which bypasses the engine core after exiting the fan section to the mass flow of air which passes through the core. Generally, the higher the bypass ratio, the higher the efficiency.
[5] SFC is Specific Fuel Consumption, the ratio of the fuel consumption (in units of lb/hr in this case) to the engine thrust (in lb)

rate of approximately 0.7% per year. The developments have typically included advanced compressor blade aerodynamics, and new materials and coatings for the turbine stages. The Trent 900 also introduced contra-rotating HP and IP components, with further gains in aerodynamic efficiency. Blade tip clearance control was also used in the turbine stages. Further fan efficiency improvements are being made with the Trent 1000. Throughout the Trent engine development continual enhancements were made to the combustion chamber, with tiled construction and new coatings to reduce NOx emissions.

5.1.5 UK and EU Research Programmes

Current UK and EU collaborative research programmes are addressing a number of technology areas that are focused on reducing the environmental impact of aviation, e.g. New Aero engine core Concept (NEWAC), Efficient and Environmentally Friendly Aero Engine (EEFAE). The following roadmap provides a top level view of some of the main programmes currently active:

Figure 56 - Aero Engine Technology for Environmentally Friendly Aircraft © NEWAC



SILENCER is focussed on aviation noise reductions and is therefore not discussed in this report.

In March 2000 the European Commission launched the Efficient and Environmentally Friendly Aero Engine (EEFAE) project. From this two activities were formed; Advanced Near-Term Low Emissions (ANTLE) and the Component vaLidator for Environmentally friendly Aero eNgine (CLEAN).

The ANTLE engine uses the approach of incorporating higher efficiency components than current designs on a three-shaft engine architecture. The target for this is a 10-12% reduction in CO_2 emissions and a 60% reduction in NOx. CLEAN is looking at the validation of the technologies for a future Intercooled Recuperated Aero (IRA) engine, incorporating high efficiency compressor, combustor, and turbine modules. The target is for reductions in emissions of 20% and 80% for CO_2 and NOx respectively; although flight testing of an IRA engine is not expected before 2015 and in-service application before 2020. These programmes have further links with other EU research tasks such as VITAL (enVIronmenTALly friendly aero engine, investigating very high bypass ratio engines through different architectures) and NEWAC (New Aero engine core Concept, investigating the advantages to be gained through the adoption of more complex engine cycles, such as intercooled and recuperative cores).

5.1.6 Clean Sky Joint Technology Initiative (JTI) programme

The Clean Sky JTI programme primarily addresses airframe improvements and, as such, is discussed in Section 5.2.3. However, one element of the programme addresses Sustainable and Green Engines. This element aims to design and build five engine demonstrators to integrate technologies for lightweight low pressure systems, high efficiency, low NOx and low weight cores and novel configurations, including open rotors and intercoolers. This will address engines in the 2020 timeframe and give consideration to the technologies that may be used during this period. The improvements in CO_2 emission obtained are likely to be consistent with those discussed in Sections 2 and 3 of this report, but the programme will provide the opportunity to demonstrate their achievement and encourage their adoption on next-generation production aircraft.

5.1.7 The Environmentally Friendly Engine (EFE)

EFE is a UK programme, led by Rolls-Royce, embracing a diverse range of initiatives, focusing on engine hot end (combustor and turbine) technologies. It incorporates a lean burn combustor for reduced NOx emissions, high temperature turbine components to reduce CO_2, reduced cooling air requirements delivering improvements to both CO_2 and NOx, and improved efficiency of the HP turbine leading to reduced engine weight, fuel burn and CO_2. At the front end, improved intake and nacelle aerodynamics should lower drag associated with the overall engine installation, leading to lower fuel burn and CO_2.

Engine weight can be driven down through innovation in materials and manufacturing techniques, as well as overall engine design. An example of this thrust is the trend towards reducing the number of compressor stages while achieving the same performance, and the development of blisk[6] components. However, gains from this are likely to be small. High temperature composite materials (up to 1650°C for Carbon Matrix Composites) should be suitable for engine applications, resulting in higher operating temperatures, greater efficiency, and reduced fuel consumption as well as reduced weight. Inter-Metallic Composites could also be used in cold end compressor sections, leading to as much as 50% reduction in weight of the affected components.

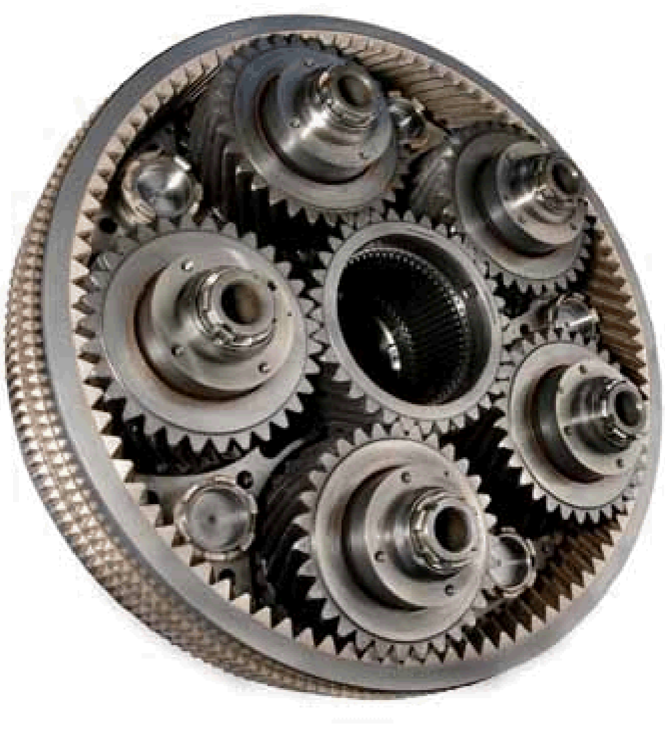
[6] Integrally bladed compressor disk. A blisk is lighter than a traditional disk with separate blades and allows some improvements to the aerodynamics.

5.1.8 Other engine development and demonstrator programmes

<u>Geared turbofan (GTF)</u>

The conventional architecture of a typical turbo-fan engine directly couples the low pressure (LP) turbine and fan through a rigid rotating shaft, referred to as the Direct Drive Turbo Fan. However, this arrangement has inherent inefficiencies since the fan works better at low speeds while the turbine is more efficient rotating at higher speeds. To address this issue, some aero-engine designers have considered the introduction of a gear train to reduce fan rotational speeds to achieve higher overall engine efficiency. It has been claimed that this creates a quieter, more powerful engine which requires less fuel, emits less CO_2, and costs 30% less to maintain. Further claims also include reduced NOx emissions. GTFs for smaller business jet aircraft have been in service for a number of years and the long-established Honeywell TFE731, and more recent Pratt & Whitney PW1000G are typical examples. A scaled up version of this type of engine was cleared for flight testing in April 2008. The initial applications for the GTF will be the Mitsubishi Regional Jet and the Bombardier C_Series, both expected to enter service in 2013. Further applications may be new variants of the Boeing 737 and Airbus A320 series aircraft later in the decade. Combining the improvements from the geared fan with other advances (engine bypass ratio, engine pressure ratio, component efficiency improvements), it is anticipated that the GTF will burn 12 to 15% less fuel than other engines of comparable thrust. Given average utilisation this could equate to 1500 tonnes less CO_2 emissions per aircraft per year for those aircraft to which the engine might be fitted.

Figure 57 - Pratt & Whitney Geared Turbofan ©Pratt&Whitney



The improvements in fuel consumption (and CO_2 emissions) attributed to the GTF engine arise from the combination of its very high bypass ratio (expected to be about 12), the fan and LP turbine efficiency improvements arising from the use of the gearbox and other incremental improvements which would be expected to be incorporated into an engine of its size in the 2015 timeframe (such as the high pressure ratio and turbine temperatures). Allowing an improvement of 5% in specific fuel consumption (sfc) from these general technology improvements by 2015 (see section 5.1.3), this would suggest an improvement of about 8-10% for the GTF-specific aspects of the concept.

In the longer timeframe (to 2025), a number of technical challenges would need to be overcome to produce even higher bypass ratios in larger engines, as fitted to long-haul aircraft (particularly the development of even larger gearboxes, or other means of avoiding the efficiency penalties of having the fan and LP turbine rotating at the same speed). If they are, it would be reasonable to assume that similar levels of improvement (8-10%) in fuel consumption could result from these developments for the larger aircraft.

<u>Unducted Fan (UDF)/Open Rotor</u>

Rear-mounted "open-rotor" engines (also known as unducted fans or UDF engines, UDF being a GE trademarked name for a specific technology demonstrator engine, the GE36) would offer reduced fuel consumption for short-haul applications due to their higher propulsive efficiency. UDF engines have been technically demonstrated, and are considered to be best suited for short to medium range aircraft. Variations of this concept have included the Progress D-27, with two rear-mounted contra-rotating prop-fans, which were used on the Antonov An-180, and were also used in a tractor configuration on the An-70. CFM International have also been researching next generation concepts, under the LEAP56 (Leading-Edge Aviation Propulsion), including open rotor research and counter-rotating fan technologies. From the early open rotor concepts, advances in technologies result in potential benefits greater than the initial designs, including:

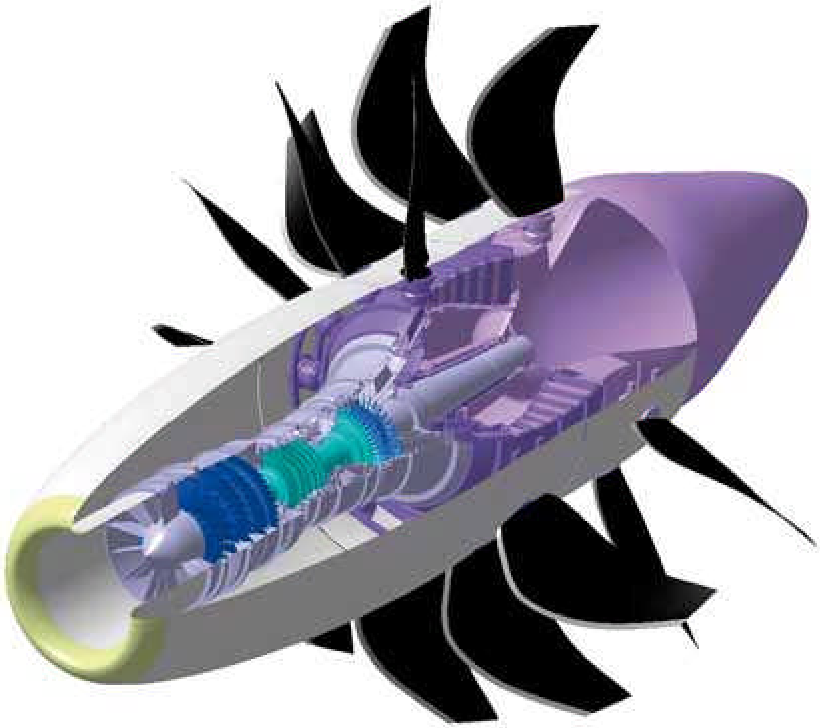
- Latest turbine and compressor technology, materials, and coatings, with improved aerodynamics and reduced cooling air requirements, resulting in improved efficiency and fuel consumption.
- Advanced propeller design with improved aerodynamics and pitch control.
- Today's lean burn combustor design provides reduced NOx emissions.
- New materials and manufacturing techniques result in reduced weight.

