Vertical Flight Efficiency En-Route (VFE-ER)

By David Brain and Francisco Hoyas (EUROCONTROL)

Vertical Flight Efficiency En-Route (VFE-ER)

Proposal to identify inefficiencies in the Vertical trajectory during Cruise

Reducing fuel burn and CO_2 emissions remains one of the most pressing challenges for the aviation sector. While much attention has been given to technological innovation and sustainable aviation fuels (SAF), operational improvements—particularly in how aircraft fly—offer immediate and scalable opportunities for environmental gains. This study focuses on the cruise phase of flight, to identify and quantify the inefficiencies in flying at sub-optimum cruising levels that leads to excess fuel consumption. By developing a methodology to assess VFE en-route, this work aims to support data-driven improvements in flight operations and airspace management that can directly reduce the environmental footprint of aviation.

In the 2022 ICAO Environment Report[1], ICAO reported how the Committee on Aviation Environmental Protection (CAEP) had undertaken the first global vertical flight efficiency (VFE) analysis for the climb and descent phases of flight. In this analysis - in the absence of a fit for purpose methodology to measure VFE in the en-route phase - there was insufficient time and effort available to continue the work within CAEP Working Group 2 (WG2). To address this challenge, a small global group of experts worked together to develop two new methodologies to measure global VFE in the en-route phase under the umbrella of EUROCONTROL, the European Organization for the Safety of Air Navigation.

The key challenges involved identifying an appropriate set of methodologies, data sources and performance indicators, together with agreeing on a set of assumptions to minimise the uncertainties associated with such a global analysis.

The data source used in this study was global Automatic Dependent Surveillance–Broadcast (ADS-B) ADS-B data provided by Flightradar24. Where gaps in ADS-B coverage were identified e.g. over the Oceans, assumptions were made to connect multiple parts of the same profile. The performance indicator selected – average time spent at inefficient cruising levels - was a variant of the Global Air Navigation Plan (GANP) indicators on VFE (KPI17 – level-off during climb; and KPI19 – level-off during descent), adapted for the en-route phase. This indicator was selected as it could be applied to all ICAO regions, at sub-regional or national levels and also be applied to different data sources.

One of the key aspects of the methodologies to be developed for the en-route analysis was to ensure alignment with the VFE study of the climb and descent phases in terms of definitions of flight phase and indicator usage. This would ensure that both analyses (climb / descent and en-route) could be undertaken with the same data set, using the same data points, employing similar performance indicators using 'TIME' with no overlapping of data points in the various flight phases.

In the VFE en-route study, the measurement of (in) efficiency was focused on the level segments that are flown during the cruise phase at inefficient flight levels below a calculated Reference Flight Level (FL), with the following principles agreed:

- The source of data to compare with the Reference FL was:
  - For pre-tactical analysis (planned trajectories): Flight Plan data; and
  - For tactical analysis (flown trajectories): real Correlated Position Report(CPR), Flight Data Monitoring (FDM) or ADS-B data source.

1 https://www.icao.int/environmental-protection/Documents/EnvironmentalReports/2022/ICAO ENV Report 2022 F4.pdf

- Only time flown below the Reference FL was considered inefficient, with some margins explained below.
- For all studies where the whole flight was analysed, the vertical profile between the Top of climb (ToC) and the Top of descent (ToD) is compared with the reference FLs.
- To adapt the study to a more local analysis (i.e. a Flight Information Region (FIR), specific airspace or country), the vertical profile of the cruise phase between the entry and exit points of the specific geographical entity was compared with the Reference FL that corresponds to that airspace.
- Time at inefficient levels can be converted into excess fuel figures based on the Base of Aircraft Data(BADA), an aircraft performance model developed and maintained by EUROCONTROL[2], aircraft type performance database.

Reference FL Calculation (FL1 and FL2)

The FL used to compare the planned/actual profiles with is called the **Reference FL**. Airbus defines the Optimum Flight Level as "*The Optimum FL, (.........) is the flight level which provides the greatest specific range (nm/kg) at a given gross weight*"[3] i.e. NM flown per unit of fuel burn). The optimum FL of a flight depends on various factors, like aircraft type, weight, wind, cost index, tropopause altitude, weather conditions, etc. not to mention the air traffic management (ATM) conditions and traffic flows. For the purpose of a study or performance monitoring, not all of these factors can be taken into account, so the calculation of this Reference FL is unlikely to fully match the definition of optimum FL, hence the term "Reference FL".