The configuration of the open rotor design can be in either the puller or pusher configuration, with propellers mounted in front or behind the engine respectively. These may also consist of a single propeller or contra rotating propellers; this latter approach can increase the effective thrust of the engine, although blade aerodynamic interactions can increase noise levels. An example of a contra rotating pusher engine is shown in Figure 58 below.

When first tested, the greatest problem with the UDF-style engines was the extremely high noise levels arising from the aerodynamic interaction effects of the contra-rotating fan blades. It is now considered that developments in technology since then will allow these noise problems to be overcome for regional and short-haul (e.g. Boeing 737/Airbus A320) aircraft. However, given the noise issues and the difficulties in integrating the large fan diameter with the rest of the aircraft, it is unlikely that such designs will be applied to larger, long-haul aircraft.

The improvements in fuel consumption and emissions from UDF engines are discussed in Section 5.3.1 of this report.

Figure 58 - Open Rotor Engine Cross-section. ©CFM International



5.1.9 Potential Effect on CO_2 Emissions (at Aircraft Type Level)

Incremental innovations in core engine technologies could cumulatively deliver thermodynamic and propulsive efficiency improvements equivalent to a fuel burn and CO_2 emission reduction of 6-10% by 2025. Engines due for entry into service in the middle of the next decade (exemplified by the GTF engine) on regional and short-haul airliners, have the potential to deliver reductions in fuel consumption of 12-15% relative to a 2005 baseline, with 8-10% of that being attributable to the GTF-specific elements. It is expected that improvements of a similar magnitude, due to the adoption of even higher bypass ratios, would be available for long-haul aircraft by 2025. As described in the previous sections there are a number of research activities that are aiming to contribute towards and achieve the ACARE 2020 targets, with a potential for reductions in CO_2 emissions of the order of 20% by 2020.

Beyond 2025, it would be expected that evolutionary improvements in engine fuel consumption and CO_2 emissions would continue, but probably at a reduced rate. In our expert opinion, a figure of 0.25 to 0.5% per annum overall improvement in fuel consumption would be reasonable, giving a reduction in fuel consumption of between 6 and 13% by 2050.

5.1.10 Conclusion

Engine technology is likely to continue to advance in a progressive manner, with each new generation of engine being more efficient and/or lighter weight than the previous one. Some particular technologies are likely to give additional step-change improvements. A summary of the improvements expected to 2050 is given in the following table.

Table 9 Summary of evolutionary CO_2 improvements to 2050

	Short Haul	**Long Haul**
Core engine technologies to 2015	3-5%	3-5%
GTF technology	8-10%	
Core engine technologies 2015 to 2025	3-5%	3-5%
Ultra-High Bypass Ratio technology		8-10%
Core engine technologies 2025 to 2050	6-13%	6-13%
Maximum achievable by 2050	**33%**	**33%**

The timing and rate of improvement will be dependent on commercial drivers, primarily costs (of fuel and engine development), market forces and legislation.

5.2 Airframe Technology

5.2.1 Introduction

Airframe design has also benefited over many years from improvements in modelling (e.g. Computational Fluid Dynamics (CFD)), wind tunnel testing, aerodynamic theory and advanced materials. All have contributed to reducing weight or drag and delivered fuel and therefore CO_2 emissions savings. There are many programmes seeking to capture further efficiency improvements in the coming decades.

5.2.2 Current Technical Status and Future Development

In this section, weight reduction and drag reduction are examined separately – as far as that is practicable.

Weight Reduction: The principal means of achieving airframe weight reduction has been the gradual, but accelerating transition from the use of metallic alloys to lighter composite materials in aircraft structure.

In current production aircraft it is common to find wing and tail sections, and some propeller and rotor blades made from advanced composites, in addition to a significant quantity of the internal structure and fittings. The airframes of some smaller aircraft are made entirely from composites, as are the wing, tail and body panels of large commercial aircraft.

Each successive generation of airliners is incorporating ever greater proportions of composite materials within their structure. The weight saving in comparison with conventional metal alloys is in the order of 20%. Composite materials make up approximately 12% of the B777, while nearly 50% of the operating weight of the B787 Dreamliner comprises such materials, making it considerably lighter than other aircraft of a comparable capacity. Boeing claims that the B787 will be 20% more fuel efficient than today's similarly sized aircraft flying comparable missions, and 27% more fuel efficient than the types it will supersede[7]. Airbus also has similar development programmes for composite materials.

The increased use of high specific strength materials such as carbon fibre reinforced plastics and the tailorability of composite materials also lead to more efficient structural design.

Although composite materials offer significant advantages, the initial investment in their development and certification is high while safe disposal of scrap material remains an active environmental issue.

Further applications for new light weight materials include aircraft cabin fittings, which may have potential for additional weight savings. However, development and certification costs may make this less attractive to manufacturers.

The full benefits of lighter materials will not be realised initially because of two factors; lack of in-service history and the need to manage composite and metal aircraft in a single maintenance system.

Lack of in-service experience with composites simply leads to heavier, less efficient design due to the need for greater conservatism.

The situation is more complex with maintenance. Civil aircraft structural safety is assured on the basis that visible damage is repaired and invisible damage has a safe life as least as long as the interval to the next inspection and maintenance check that would detect it. Unfortunately, composites are vulnerable to damage that is not visible on the outer surface of the component. Impact damage, for instance, will manifest as a significant feature on the rear of a panel, leaving the other surface unchanged. As a consequence, design for damage tolerance in composites has to be much more conservative than in metals.

Both issues could be tackled through the application of Structural Health Monitoring equipment to monitor behaviour in service and detect damage. However such systems add weight and are currently insufficiently sensitive to characterise damage. However, through successful development and implementation of techniques involving active maintenance, systems and structural health monitoring, airframers may obtain further added-value and sustainability benefits, specifically:

(1) ability to maintain on condition, reducing the need for damage tolerance margins in design;

[7] Not all these improvements can be attributed to weight reductions

(2) improved maintenance efficiency and availability through directing in depth inspections to areas of concern or permanently instrumenting vulnerable areas of structure[8]; and

(3) more efficient future structures by optimisation of design margins (estimation for further cost & weight reductions may be up to 15%, hence reducing CO_2 emissions, depending on rate of take-up of primary composite structures, and fuel consumption savings of up to 12% through design weight optimization).

Lift/Drag Ratio Improvement: There are a number of mechanisms through which an aircraft's lift/drag (L/D) ratio might be improved. Some such as increasing wing span and reducing vortex drag have limited potential.

Devices such as winglets are used to improve the L/D ratio and although adding some weight, these wingtip devices do provide an overall aerodynamic advantage in some applications. Riblets are also used to weaken the effects of turbulence over a wing and hence reducing the associated drag. These are small items, usually a plastic skin, that are bonded to the wing surface. In some applications the use of riblets can potentially reduce drag by around 2%.

Improved aerodynamic design and shape of the aircraft can also be used to optimise the efficiency of the platform, enabling a smoother boundary layer across the surfaces, resulting in reduced drag.

Longer-term solutions include laminar flow control and more radical blended-wing-body (BWB) architectures; this latter item is covered later under Potential Step Changing Concepts.

Extending the laminar flow over an aircraft surface reduces the drag; and to achieve this there are two types of laminar flow control, passive and active. Passive control involves designing the surface such that the pressure decreases in the flow direction, whereas active control involves the use of suction or surface cooling to maintain laminar flow. Some predictions for the use of laminar flow control suggest a fuel burn reduction for medium range aircraft in the region of 15%.

On a typical transonic wing, a 25% run of laminar flow on the upper and lower surfaces will result in approximately a 25% reduction in profile drag. The net benefit of such an improvement will depend on the effort (cost) for achieving the laminar flow, and on how fully the benefit is exploited in terms of sizing the aircraft. Earlier studies have suggested the potential for up to 10-20% reductions in block-fuel consumption as a result of laminar flow. The Boeing 787 was designed to achieve extended laminar flow on the nacelles. This is the first application of laminar flow control to large commercial transports.

5.2.3 Improved Lift/Drag - EU Research Programmes

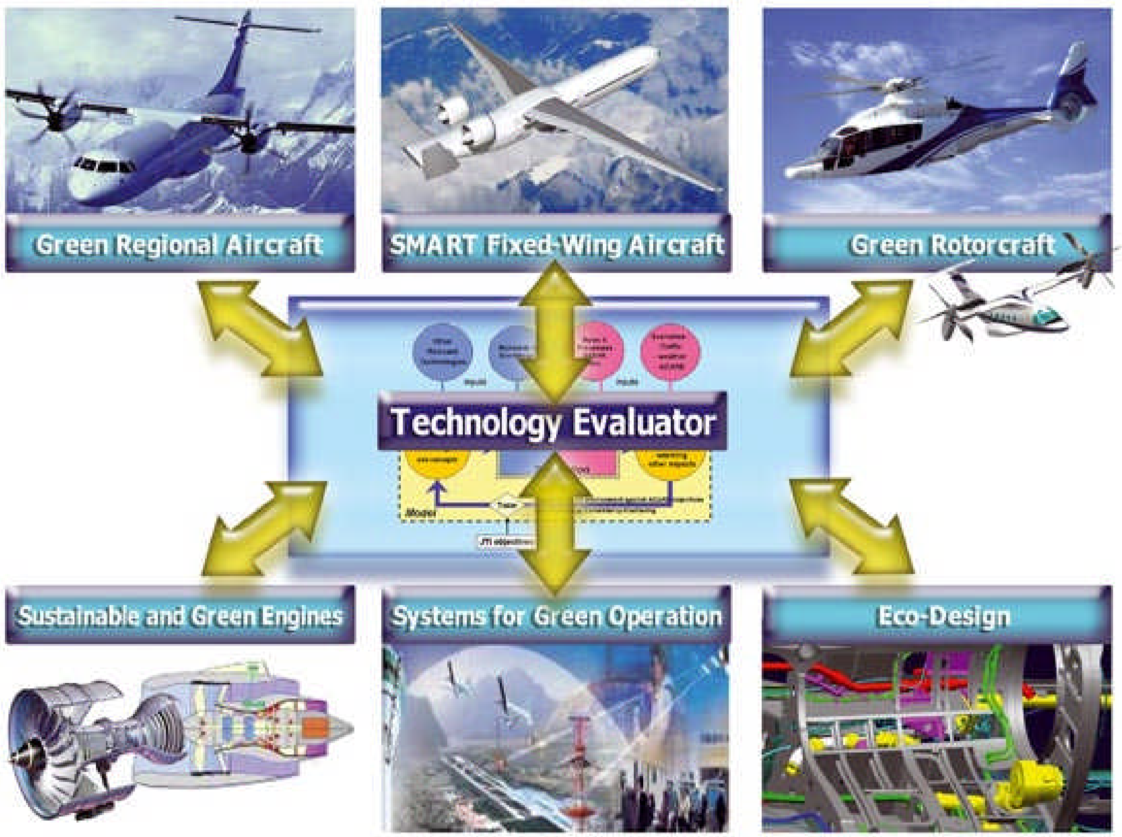
A number of EU Research Programmes are currently underway, investigating potential improvements in aircraft performance, leading to reductions in fuel consumption (and hence of CO_2 emissions). These programmes include Next Generation Composite Wing (NGCW), Integrated Wing, More Affordable Aircraft

[8] There is no structural weight saving through improved maintenance but a possible small effect on CO_2 emissions due to reduced flights back to maintenance bases for diagnosis and less transport of unnecessary spares

structure lifecycle through eXtended, Integrated, & Mature nUmerical Sizing (MAAXIMUS) and New Aircraft Concept Research (NACRE).

In the Clean Sky JTI programme, there are six areas that currently make up the "Clean Sky" programme: *SMART Fixed Wing Aircraft (SFWA), Green Regional Aircraft, Green Rotorcraft, Sustainable and Green Engines, Systems for Green Operations,* and *Eco-Design.* As shown in the CLEAN SKY overview:

Figure 59 - "Clean Sky" Focus Areas ©CLEAN SKY



The most relevant strands in the context of this study into CO_2 abatement opportunities are the SMART Fixed Wing Aircraft (SWFA), Green Regional Aircraft and Sustainable and Green Engines.

The SFWA programme is working towards a goal of a 10-20% reduction in fuel burn and CO_2 emissions for medium to long range aircraft relative to 2000 levels. The programme encompasses passive and active flow and load control technologies for new wing designs and taking engine technologies such as the geared turbofan to higher levels of maturity, including the assessment of changes to aircraft architecture which may ultimately result.

Green Regional Aircraft is aimed at delivering a low-weight aircraft using smart structures, and the integration of technology developed in other programmes, such as engines, energy management and new system architectures, with consideration of the technologies that may be most complementary to the emissions reduction goals set for regional aircraft entering the market in the 2020s.

5.2.4 Potential Effect on CO_2 Emissions (at Aircraft Type Level)

Weight Reduction: Based on the available information and analysis, it is estimated that reductions in fuel consumption of the order of 10-20% are available from weight reduction through use of lighter materials, in the medium term. In addition, it is considered that reductions perhaps up to 12% are available through optimisation of structure in the same medium term (2025).

Improved Lift/Drag; Improvements in aerodynamics could reduce drag by around 10%. There is potential for 20 - 30% reduction in fuel burn, through developments in airframe technologies.

5.2.5 Conclusion

As with engine technologies there is a large amount of research and development being performed on airframe technologies to continually improve aircraft efficiency with a view to reducing the emissions produced. Trying to achieve these goals while optimising the trade off between a number of key parameters and within cost restrictions is a complex and challenging process. Output from the technologies and research activities will feed a steady line of improvements in to the aviation environment; a large scale, step change, improvement will be a longer term focus.

5.3 Potential Step Changing Concepts

5.3.1 Prop Fans or Unducted Fans (UDF)

Current ducted fans are restricted by the trade off between increased diameter and weight and drag (nacelle etc), hence the unducted, prop-fan concept. Developed through the 1970s, driven mainly by increasing fuel costs, the UDF concepts were demonstrated in the late 1980s, however, the subsequent fall in fuel prices reduced the priority and uptake of this engine type.

Developments in propeller design have improved to allow increased efficiency at high airspeeds.

Open Rotor: Rear-mounted “open-rotor” engines (also known as unducted fans (UDF)), would offer better fuel burn performance for short-haul flying due to their higher propulsive efficiency. To maximize the potential, in terms of efficiency, it is likely that engine/airframe integration will need careful consideration at the design stage by the manufacturers involved, but could lead to a new aircraft design with significant reductions in emissions produced. Some companies believe that significant difficulties in fixing such large engines under the wings of a narrow-body aircraft would make rear-mounting the best solution and represent a new airframe configuration, possibly including canard wings. High rear-mounted engines may have implications for maintenance procedures, times and associated costs, in comparison the current popular under-wing engine configuration is very easily accessed for maintenance checks and work.

The easyJet ecoJet concept adopts an open rotor configuration and is claimed to reduce CO_2 by 50%, 25% of which is from the engine, 15% from the reduced weight of the airframe, and the remaining 10% by improvements to the Air Traffic Control. The putative benefits from this concept are yet to be proven.

General Electric, in collaboration with NASA, is reviving studies of the previous GE36 unducted fan, or "open rotor" concept and is also planning to launch the next-generation CF34 technology effort to develop families of fuel-saving engines.

Figure 60 - easyJet ecoJet design ©easyJet

A combination of an all-laminar flying wing powered by UDF engines could offer additional significant improvements in efficiency, although research into each of these concepts and the most effective integration continues.

The UDF engines offer the potential for improvements of over 15% reduction in fuel consumption for some applications, compared to current equivalent turbofan engines; some predictions are as high as 25-30% reductions for single aisle aircraft.

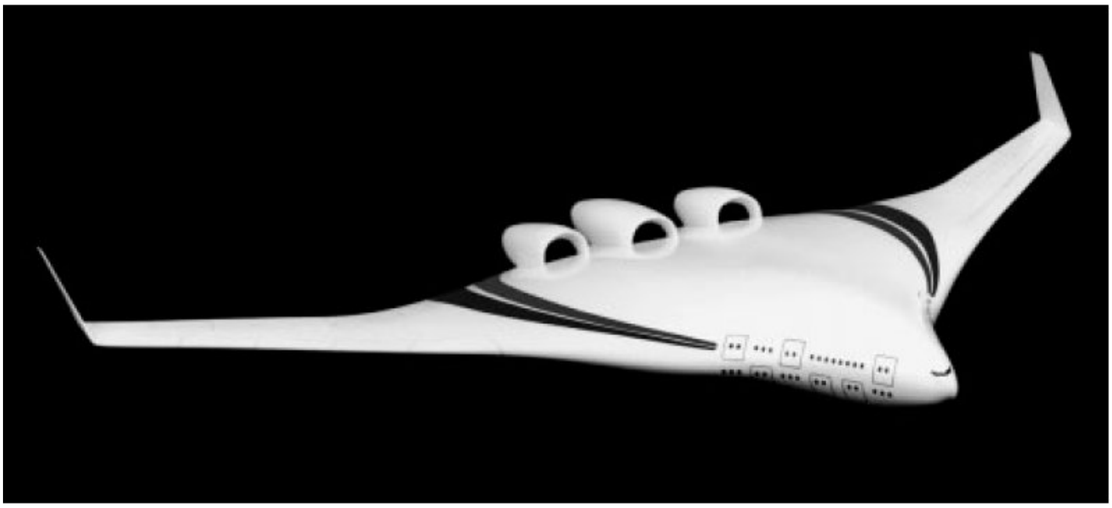
There is a high degree of expectation that the replacements for the Airbus A320 and Boeing 737, now expected in about 2024, will feature some form of advanced propulsion system, possibly of the UDF variety.

5.3.2 Blended Wing Bodies (BWB)

Blended Wing Body concepts have been considered for a number of years with increasing interest. BWB aircraft are defined as having a flattened and airfoil shaped body, with separate wing structures that are smoothly blended to the body; as compared to flying wings which are defined as having no separate body. Potential concepts include large passenger-carrying, long range aircraft.

Substantial research continues to be carried out into BWB concepts, with full wind tunnel modelling in some cases, notably NASA and Boeing. There is no doubt that technically a BWB aircraft could be developed for airline use and claimed figures suggest significant benefit over conventional aircraft of similar load, speed, and range. The benefits of the BWB design are greater aerodynamic efficiency (L/D ratio), reduced need for tail/fin surfaces, a more structurally efficient design, and high cruise altitude. This further extends with the inclusion of full laminar flow control. This is not a new idea; Handley Page had a laminar flow airliner concept in the early 1960’s.

Figure 61 - Computer Generated Model of the NASA BWB



The whole aircraft contributes significantly to lift generation (wings and body) resulting in higher aerodynamic efficiency. Studies focussed on longer range missions for larger aircraft claim savings up to 32% ([12] to [14]). However, for comparative technology levels, a widespread application of BWBs over a range of “wide-body” sizes and a range of mission lengths is estimated to realise fuel savings in the region of 20% [11].

There are many unresolved and contentious design and certification issues which impose a very high development tariff on a BWB project. These include:

- Accommodating the BWB at airports (wingspan wider than gate, deplaning), requiring infrastructure changes
- Public acceptability, with potentially no or few windows, very wide seating layout.
- For large variants with high number of passengers, evacuation in emergency is challenging relative to current regulatory requirements.

Each of these barriers is significantly reduced in freighter applications. However a question remains as to whether a large enough market exists to justify development.

5.4 Improvements to existing aircraft types

With an in-service life averaging 25 years for an individual airframe and total time in service from first entry to last retirement reaching up to 50 years for an aircraft type, there is potential for retrofitting and upgrading existing aircraft systems as technology becomes available. This section reviews a number of technical improvements to airframe and engine as well as summarising operational and maintenance issues.