Based on the Great Circle Distance between the aerodrome of departure (ADEP) and the destination (ADES), two different calculations were made to set the Reference FL:

- Reference FL1: Flights with a city pair distance greater than 1000 NM use a Reference FL derived from the BADA database based on aircraft performance.
- Reference FL2: Flights with a city pair distance below 1000 NM use a Reference FL derived from a statistical calculated value.

Note: For flight lengths below 1000NM, it is assumed that traffic levels/airspace complexity are the main constraints to aircraft reaching their optimum level. Aircraft are lighter, so the optimum FL based only on fuel consumption (BADA) becomes too high, with the sector length short enough for the flight not to climb as high as the BADA optimum FL. This value is under discussion and could be lower to 500 NM, based on future analysis.

In developing the Reference FLs for all aircraft types and distances flown, a number of considerations were made:

- If an optimum FL is estimated to be an intermediate value, it is always rounded down e.g. an optimum FL of FL387 will actually be rounded down to a Reference FL380;
- A 1000ft buffer is created below the Reference FL segments to account for Flight Level Allocation Scheme (FLAS)[4]; and,
- Depending on the calculation of the optimal FL for each a/c type and stage length, the Reference profiles will consist either of a single level segment or of a set of level segments connected by climb segments (to reflect real-time climbing of aircraft on medium / long-haul flights as weight decreases.

Reference FL1 - BADA calculation

Each aircraft type has three associated weights in BADA (low, nominal and high) together with its corresponding performance at each FL, fuel burn and speed. Based on the data in the BADA performance tables, an optimum FL can be calculated for each weight based on maximum Specific Range (NM/kg) values extracted from speed, fuel flow and FL. Speed correction or Cost Index variations are not taken into account, as that information is not available for each individual flights, so the nominal speeds of BADA at each level are the only ones taken into account.

2 https://www.eurocontrol.int/model/bada
3 https://ansperformance.eu/library/airbus-cost-index.pdf
4 https://skybrary.aero/articles/flight-level-allocation-scheme-flas

Stage Length	1	2	3	4	5	6	7	8	9
Trip Length Range (nm x 1000)	0-0.5	05-1	1-1.5	1.5-2.5	2.5-3.5	3.5-4.5	4.5-5.5	5.5-6.5	>6.5
Representative range (nm)	350	850	1350	2200	3200	4200	5200	6200	
Takeoff Weight (lb)									

FIGURE 1: Stage Lengths and representative range.

In order to assign a relevant Reference FL to each flight, the first assumption made is the weight of the aircraft at take-off. BADA and Aircraft Noise and Performance (ANP) data are used to assign a specific weight for each stage of an overall stage length (SL) of a city pair distance for each aircraft type, assuming a fixed load factor. As ANP data uses more weights, based on the Stage Length (SL) or distance of the flight, an interpolation/extrapolation is made from the BADA values, so a table of optimum FLs can be created for each ANP weight, corresponding to each sector length of the SLs defined, for each aircraft type.

With this assumed weight for each SL, a Reference FL can be determined for each stage of an overall stage length (city pair distance) to represent medium/longer-haul flights performing step climbs. This process also provides a fuel burn rate in kg/min and kg/nm (for each aircraft type and stage length) to support fuel burn calculations, from where the optimum fuel burn FL is determined.

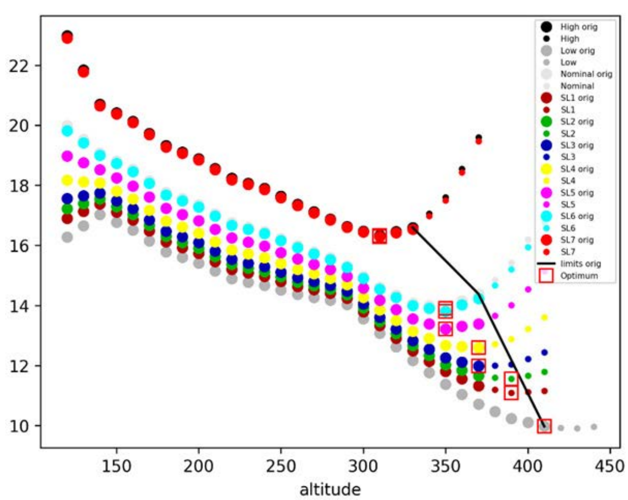
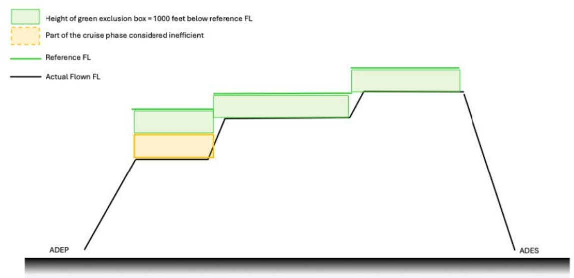


FIGURE 2: Example of using Stage Lengths from ANP and BADA data to identify the lowest fuel burn rates.