Improvements to existing airframe types may be through two mechanisms – retrofits onto existing airframes or upgrades to new build aircraft. The latter may results in a changed variant number for the aircraft or not. The scope for such improvements is clearly greater for new build aircraft than for existing airframes – additional changes may be necessary to include the new technology (e.g. the addition of winglets may require modifications to the wing structure to support them) and the expected service life will be longer, giving more time to repay the investment. Nonetheless, there are examples of retrofits of airframe and engine technology to existing aircraft.

The drivers to implement new technology on existing types will vary with the economic climate. Significant rises in fuel price may encourage the adoption of new technology on existing types as the time and cost to implement them will be very much less than the development of a completely new type. For the present discussion, the assumptions will be that of a central case, or business-as-usual, scenario. Additional options would become available in other scenarios.

Although there are some cases of changes to an airframe design, the majority of continuing improvements to an aircraft type occur through changes to the engines. For new build aircraft, these improvements can be incorporated as soon as they become available (provided that any required modifications to the structure or airframe-engine interface are already designed). For a retrofit to an existing airframe, they are more likely to occur when the engine would be removed anyway, which may entail a wait of several years.

The CFM International CFM56 fitted to the initial examples of the Airbus A320 was the CFM56-5A1, which was certificated in 1988. More recent examples of the aircraft may be fitted with the CFM56-5B4/P, which features 3D design technology in the high-pressure compressor (HPC) and the high- and low-pressure turbines (HPT and LPT). This technology is stated to improve the specific fuel consumption by 3%. This engine was certificated in 1996, giving a rate of improvement of 0.38% per annum. A further improvement, known as the Tech Insertion package, became available in 2004 and offered a further 0.5 to 0.8% improvement in fuel consumption. Overall, this results in an average improvement rate of up to 0.24% over 16 years.

Similarly, the CFM engines fitted to the Boeing 737 aircraft improved from the CFM56-3 to the CFM56-7B, giving improvements of 7% in specific fuel consumption with 13 years between the certification dates on the two engine types. This gives an annual improvement of 0.56%. However, in this case the more recent engine was fitted to an upgraded airframe (the “Next Generation 737”), so this improvement is embedded in the differences between the two aircraft types. A further evolution of the -7B engine is expected to contribute about half of a 2% improvement in fuel consumption for the Boeing 737 by 2011.

The Rolls-Royce Trent 900 engine entered service on the Airbus A380 in 2008. Rolls-Royce have now announced a performance improvement package, to produce the Trent 900EP, with an entry into service date of 2012. This package will use compressor technology from the Trent 100 engine and is expected to give a 1% improvement in fuel consumption. This, therefore, gives an average 0.25% improvement per annum.

Other historic engine improvements can be seen in the Pratt & Whitney JT8D engines fitted to the MD80 series aircraft. Between October 1980 and February 1986 the engine fuel consumption was improved by 2% (in the change from the JT8D-217A to the JT8D-217C), giving an average of 0.45% p/a.

On the airframe side, Airbus has recently announced the availability of “Sharklet” winglets on new build A320 aircraft from late 2012. These are expected to give a 3.5% improvement in fuel burn (an average of 0.15% p/a since the types introduction into service in 1988), but will only be available on new build aircraft because of the strengthening required to the wing structure.

In September 2008, Boeing announced a Performance Improvement package (PIP) for its 777 model, incorporating improvements to the wing aerodynamics. This was expected to give a 1% improvement in fuel consumption and is available for retrofit as well as being the standard for new build aircraft. The 777 entered service in 1995, so this represents an annual improvement of nearly 0.1%.

Overall, it is clear that aircraft designs tend to receive improvements to their performance during their production lifetime. Some of the improvements in fuel consumption will be offset by increases in weight (due, for example, to the fitment of heavier cabin furnishings and in-flight entertainment systems during cabin refurbishments). Nonetheless, it seems reasonable to suggest an annual 0.25% improvement in fuel consumption for an aircraft type.

Whether this improvement should be applied to all types in the forecast is less clear. Although the improvements are sometimes applied to existing airframes as a retrofit, the majority of improvements are only introduced on new build aircraft. The improvement should, therefore be applied to replacement aircraft as they enter the fleet.

5.5 Overall Fuel Efficiency Development to 2050

Many of the technology developments discussed in this section are expected to contribute to improving aircraft fuel efficiency by 2025, with a major portion of that available before 2020. Thus, these technologies will provide the improvements necessary to achieve the ACARE 2020 Vision.

Beyond 2025, the only major change in aircraft configuration identified so far is the potential introduction of the blended wing body design. Although there has been, and continues to be, considerable research into this concept, it is less clear when such a design might enter service. Most of the problems with introducing such an aircraft, as described above, are more to do with infrastructure and public acceptability than with the aircraft technology. Thus, it is unlikely that such an aircraft will enter service before the 2030-2040 timeframe.

It is expected that engine technology will continue to evolve, even after the introduction of step-changes such as open rotor designs, probably by 0.25 to 0.5% per annum (see Section 5.1.9). Assuming similar incremental improvements in airframe technologies, it would be expected that total improvements of 0.5 to 1.0% per annum should be achievable. Assuming the achievement of the ACARE target of a 40% improvement in aircraft fuel efficiency (the other 10% of the ACARE target of 50% is attributed to improvements in the Air Traffic Management system) compared to a 2005 baseline, this would imply a reduction of 48.4% to 55.6% for new aircraft entering service in 2050, compared to the same baseline.

For the implementation of these continuing improvements, it is recommended that new aircraft types are created, using the same classes as for the ACARE-compliant types, with initial dates of 2030 and 2040. Assuming an average of 0.75% per annum improvement in aircraft technology, these new types would have fuel burns of 92.75% and 86.0% of the relevant ACARE-2020-compliant types on initial entry into service. The current ACARE-compliant types do not include an aircraft in Class 6 (over 500 seats). It is recommended that a new aircraft type is generated for this class for 2030 and 2040, using the same factors applied to the Airbus A380 aircraft.

In addition to these factors, it is recommended that continuing improvements are applied to these types at a rate of 0.25% per year, so (for example) aircraft entering service in 2035 will have fuel burns of 0.9975 to the power of 5 (=98.76%) times the 2030 type.

The aircraft fuel efficiency improvements to 2050, and the recommendations for their implementation in the methodology, are summarised in the following two tables.

Table 10 Summary of future aircraft technology efficiency improvements

Technology	Efficiency Improvement Lower Bound	Efficiency Improvement Upper Bound	Entry Into Service Date
Core Engine Technologies to 2015	3%	5%	
Core Engine Technologies 2015 to 2025	3%	5%	
Geared TurboFan Technology	8%	10%	2015
Ultra High Bypass Ratio Technology	8%	10%	2025
Core Engine Technologies 2025 to 2050	6%	13%	
Airframe Weight Reduction (including composite structures)	10%	20%	2025
Structure Optimisation	0%	12%	2025
Improved Aerodynamics (including laminar flow technology)	5%	20%	2030
Open Rotor Engines	12%	30%	2025
Blended-Wing-Body Aircraft	16%	32%	2040

Table 11 Fuel burn of future generations of aircraft relative to the Year 2000 baseline

Seat Class	Base Aircraft	Fuel Burn Reduction relative to Base	
		2030 Aircraft	2040 Aircraft
1	ATR42-300	44.35%	48.40%
2	Boeing 737-400	44.35%	48.40%
3	Boeing 757-200	44.35%	48.40%
4	Boeing 777-200	44.35%	48.40%
5 – Twin Engined	Average of Boeing 777-200 and Airbus A340	44.35%	48.40%
5 – Four Engined	Boeing 747-400	44.35%	48.40%
6	Airbus A380	44.35%	48.40%
All Classes	Ongoing annual improvement to new-build aircraft		0.25%

6 Modifications to Method

The current method for calculating fuel burn (and CO_2 emissions) for a future fleet starts by assigning operations to an aircraft type, then to a “representative” type from CORINAIR. The fuel burn for each operation is then calculated using the distance between the departure and arrival airports together with curves fitted to the CORINAIR data for the representative type. Additional factors may then be applied to account for air traffic management inefficiencies and other influences on the fuel burn. The CO_2 emission is calculated by applying a standard factor (3.15) to the fuel burn.

This approach is fundamentally sound and its continued use is supported. However, there are some changes to the detail of the calculation that are recommended to improve its accuracy and fidelity. These recommendations are discussed here.

6.1 Supply Pool

The supply pool for introducing aircraft to the future fleets should be reviewed with a view to updating the entry-into-service and out-of-production dates for specific aircraft types.

- The Airbus A340-300 should not be available after 2008
- The Airbus A340-600 should not be available after 2012
- The Boeing 777-200 and 777-300 (other than the -200LR and -300ER variants) should not be available after 2020
- New variants of the Airbus A320 and Boeing 737 series aircraft should be created with an availability date for entering the fleet of 2016
- It would be sensible to delay the introduction of the ACARE-compliant aircraft in Classes 2 and 3 until 2024, with the Airbus A320 and Boeing 737 series ceasing to be available after 2026
- The Boeing 787 should be available to enter the fleet from 2011
- The Boeing 747-8 should enter the supply pool from 2012 and should represent 20% of the supply for the seat class (Class 5).
- The Bombardier C Series should be available to enter the fleet from 2013

6.2 Fuel burn calculation for existing and near-term future types

The CORINAIR dataset should continue to be used for the calculation of fuel burn for existing types, though the following adjustments are recommended.

- The A320 should have its fuel burn raised by 4.2% relative to the CORINAIR data
- A new A321 aircraft should be created, with a fuel burn equal to the “new” A320 plus 15.8%
- A new A319 aircraft should be created, with a fuel burn equal to the “new” A320 minus 4.2%

- A new Boeing 737-600 aircraft should be created, with a fuel burn equal to the 737-400 minus 12.2%
- A new Boeing 737-700 should be created, with a fuel burn equal to the 737-400 minus 5%
- The Boeing 737-800 and 737-900 aircraft should continue to be treated as an Airbus A320, but using the "new" fuel burn data
- The new variants of the Airbus A320 and Boeing 737 families, to be introduced from 2016, should have their fuel burn set to the equivalent "pre-2016" variants minus 15%
- The Boeing 767 should have its fuel burn raised by 7% relative to the CORINAIR data
- A new Boeing 777-300ER aircraft should be created, with a fuel burn equal to the 777-200 plus 12%.
- A new Airbus A340-600 aircraft should be created, with a fuel burn equal to the A340 plus 36%
- A new Airbus A380 aircraft should be created, with a fuel burn equal to the Boeing 747-400 plus 15.5%
- A new Airbus A350 aircraft should be created, with a fuel burn equal to the "new" Boeing 767 plus 7%. This model should be used for all variants of the A350.
- A new Boeing 787 aircraft should be created. The fuel burn vs. distance data should be derived using the PIANO-X model for the Boeing 787-8. This should be used to represent all Boeing 787 variants.
- The Boeing 747-8 aircraft should be modelled using the Boeing 747-400 data.
- A new Bombardier C Series aircraft should be created, with a fuel burn equal to the new (but still "pre-2016") A319 minus 20%

6.3 Fuel burn calculation for longer-term future types

The continued use of the ACARE-compliant type fuel burn data is supported. Note that none of the aircraft from which these data were derived are required to have their fuel burn data modified in the above paragraphs

For forecasts beyond year 2030, new aircraft should be created as follows.

- New "2030 Generation" aircraft should be created in each seat class, with a first availability of 2030. The aircraft in classes 1 to 5 (twin and four-engined) should have their fuel burn set to the ACARE-compliant types minus 7.25%. The class 6 aircraft should have its fuel burn set to that of the A380 minus 7.25%
- New "2040 Generation" aircraft should be created in each seat class, with a first availability of 2040. The aircraft in classes 1 to 5 (twin and four-engined) should have their fuel burn set to the ACARE-compliant types minus 14.0%. The class 6 aircraft should have its fuel burn set to that of the A380 minus 14.0%
- In each case, the fuel burn of new aircraft introduced to the fleet after the initial year should have their fuel burn reduced by 0.25% per annum

6.4 Curve fitting

The current approach uses curve fits to the CORINAIR data to simplify the calculation of fuel as a function of flight distance. As described in this report, some of these curve fits are not as good a fit to the underlying data as would be desired. The ideal means of improving the fit would be to replace the curve fits by an interpolation algorithm. However, it is recognised that this would considerably increase the complexity of the calculations so, assuming that the curve fits are retained, the following improvements are recommended.

- The Airbus A330, A340, Boeing 747-400, 767 and 777 aircraft should employ fifth order curve fits. The simplest approach would probably be to employ fifth order equations for the calculation of fuel burn for all aircraft types, but to set the coefficients for the fourth and fifth order terms to zero for aircraft that do not require modification.
- The linear extension equations should be modified for all aircraft so that the gradient is equal to that of a straight line fitted to the final three points in the underlying data. The intercept should then be calculated so that the straight line intercepts the cubic (or quintic) curve at the relevant transition range.

7 Review of Central Case Assumptions

As well as considering the central case scenario, on which the preceding sections were based, the intention behind this report is to consider alternative scenarios. To set these alternative scenarios in context, this section describes the assumptions underpinning the "Central Case", reviewed in this report.

The Central Case is essentially a "business as usual" case, with continued growth in demand for air travel expected, and the expansion of UK airport capacity in line with the recommendations in the 2003 Air Transport White Paper [15].

The forecast of unconstrained demand depends on projections of economic growth, trade, exchange rates and fares. The projections of economic growth are based on projections of GDP for the UK and other countries, derived from UK Treasury and IMF WEO forecasts respectively. UK consumer spending is then assumed to grow at a rate of 0.25% less than UK GDP. Trade is assumed to grow in line with GDP and exchange rates are assumed to remain at today's[9] levels. The forecasts of growth in air fares are derived from projections of fuel price, aircraft efficiencies and non-fuel costs. For the Central Case, it is assumed that oil prices vary in line with scenario 2 of the DECC's Fossil Fuel Price Assumptions communication [16]. In this, it is assumed that oil will drop from $102 per barrel in 2008 to $75 per barrel in 2015, then rise again to $90 per barrel in 2030 (all in 2008 prices). Additional passenger costs are applied so that they cover the contribution of aviation to climate change costs (Air Passenger Duty – APD – is included within these costs).

The unconstrained demand forecast is then modified to reflect the constraints of airport capacity, producing the constrained demand forecast. This uses the Passenger Airport Choice Model to forecast the choice of passengers for individual UK airports (based on work to explain and reproduce the current choices of airports). The assumptions on airport capacity in the central case include improvements to airport infrastructure to maximise use of existing runway capacity, a second runway at Stansted from 2015 and a third runway at Heathrow from 2020. The resulting constraints on capacity are forecast to limit the demand to 455mppa in 2030.

The conversion from constrained passenger movements to Air Traffic Movements (ATMs) is then performed using existing aircraft sizes and assumptions about the size of aircraft which replace the current aircraft as they are retired. The assumed age at which an aircraft is retired varies from type to type, but generally lies between 15 and 30 years.

The calculation of fuel burn and CO_2 emissions then uses the ATMs derived from the constrained demand forecast together with modelling of individual aircraft types, as described in Section 2.

The central case assumptions are summarised in Table 12.

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[9] In this context, "today" is defined as the average of the previous 12 months.

Table 12 Key assumptions for Central Case

Demand for air travel will continue to grow
Consumer spending grows at 0.25% less than UK GDP
Oil price in 2015 to be $75 per barrel
Oil price in 2030 to be $90 per barrel
Improvements to airport infrastructure to maximise the use of available capacity
A second runway at Stansted Airport from 2015
A third runway at Heathrow Airport from 2020
Aircraft retirement ages from 15 to 30 years

8 Assessments of Alternative Scenarios

Three scenarios have been assessed, as agreed with DfT:

- Scenario 1 reflects high (a) and low (b) oil price projections, in line with, respectively, scenarios 4 and 1 from the DECC communication on fossil fuel price assumptions [16].
- Scenario 2 reflects the lower end of the plausible range of fuel efficiency improvements to 2050.
- Scenario 3 reflects the upper end of the plausible range of fuel efficiency improvements to 2050.

The following sections cover these three scenarios in turn, covering the likely drivers for aircraft technology under these scenarios, together with recommendations for implementing them into the modelling.

The descriptions of likely efficiency improvements in the following sections are based on information in a report to the Committee on Climate Change [11]. The assumptions of the effects on entry into service dates and retirement ages are based on expert judgement, taking into account the time taken to develop new aircraft and the frequency of introduction of new types.

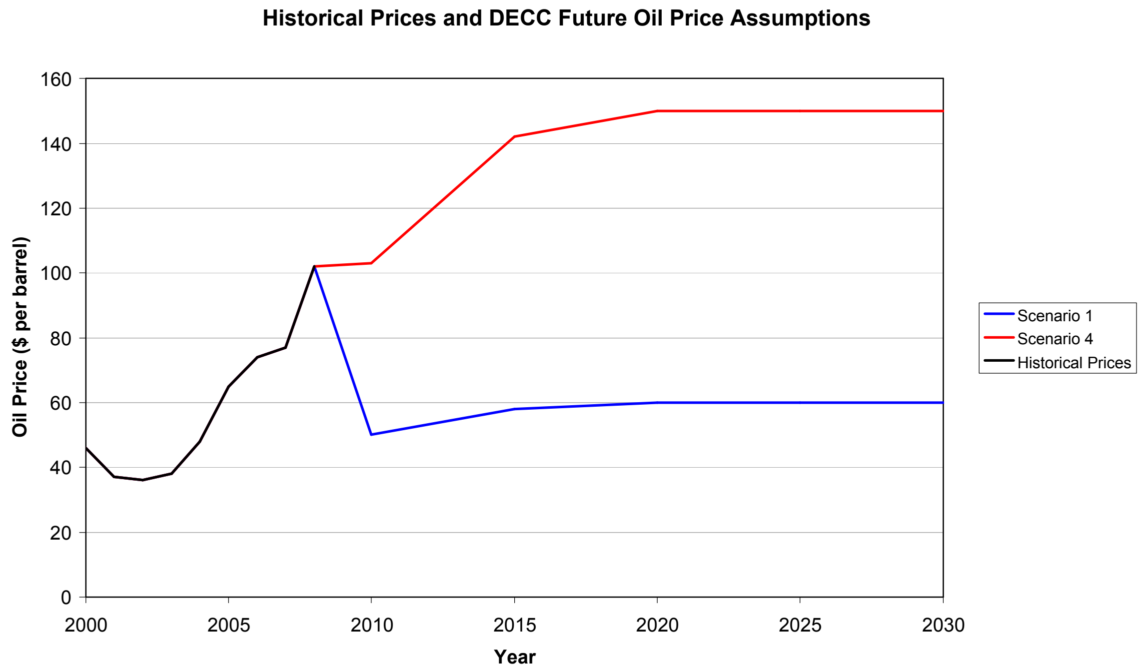
8.1 Scenario 1 – high and low oil price projections

This scenario uses fuel price projections from DECC's Fossil Fuel Price Assumptions communication [16]. While the DECC assumptions essentially cover the direct impact on oil price (and hence the price of aviation fuel), the resulting projections of price variations can also be used to represent the effects of other mechanisms for increasing the cost of using fuel, such as the increased costs of purchasing the required credits under the EU Emissions Trading System (EU ETS). However, none of the DECC scenarios would represent the case where high oil prices were accompanied by high levels of these other mechanisms.

The fossil fuel price assumptions showed a significant increase in the oil prices for the base year compared to DECC's previous set of assumptions [17] ($102 per barrel in 2008 [in 2008 prices], up from $73 in 2007 [in 2007 prices] from the previous set of assumptions). However, the longer term projections were relatively unchanged with, for example, the Scenario 4 price for 2030 being $150, the same as the High High scenario in the previous set of assumptions.

For the current discussion, Scenario 1a is based on Scenario 4 of the DECC document, with a projected price of $150 per barrel (in 2008 prices) in 2030 and Scenario 1b is based on Scenario 1 of the DECC document, with a projected price of $60 per barrel in 2030. From 2008 to 2030, these two sets of assumptions show an increase of 47% (an annual average of 1.8%) and a reduction of 41% (equating to an annual average of 2.4%), respectively.

Figure 62 DECC Oil Price Assumptions, scenarios 1 and 4, April 2009



The DECC assumptions on oil prices for their Scenarios 1 and 4 are shown in Figure 62. As can be seen, most of the changes from the current price occur before 2015, with relatively stable prices thereafter.