Figure 3 demonstrates how the Reference FL (in green) may change over time as an aircraft passes between stage lengths, as the Reference FL gets higher as the aircraft weight decreases. That way, step climbs are allowed at each portion of 1000 NM (which corresponds with Original Equipment Manufacturer (OEM) assumptions on aircraft weight loss over distance).



Stage Length	weight	fist 500NM	500-1000	1000-1500	1500-2500	2500-3500
1	60636	390				
2	63273	380	390			
3	66000	370	380	390		
4	70864	350	370	380	390	
5	77182	330	350	370	380	390

FIGURE 3: Example of step climb flight.

Reference FL2 - Statistical calculation

Flights with sector lengths below 1000 NM are usually flown with the aircraft not fully loaded with its maximum fuel capacity. In such cases, the optimum FL based on fuel consumption (BADA) is likely to be high. However, the sector length may be too short for the flight to reach the BADA optimum FL, or there may be a myriad of other reasons - e.g. operational constraints - that limit the possibility of reaching the optimum level.

All flights with stage length of less than 1000nm were compared with a Reference FL calculated statistically (Figure 4). The Reference FL2 was based on the FLs flown on specific city pairs using a much larger database of flights. For each aircraft type, all flights using that aircraft type, on a certain city pair distance are aggregated in 'bins' of city pair distances. The reference profile is determined for each aircraft type and each city pair distance, considering 50NM bins (i.e. 300NM, 350NM,...1000NM etc.). The reference FL for each aircraft type/city pair 'bin' is obtained from the 80th percentile of the observed planned/actual altitudes of the flights.

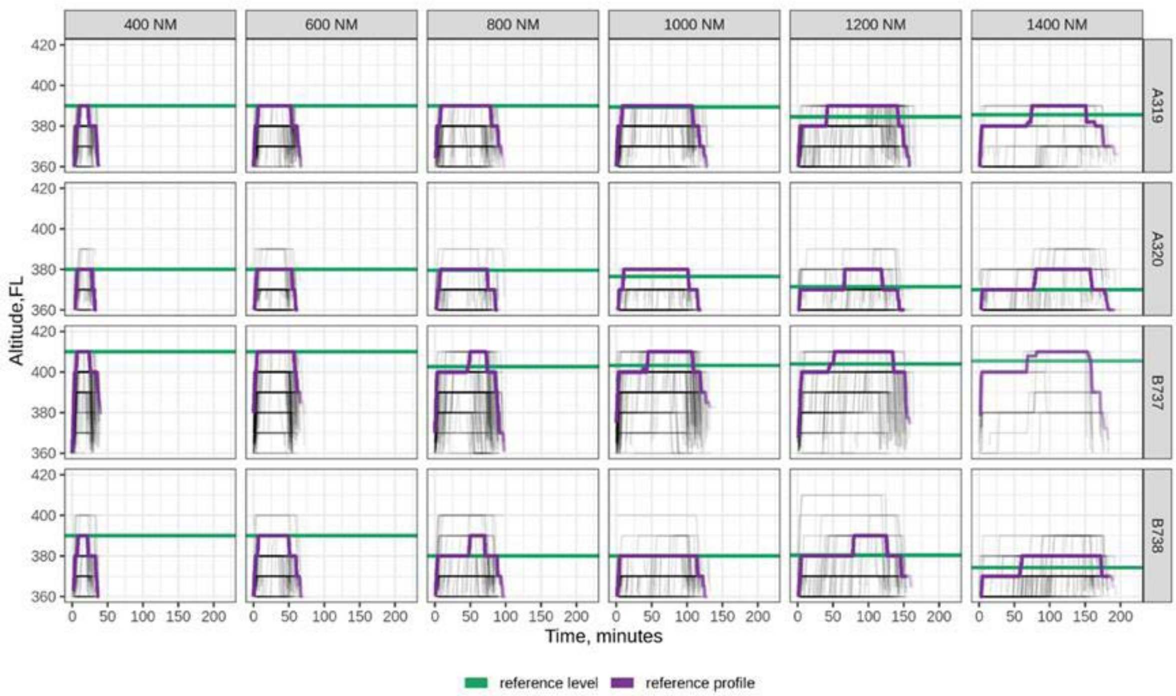


FIGURE 4: Example of statistical Reference FL2 calculation.