8.1.1 Scenario 1a – high oil price projection

According to information on the Air Transport Association website[10], fuel costs currently account for approximately 22% of an airline's operating costs (based on a 2nd Quarter 2009 fuel cost of $80.7 per barrel). The DfT's *UK Air Passenger Demand and CO_2 Forecasts* document (2009) [1] describes assumptions for the future development of non-fuel costs; for short-haul and domestic airlines they are assumed to reduce by 2.4% per annum from 2010 to 2015 and then by 1.9% p/a from 2015 to 2020, for long-haul airlines they are assumed to reduce by 1.6% p/a from 2010 to 2015 and 1.1% p/a from 2015-2020. In both cases, non-fuel costs are assumed to remain constant after 2020. Taking an average of these rates indicates a reduction of 16% in non-fuel costs between 2010 and 2020. Using this change in non-fuel costs and the DECC projections of fuel prices, by 2030 the central case scenario would result in fuel costs representing about 27% of the total operating costs in 2030. The DECC Scenario 4 assumptions would then increase this to approximately 39%.

It is difficult to determine with confidence the effect of such cost changes on the aircraft types which will be available and acquired by the airlines, as these depend on a wide variety of influences. If a fuel cost increase was temporary, followed by a drop back to current levels (as happened in the 1980s), there is a good chance that manufacturers would expend considerable sums on developing new technology but with little effect on the aircraft coming into service (again, like the 1980s, when there

[10] http://www.airlines.org/NR/rdonlyres/1DBE8E42-53BD-4ABF-9662-D71A6A9166C6/0/CostIndexTables.xls

was significant development of unducted fan, or open-rotor, engines which have still not penetrated the fleet significantly).

A similar example occurred in 2007-08, when oil prices were high and airlines passed most of the additional costs onto the passengers through fuel surcharges. This may have affected demand, but is unlikely to have had any impact on the development of new aircraft types.

The key element in this high oil price scenario is that the future oil price is predictably high and hence more likely to lead to an acceleration in the development of new technology and the acquisition of it by the airlines.

Given the timescales involved in developing a new aircraft, it is highly unlikely that any aircraft which is already in development, or being considered for imminent development, could be brought into service earlier than currently envisaged by a significant margin. Therefore, under the high oil price scenario, the acceleration of aircraft development and availability in the supply pool will only occur after about 2020. Equally, given the expectations for aircraft types expected to appear later this decade, it is unlikely that there would be any significant changes in the acquisition strategies of airlines before about 2016.

Beyond 2016, it is likely that airlines would respond to higher fuel prices by retiring their older aircraft early and replacing them with only the best available technology. As well as increasing demand for new aircraft types, this would significantly reduce demand for old (but still in production) types, leading to the end of production for the older types considerably earlier than currently anticipated. However, the effect of this on the fleet would be reduced due to the rapid drop in value of an airline's existing aircraft, thus leading to economic difficulties in disposing of old aircraft and replacing them with new ones. The precise effect of this on the fleet is related more to economic influences than technical ones, so is beyond the scope of the current report.

Given that most of the aircraft technology development envisaged under a "Central Case" scenario is already targeted at reducing fuel consumption, even after 2020 it is unlikely that a high oil price scenario would lead to significantly different technologies appearing; it would be more likely to lead to the same technologies appearing earlier. A possible exception to this could occur in regional aircraft (of up to 110 seats), where a strong emphasis on fuel consumption (and CO_2 emission) could lead to the development of larger turboprop aircraft to replace jet aircraft such as the Embraer 170, 190 and 195, provided that passengers and airlines would be willing to accept a small reduction in cruising speed and restricted range. Current turboprops, such as the Bombardier Dash 8 Q400 and the ATR72, are widely credited as offering around a 30% reduction in fuel burn compared to similar sized jet aircraft (see, for example, [18] and [19]) and it would be expected that a future advanced turboprop would offer a similar advantage over a future jet aircraft at this size. Therefore, when generating a CO_2 forecast for a high oil price scenario, it would be sensible to introduce an additional aircraft type, entering service from 2020, similar to the current ACARE-2020-compliant Seat Class 2 aircraft, but with turboprop engines and a fuel burn reduced by 25%. To reflect the turboprop nature of the type, the range should be limited to 1500nm. This would give the aircraft a fuel burn approximately 17% lower than the existing Bombardier Dash 8 Q400 (based on the CORINAIR data) for a 40% increase in passenger numbers.

Thus, for this high oil price scenario, based on DECC Scenario 4, it would be reasonable to assume that new aircraft types, such as the ACARE 2020-compliant types (including the new turboprop type in Seat Class 2), the 2030 types and the

2040 types, would be available earlier than currently anticipated. Given that the ACARE-2020 compliant types are currently scheduled to enter the supply pool in ten years time and that additional new generations are then due to enter the pool ten and twenty years later, it would be reasonable to expect that the entry into service of these types could be brought forward by two years under the scenario discussed above. These types would then enter the supply pool more rapidly than under the central case scenario, achieving 100% of their market share after 10 years of production. The airlines would be expected to retire older aircraft earlier, probably by four years relative to the central case assumptions.

<u>Summary</u>

For Scenario 1a (high oil price projection), it would be reasonable to assume that new aircraft types, such as the ACARE 2020-compliant types, the 2030 types and the 2040 types, would be available two years earlier than under the Central Case. They would then enter the supply pool more rapidly, achieving 100% of their market share after 10 years of production. In Seat Class 2, an additional new aircraft should be created, with similar characteristics to the ACARE-2020 aircraft but using turboprop engines. The fuel burn of this new type should be set to 75% of the ACARE-2020 jet type. The maximum range should be set to 1500nm. This new turboprop type should take 50% of the market for the ACARE-2020 type in this seat class (with the jet type, as currently modelled, taking the other 50%). The retirement ages of aircraft types should be reduced by four years compared to the Central Case.

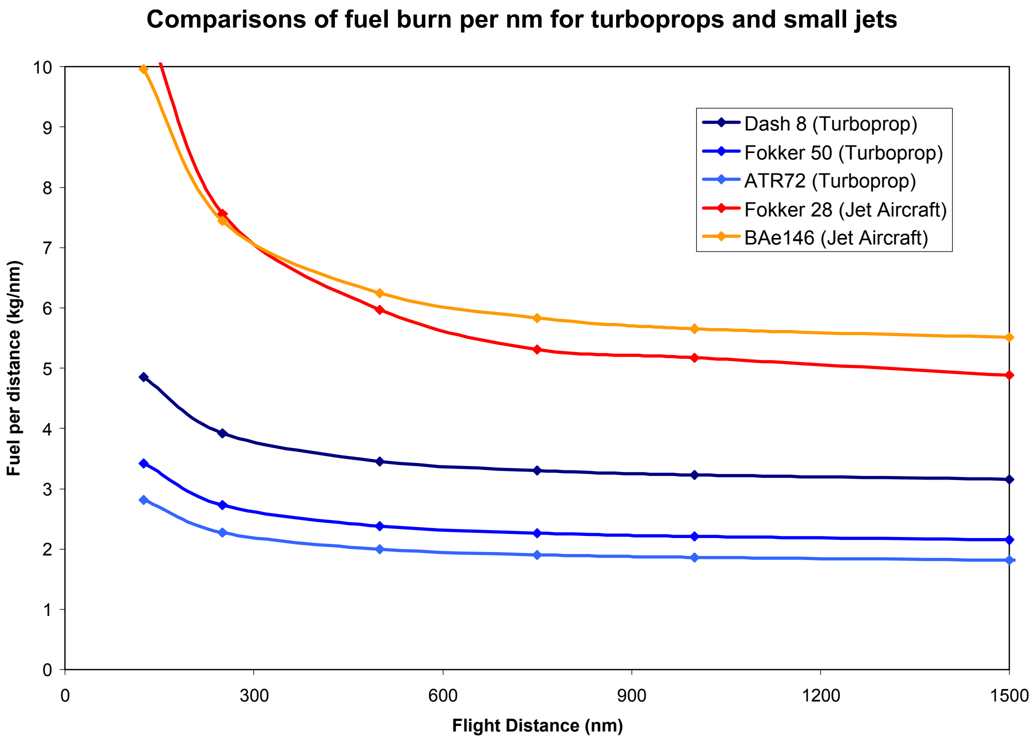
8.1.2 Scenario 1b – low oil price projection

Using a similar analysis of fuel prices to that discussed in Section 8.1.1, the DECC Scenario 1 assumptions would reduce the fraction of airlines' costs attributed to fuel from 27% (for the central case) to approximately 20%.

Under such a scenario, the incentives to replace aircraft would be reduced, and the development of new technologies would be slowed. When aircraft are retired, old (but still in production) aircraft types would be an attractive option as replacement, as the initial purchase price would be expected to be lower than the newer technology types. Thus, many existing types would continue in production (and hence be available in the supply pool) longer than under the central case. Nonetheless, there would still be competition among the major manufacturers, so technological progress would be made but it would be expected to enter service later than under the central case.

It is unlikely that new turboprop aircraft would be built at the larger sizes (e.g. 110 seats) as there would be little cost advantage arising from the reduced fuel burn and customer preference is likely to always be for jet aircraft. Indeed, such a scenario could lead to the re-appearance of jet aircraft in the 50-70 seat class, such as the Bombardier RJ-700 and the Embraer ERJ-145 and 170, with a slightly higher fuel burn that today's turboprop aircraft. For the CO_2 forecasts, these jet aircraft are modelled using data for the Fokker 28 or the BAe146. A comparison of the fuel burn between these two types and some turboprop types is shown in Figure 63.

Figure 63 Comparisons of fuel burn between turboprop types and small jets



The difference between the fuel burn between the jets and turboprops can be seen, though it should be noted that the BAe146 is larger than the other types.

<u>Summary</u>

For Scenario 1b (low oil price projection), it would be reasonable to increase the retirement ages of all aircraft types by two years and delay the introduction into the supply pool of the ACARE-compliant (2020, 2030 and 2040) types by two years. The rate at which these new aircraft enter the supply pool should be unchanged from that for the Central Case. Similarly, the dates at which aircraft types are removed from the supply pool should be extended by two years. In Seat Class 1, the existing small jet types, the RJ-700, ERJ145 and 170, should have their dates of removal from the supply pool extended by five years.

8.2 Scenario 2 – Lower bound of fuel efficiency improvements

This scenario addresses what the results would be of future aircraft technologies achieving the lower end of plausible bounds.

The technologies applicable to future aircraft types, derived from information in a report to the Committee on Climate Change [11] and discussed further in Section 5, include evolutionary enhancements to conventional engines, Geared TurboFan engines, Ultra-High Bypass Ratio engines, open rotor engines, composite structures, weight reduction, improved aerodynamics and blended wing body aircraft. The potential improvements in fuel burn arising from these technologies relative to a 2006 baseline, and their likely dates of introduction, are shown in the following table. In this table, “core engine technologies” includes increases in engine pressure ratio and maximum temperatures, together with enhancements to component efficiencies (through improved aerodynamics, for example).

Table 13 Lower bounds for potential airframe and engine technology improvements

Technology	Efficiency Improvement Lower Bound	Entry Into Service Date
Core Engine Technologies to 2015	3%	
Core Engine Technologies 2015 to 2025	3%	
Geared TurboFan Technology	8%	2015
Ultra High Bypass Ratio Technology	8%	2025
Core Engine Technologies 2025 to 2050	6%	
Airframe Weight Reduction (including composite structures)	10%	2025
Structure Optimisation	0%	2025
Improved Aerodynamics (including laminar flow technology)	5%	2030
Open Rotor Engines	12%	2025
Blended-Wing-Body Aircraft	16%	2040

It should be noted that not all of these technologies can be exploited on a single airframe. For example, geared turbofans and open rotor engines are both likely to appear on single-aisle aircraft, while ultra-high bypass ratio engines will appear on twin-aisle aircraft.

From the foregoing, it is possible to estimate minimum technological advances that would be expected on new aircraft in different future years. The data in Table 13 are relative to a base year of 2006, whereas the ACARE 2020 target is relative to a base year of 2000. Therefore, there is a need to account for the years from 2000 to 2006. The data that would be calculated from Table 13 for the period 2006 to 2020 give average improvements of 1.7% and 1.3% per annum for single aisle and twin aisle aircraft respectively. Therefore, as a conservative estimate, an improvement rate of 1% per annum has been applied for the period from 2000 to 2006 to calculate the data in Table 14.

Table 14 Lower bound of likely efficiency improvements, given the adoption of all measures in Table 13

Year	Single Aisle	Twin Aisle
2020	25.8% [(a)]	21.7% [(e)]
2030	34.1% [(b)]	31.2% [(f)]
2040	35.7% [(c)]	43.6% [(g)]
2050	37.3% [(d)]	45.0% [(h)]

Notes
(a) Core Engine Technologies (to 2015) + 0.5xCore Engine Technologies (2015 to 2025) + Geared TurboFan + 0.8xComposite Airframe + 0.5xImproved Aerodynamics
(b) Core Engine Technologies (to 2015) + Core Engine Technologies (2015 to 2025) + 0.2xCore Engine Technologies (2025 to 2050) + Open Rotor + Composite Structure + Improved Aerodynamics
(c) Core Engine Technologies (to 2015) + Core Engine Technologies (2015 to 2025) + 0.6xCore Engine Technologies (2025 to 2050) + Open Rotor + Composite Structure + Improved Aerodynamics
(d) Core Engine Technologies (to 2015) + Core Engine Technologies (2015 to 2025) + Core Engine Technologies (2025 to 2050) + Open Rotor + Composite Structure + Improved Aerodynamics
(e) Core Engine Technologies (to 2015) + 0.5xCore Engine Technologies (2015 to 2025) + 0.8xComposite Airframe + 0.5xImproved Aerodynamics
(f) Core Engine Technologies (to 2015) + Core Engine Technologies (2015 to 2025) + 0.2xCore Engine Technologies (2025 to 2050) + Ultra-High Bypass Ratio + Composite Structure + Improved Aerodynamics
(g) Core Engine Technologies (to 2015) + Core Engine Technologies (2015 to 2025) + 0.6xCore Engine Technologies (2025 to 2050) + Ultra-High Bypass Ratio + Composite Structure + Improved Aerodynamics + Blended Wing Body
(h) Core Engine Technologies (to 2015) + Core Engine Technologies (2015 to 2025) + Core Engine Technologies (2025 to 2050) + Ultra-High Bypass Ratio + Composite Structure + Improved Aerodynamics + Blended Wing Body

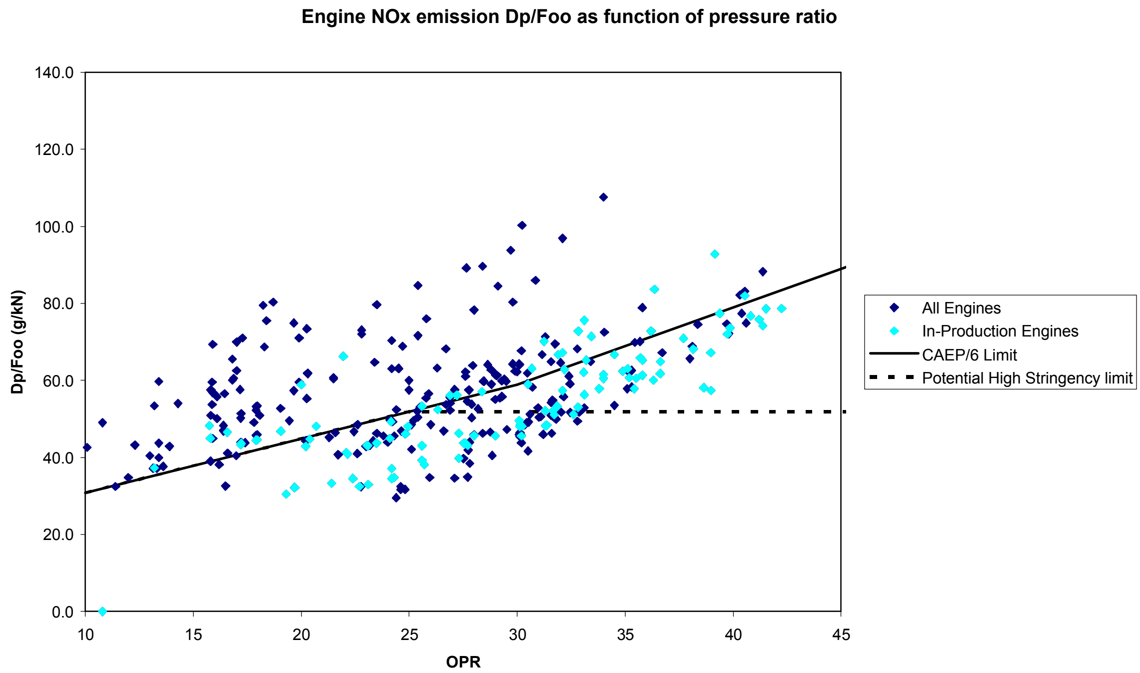
The values in Table 14 represent reasonable lower bounds of the efficiency improvements, assuming that the technologies are implemented on the aircraft. Evidently, under some scenarios, the incentives to include certain technologies would be reduced, so they might not appear on aircraft, reducing the improvements in efficiency.

There are a number of conditions which could give rise to low levels of efficiency improvements. An ongoing global financial crisis (or very slow recovery from the present one) would give rise to a reduced demand and cause the financial position of airlines to continue to be difficult. This would lead to a reduced demand for new aircraft and, hence, less money and resources available for technology development. Existing airframes would be retired later, new technology would appear later and existing types would be produced for longer.

A situation where noise issues dominate aircraft development (even over fuel consumption and CO_2 emissions) would result in new aircraft being developed, but without the full fuel reduction technology that would otherwise be available. Open rotor engines would, almost certainly, not be developed and greater emphasis would be placed on reducing the noise from turbofans (whether geared turbofans or ultra-high bypass ratio varieties). The requirement to reduce the noise made by the fan would lead to larger engine diameters, giving rise to greater mass and drag. The need to manage jet noise around airports while still providing adequate performance during cruise, might require greater variability in the engine nozzle diameters, increasing engine complexity and mass. These changes would reduce the improvements that would otherwise be made to fuel efficiency.

Another example would be a situation where local air quality issues (particularly oxides of nitrogen – NOx) dominate. This would allow the open rotor engines to be developed, but would limit the increases in engine pressure ratio that would be possible and hence reduce the engine efficiency improvements achievable. The following figure shows all engines currently in the ICAO Engine Emissions DataBank (EEDB) [20], with the in-production engines highlighted, as a plot of the NOx certification parameter, Dp/Foo, against the engine overall pressure ratio (OPR). Also shown is the current ("CAEP/6") certification limit and an indication of a certification limit which could arise under such a situation with local air quality issues dominant. It can be seen that, although the majority of the in-production engines meet the current certification criteria, considerable improvements would be required for the higher pressure ratio engines (beyond about 35) to meet the tighter limit.

Figure 64 Certification NOx emissions from engines in ICAO databank compared to CAEP/6 limit and a potential future high stringency limit



To implement Scenario 2, the main changes to be made to the central case are to the ACARE-2020 compliant types and their 2030 and 2040 equivalents. From Sections 2 and 5, the 2020 aircraft are defined as an existing type with a 40% reduction in fuel consumption and the 2030 and 2040 aircraft are proposed to be the same with a further 7.25% and 14% reduction in fuel burn respectively.

Based on the data in Table 13 and Table 14, the proposed data for these aircraft types are as follows.

Table 15 Reductions in fuel burn for future aircraft types, relative to the relevant base aircraft for the Seat Class, assuming selective adoption of the measures in Table 13

	Single Aisle (Seat Classes 1,2,3)	Twin Aisle (Seat Classes 4,5,6)
ACARE-2020	26%	22%
2030	31%	31%
2040	33%	33%

The data in this table differ from those in Table 14 as the advantages from the blended-wing-body aircraft and the open rotor engines have been removed as they are more revolutionary technologies and hence higher cost to develop. Thus, it is plausible that they would not be developed and appear in the fleet under this scenario. On the single aisle aircraft, the open rotor engines on the 2030 and 2040 aircraft types have been replaced by geared turbofans. It is highly probable that the other technologies in Table 13 would be developed under this scenario, though they would not be optimised as well as they might under other scenarios.

As for the low oil price scenario (Scenario 1a), the new aircraft types would be expected to penetrate the supply pool at the same rate as under the central case. The retirement ages of all types should be increased by two years.