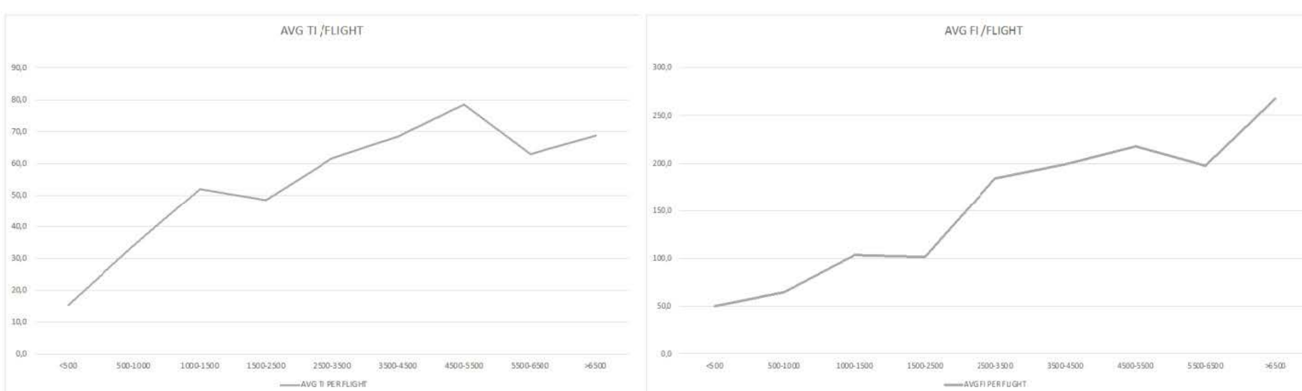


FIGURE 5: Examples of TI (Time Inefficiency) and FI (Fuel Inefficiency) per stage length.

When the statistical Reference FL was above the BADA Reference FL1 for that city pair distance, the BADA Reference is used, as it makes no sense to establish a Reference FL that is above the one that gives the minimum fuel burn per distance flown.

Calculation of the Inefficiency

The analysis of vertical flight inefficiency compares the reference profile of each flight (based on aircraft type and stage length) to the planned or actual flown profile and delivers the amount of Time flown at an inefficient FL (Time Inefficiency TI) and the Fuel Burn difference between the planned/actual and the Reference FL (Fuel Inefficiency FI) see Figure 5.

The main KPI chosen for the result was the Average Time at Inefficient FL per flight. The main reason for this is to align results with the climb and descent phases, where the main KPI is average time in level flight per flight. For the en-route phase the values are expressed in minutes instead of seconds (used for the climb and descent). The secondary KPI is Fuel inefficiency per flight.