8.3 Scenario 3 – Upper bound of fuel efficiency improvements

This scenario addresses the upper bound of likely efficiency improvements due to aircraft technology improvements. The range of technologies, and their potential for reducing fuel consumption, are shown in Table 16

Table 16 Upper bounds for potential airframe and engine technology improvements

Technology	Efficiency Improvement Upper Bound	Entry Into Service Date
Core Engine Technologies to 2015	5%	
Core Engine Technologies 2015 to 2025	5%	
Geared TurboFan Technology	10%	2015
Ultra High Bypass Ratio Technology	10%	2025
Core Engine Technologies 2025 to 2050	13%	
Airframe Weight Reduction (including composite structures)	20%	2025
Structure Optimisation	12%	2025
Improved Aerodynamics (including laminar flow technology)	20%	2030
Open Rotor Engines	30%	2025
Blended-Wing-Body Aircraft	32%	2040

Similarly to Table 14, Table 17 below shows the upper bound of likely technological improvements, relative to a base year of 2000.

Table 17 Upper bound of likely efficiency improvements

Year	Single Aisle	Twin Aisle
2020	46.4% [(a)]	40.4% [(e)]
2030	67.4% [(b)]	58.1% [(f)]
2040	69.1% [(c)]	73.0% [(g)]
2050	70.9% [(d)]	74.5% [(h)]

Notes

(a) Core Engine Technologies (to 2015) + 0.5xCore Engine Technologies (2015 to 2025) + Geared TurboFan + 0.8xComposite Airframe + 0.5xImproved Aerodynamics

(b) Core Engine Technologies (to 2015) + Core Engine Technologies (2015 to 2025) + 0.2xCore Engine Technologies (2025 to 2050) + Open Rotor + Composite Structure + Improved Aerodynamics

(c) Core Engine Technologies (to 2015) + Core Engine Technologies (2015 to 2025) + 0.6xCore Engine Technologies (2025 to 2050) + Open Rotor + Composite Structure + Improved Aerodynamics

(d) Core Engine Technologies (to 2015) + Core Engine Technologies (2015 to 2025) + Core Engine Technologies (2025 to 2050) + Open Rotor + Composite Structure + Improved Aerodynamics

(e) Core Engine Technologies (to 2015) + 0.5xCore Engine Technologies (2015 to 2025) + 0.8xComposite Airframe + 0.5xImproved Aerodynamics

(f) Core Engine Technologies (to 2015) + Core Engine Technologies (2015 to 2025) + 0.2xCore Engine Technologies (2025 to 2050) + Ultra-High Bypass Ratio + Composite Structure + Improved Aerodynamics

(g) Core Engine Technologies (to 2015) + Core Engine Technologies (2015 to 2025) + 0.6xCore Engine Technologies (2025 to 2050) + Ultra-High Bypass Ratio + Composite Structure + Improved Aerodynamics + Blended Wing Body

(h) Core Engine Technologies (to 2015) + Core Engine Technologies (2015 to 2025) + Core Engine Technologies (2025 to 2050) + Ultra-High Bypass Ratio + Composite Structure + Improved Aerodynamics + Blended Wing Body

The scenarios that would give rise to the various technologies achieving their upper bounds are those which encourage high levels of investment in developing new technology. This requires drivers, such as high fuel prices or high costs of carbon credits, a commitment to significant reductions in CO_2 emissions together with a prosperous global economy to enable the funding to be available both for aircraft development and acquisition of the new aircraft by the airlines. A continuing appetite for air travel would also be required to drive demand.

To implement this scenario, the main changes to be made to the central case are to the aircraft definitions for the ACARE-2020 compliant types (due to begin to enter service in 2020) and the 2030 and 2040 equivalent types. Based on the data in Table 17, the proposed data for these aircraft types are as follows.

Table 18 Reductions in fuel burn for future aircraft types, relative to the relevant base aircraft for the Seat Class

	Single Aisle (Seat Classes 1,2,3)	Twin Aisle (Seat Classes 4,5,6)
ACARE-2020	46%	40%
2030	67%	58%
2040	69%	73%

As for the high oil price scenario (Scenario 1b), the new aircraft types would be expected to penetrate the fleet more rapidly than under the central case, achieving 100% of replacement aircraft ten years after their initial introduction. Under the prosperous conditions associated with this scenario, airlines would tend to replace their aircraft early, so the retirement ages of aircraft types should be reduced by four years.

9 Implementation of scenarios

This section summarises the manner in which the scenarios discussed in the preceding sections should be implemented in the forecast modelling.

9.1 Scenario 1a (High Oil Price)

- A new aircraft type should be created, as a turboprop ACARE-2020 compliant type in seat class 2. This aircraft should have the same characteristics as the Class 2 ACARE-2020-compliant aircraft currently modelled, but with a 25% lower fuel burn. The range of this aircraft should be limited to 1500nm, i.e. they should not be used on routes with stage lengths greater than that distance. The fraction of the Class 2 supply pool set to the ACARE-2020 aircraft should be split equally between the jet and turboprop types.
- The ACARE-2020 compliant aircraft types should enter the supply pool two years earlier than under the central case (i.e. 2018 for most types, 2022 for the replacement for the Airbus A320 and Boeing 737).
- The 2030 aircraft types should enter the supply pool in 2028.
- The 2040 aircraft types should enter the supply pool in 2038.
- These new types should form 5% of the supply pool in the initial year (as under the central case), but should rise to form 100% of the pool ten years after their initial introduction.
- The retirement ages of all aircraft types should be reduced by four years from the central case values.

9.2 Scenario 1b (Low Oil Price)

- The introduction into the supply pool of the ACARE-2020 compliant types should be delayed by two years from the central case values.
- The 2030 and 2040 types should also enter the supply pool two years later than in the central case.
- The rate at which these aircraft enter the supply pool should be the same as under the central case.
- The retirement ages of all types should be extended by two years.
- In Seat Class 1, the RJ-700, ERJ145 and Embraer 170 should remain in the supply pool five years longer than under the central case.

9.3 Scenario 2 (Lower Bound of Fuel Efficiency Improvements)

- For seat classes 1, 2 and 3, the ACARE-2020 compliant types should have their fuel burn set to 74% of the base type as used for the central case (instead of the 60% used under the central case).
- For seat classes 4, 5 and 6, the ACARE-2020 compliant types should have their fuel burn set to 78% of the base type as used for the central case.

- For all seat classes, the 2030 aircraft types should have their fuel burn set to 69% of the base type as used for the central case.
- For all seat classes, the 2040 aircraft types should have their fuel burn set to 67% of the base type as used for the central case.
- All aircraft types should have their retirement ages increased by two years from the central case values.

9.4 Scenario 3 (Upper Bound of Fuel Efficiency Improvements)

- For seat classes 1, 2 and 3, the ACARE-2020 compliant types should have their fuel burn set to 54% of the base type as used for the central case (instead of the 60% used under the central case).
- For seat classes 4, 5 and 6, the ACARE-2020 compliant types should have their fuel burn set to 60% of the base type as used for the central case.
- For seat classes 1, 2 and 3, the 2030 compliant types should have their fuel burn set to 33% of the base type as used for the central case.
- For seat classes 4, 5 and 6, the 2030 compliant types should have their fuel burn set to 42% of the base type as used for the central case.
- For seat classes 1, 2 and 3, the 2040 compliant types should have their fuel burn set to 31% of the base type as used for the central case.
- For seat classes 4, 5 and 6, the 2040 compliant types should have their fuel burn set to 27% of the base type as used for the central case.
- The new ACARE-2020, 2030 and 2040 aircraft should form 5% of the supply pool in the initial year (as under the central case), but should rise to form 100% of the pool ten years after their initial introduction.
- All aircraft types should have their retirement ages reduced by four years from the central case values.

10 Conclusions

This report sets out the results of a review of the current methodology used by the DfT for forecasting CO_2 emissions from aircraft using UK airports. The assessment has covered the mapping of aircraft types to those in CORINAIR, the accuracy of the CORINAIR data (by comparison with data from the AERO2k greenhouse gas model) and the accuracy of the curve fits used when applying the CORINAIR fuel burn data. The supply pool data, defining which aircraft types are introduced into the fleet when existing aircraft retire, have also been assessed.

This assessment has suggested that the current methodology is fundamentally sound and its continued use is supported. However, some improvements could be made to enhance the accuracy of the calculations. Recommendations, including factors to be applied to the fuel burn for existing CORINAIR aircraft types and approaches for generating data for additional types not in the CORINAIR guidebook, have been given in Sections 6 and 9.

In addition to the assessment of the forecast methodology for the central case, some alternative scenarios have also been investigated. The alternative scenarios considered are:

Scenario 1: High and low projections of oil price

Scenario 2: Lower end of a plausible range of fuel efficiency improvements

Scenario 3: Upper end of a plausible range of fuel efficiency improvements

The high oil price scenario is expected to lead to an acceleration in the development of new aircraft technology, with an associated reduction in the retirement age of the existing types and a more rapid penetration of the supply pool by the new types. As most technology development is already focussed on reductions in fuel consumption (driven by commercial competition), no different technologies are anticipated. The low oil price scenario is expected to lead to slower development of new technology with an increase in the retirement ages of existing types.

The drivers that could cause future fuel efficiency improvements to be at the lower end of the likely range include ongoing global economic difficulties and either noise or emissions of NOx being the dominant environmental concern (even more so than climate change related to CO_2 emissions). This would restrict the technologies that appear on aircraft and the success of those that do. The reduced improvements in efficiency would lead to fuel burns of a new aircraft in 2040 being 67% of the baseline year-2000 aircraft, compared to 51.6% under the central case.

The drivers which could lead to future technology achieving the upper bound of the likely range include a strong global economy together with high fuel prices (or high carbon costs) and a commitment to significant reductions in CO_2 emissions. Under this scenario, the fuel burn of a 2040 aircraft would be between 27% and 31% of the year-2000 baseline aircraft.

Recommendations for adjustments in the modelling of future aircraft types have been made for these scenarios.

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Abstract

A review has been performed of the current method of forecasting CO_2 emissions from aircraft using UK airports. The current approach uses the CORINAIR Guidebook data to calculate the fuel burn by individual aircraft on each route. The assessment has covered the mapping of aircraft types to those in CORINAIR, the accuracy of the data (by comparison with data from the AERO2k greenhouse gas model) and the accuracy of the curve fits used when applying the fuel burn data. The supply pool data, defining which aircraft types are introduced into the fleet when existing aircraft retire, have also been assessed as have alternative scenarios for the future development of fuel process and aircraft technologies. Observations on the modelling have been made and recommendations provided for enhancing the accuracy of the calculations. From this review, recommendations have been made for defining fuel burn data for generic aircraft types to be introduced beyond the year 2030.

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