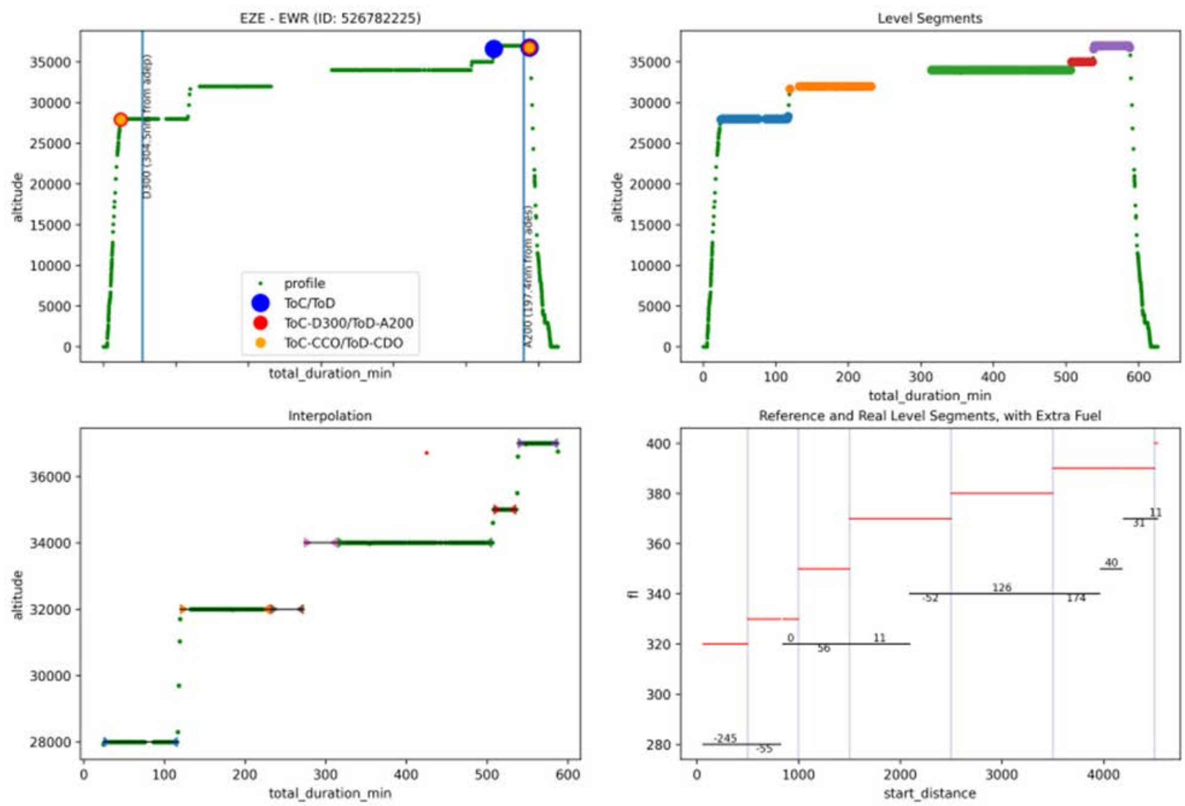


FIGURE 6: visual representation of process to measure fuel inefficiency (clockwise from top-left): identification of ToC/ToD, identification of all level segments, bridging of any gaps in profile, comparison of actual profile with Reference FL with corresponding fuel burn impacts (kgs fuel)

Results

From the total of nearly 4 million flights contained in the ADS-B data sample (4 calendar weeks of global traffic as used in the global VFE climb and descent study), the TI and FI values for each aircraft type and distance bin were used to calculate the total amount of TI and FI contained within each distance bin as part of the overall set of flight lengths (see the table in Figure 7 below). This could then be broken down to the regional level. From the results it is also possible to see how the average inefficiency per flight is skewed towards the shorter flight distances reflecting the shorter flight distances flown by the vast majority of flights.

Stage length distance (NM)	Average FI / flight (kg)	Average TI / flight (mins)	% cruise time flown as inefficient
<500	49.7	15.3	62%
500-1000	64.6	34.1	55%
1000-1500	103.2	52.0	41%
1500-2500	101.1	48.4	23%
2500-3500	184.1	61.6	18%
3500-4500	199.2	68.5	15%
4500-5500	217.9	78.5	13%
5500-6500	197.4	62.9	9%
>6500	267.6	68.7	8%
Average total/flight	**63.2**	**30.4**	**32%**

FIGURE 7: Global average FI / TI results per SL and per flight.

Conclusion

The methodology that has been used for the global VFE en-route analysis, together with its sister methodologies[5], provides a set of methodologies to measure regional and global Horizontal Flight Efficiency (HFE) and VFE in all flight phases. This analysis delivered high level results used for investigating the level of vertical inefficiency in the en-route flight phase compared with other phases of flight or HFE. It is ready and available to be used based on the assumptions made.

When wishing to delve deeper into the root causes of vertical inefficiency, or to assess the contribution of individual stakeholders to the inefficiency, further analysis is required with an accompanying further refinement of the methodology.

The factors that may be further investigated may include:

- Wind: Wind velocity and direction can change the BADA optimum FL. Due to stronger tailwinds, it might be better to fly at a lower FL than the BADA optimal FL which shortens the flight, compensating the extra fuel flow of flying lower. This should not be considered an inefficiency, but a wind optimised FL.
- Weather phenomena along the route: this might suggest flying at a lower flight level (in future, it could include contrail avoidance, if needed). It takes into account mainly forecasted turbulence that makes the AU choose to fly at a lower altitude to avoid it. The selected cruise level is then not considered inefficient, as it is the most convenient for the safety of the flight.
- Delay and other costs: The AU chooses to fly a lower FL – below the BADA optimal FL - or a vertical profile to avoid a specific airspace and reduce the overall cost (due en-route charges) or delay of the flight.
- ATM: ATM vertical inefficiency is the time spent at inefficient FLs due to ATM restrictions. For example, in Europe, RAD (Route Availability Document) restrictions - based on Network Management measures due to Capacity shortage – may define a maximum FL to be planned / flown.

Thanks for supporting the development of the methodology go to:

- US FAA
- Air Services Australia
- Boeing
- EUROCONTROL
- Novair AB (Airline)

5 Global VFE climb and Descent analysis in the 2022 ICAO Environmental Report - https://www.icao.int/environmental-protection/Documents/EnvironmentalReports/2022/ICAO ENV Report 2022 F4.pdf
Global HFE analysis in the 2019 ICAO Environmental Report - https://www.icao.int/environmental-protection/Documents/EnvironmentalReports/2019/ENVReport2019_pg138-144.pdf