Impact of trajectory restrictions onto fuel and time-related cost efficiency

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Abstract — **Efficiency improvements belong to the key objectives to modernize the worldwide Air Traffic Management (ATM) system. In Europe, the "Average horizontal en route flight efficiency" is one of the performance indicators defined along the Single European Sky (SES) Performance Scheme. Although this is a major step towards efficiency measurement improvements both on an EU-wide and local level, the current indicator does not yet fully cover all airspace user expectations. In particular, inefficiencies of the vertical and speed profile as well as delays are not reflected. The current paper contributes to a consistent efficiency assessment, applicable for the complete range of inefficiency reasons, by considering both fuel and time-related costs. It refers the cost index (CI) concept quantifying additional costs caused by trajectory restrictions.**

Keywords - efficiency, performance assessment; user preferred trajectory; cost index; fuel costs; delay costs.

I. INTRODUCTION

In the year 2012 Performance Review Report of the European Performance Review Commission (PRC) it says: "Inefficiencies are the result of complex interactions between airspace users, ANSPs and the European Network Manager. More research is needed to better understand the exact drivers in order to identify and formulate strategies for future improvement." [1] The current paper contributes to this understanding by summarizing the airspace user expectations and quantifying the impact of major trajectory restrictions onto efficiency.

Efficiency belongs to the Key Performance Areas (KPA) of the Air Traffic Management (ATM) as defined by ICAO. "Efficiency addresses the operational and economic cost-effectiveness of gate-to-gate flight operations from a single-flight perspective. In all phases of flight, airspace users want to depart and arrive at the times they select and fly the trajectory they determine to be optimum." [2] However, efficiency assessment is currently based on metrics, which address selected aspects of the user preferred trajectory, only. The next chapter provides a brief summary of these currently used metrics, followed by a deeper look into airspace user expectations in order to enable a comprehensive efficiency assessment of trajectory restrictions.

II. EFFICIENCY METRICS

A. Horizontal en route flight efficiency (en route extension)

The "Average horizontal en route flight efficiency" is one of the performance indicators of the SES Performance Scheme. It is defined as "the difference between the length of the en route part of the actual trajectory and the optimum trajectory", whereas "en route is defined as the distance flown outside a circle of 40 NM around the airport" [3].During the 1st reporting period (RP1) the calculation of the actual trajectory length is based on the flight plan filed route [4] where the optimum (minimum) trajectory length equals the great circle distance (no wind is considered). To enable efficiency assessment for trajectory segments, e.g. for performance monitoring at local (e.g. Functional Airspace Block, FAB) level the principle of the so called "achieved distance" is applied [5]. Fig. 1 highlights this assessment concept.

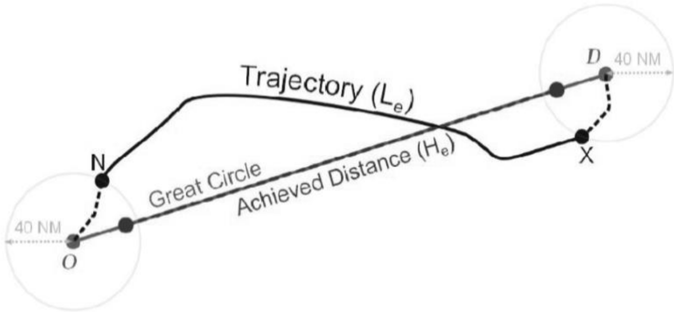

Figure 1. Determination of Actual and Optimum Trajectory [6]

The horizontal en route flight efficiency, also called en route extension, is typically expressed as follows:

$$K' = L/H - 1 \times 100 \quad (1)$$

K' ... Horizontal en route flight efficiency [%]

L ... Actual distance [NM]

H ... Great circle distance [NM]

In 2012, the average horizontal en route flight efficiency within the RP1 SES region was 5.15%. Target value for 2014 is 4.67% [4].

The reporting of this indicator is a major step to enable a better quantification of inefficiencies in the ATM. Main advantage is its somehow simple quantification in terms of comparison between the actual trajectory length and the great circle distance of a flight, supported by some partly weak assumptions (e.g. neglecting wind impact). Further, the metric does not allow for an assessment of the effects of vertical and speed restrictions as well as delays on efficiency.

B. *Additional fuel burn*

The use of fuel burn as a further metric enables a more precise efficiency assessment than route extension, only since additional factors, such as wind as well as deviations from the optimum altitude and speed are considered. Its quantification is however more difficult to perform, since limited data availability and accuracy are typical. By today only few studies use additional fuel burn as a metric for efficiency assessments. For instance, the PRU estimates the additional fuel burn in Europe at 271 kg per flight, which corresponds to approximately 6% of the minimum fuel burn [7]. Another study considers additional fuel burn at much higher values, at 23% compared to minimum fuel burn (based on flight data recorder analyses for A320 flights within Europe) [8]. However, it must in particular be considered that aircraft operators usually fly at higher speeds than Maximum Range Cruise (MRC) because time costs may also play a significant role. Consequently, the trajectory reflecting minimum fuel burn may not generally reflect the user preferred trajectory.

C. *Additional Time (Delays)*

Additional, exhaustive flight time as a further efficiency metric is nowadays almost exclusively used for assessing Air Traffic Flow Management (ATFM) restrictions and airside airport capacity constraints. This mainly concerns arrival ATFM delays, additional time within the Arrival Sequencing and Metering Area (ASMA), pre-departure delays at the stand as well as additional time in the taxi-out phase (so considering queuing effects at the departure runway) [3]. It is clear that these delays have different effects on costs for airspace users. Arrival ATFM delays and pre-departure delays mainly consider time costs. Airborne holdings and taxi out delays additionally generate a significant amount of fuel burn.

Furthermore, time costs are affected by additional factors, such as number and status of all involved passengers (e.g. in view of connecting flights) as well as airline operation network effects. Hence, using additional time is not sufficient for a complete efficiency assessment if the individual time-related costs of the flight are not taken into account.

D. *Additional Costs*

Considering the advantages and disadvantages of the above described metrics it is recommended to assess efficiency based on costs for airspace users. None of the above described metrics fully cover all airspace user expectations on their own, but all of them can be converted into costs. The PRC states: "Flight efficiency measures the difference between actual and optimum unimpeded aircraft trajectories (gate to gate). Deviations from the optimum trajectory generate additional flight time, fuel burn and costs to airspace users." [9] In order to enable a comprehensive efficiency assessment, airline operating costs need to be understood to be able to quantify these costs.

III. AIRLINE OPERATING COSTS

Operating costs of an airline comprise direct and indirect costs as illustrated in Figure 2. Direct operating costs cover all costs related to the operation of the aircraft, whereas indirect operating costs may be independent from its operation. Direct operating costs can further be subdivided into a fixed and a variable part. Fixed direct costs are related to the operation of the aircraft but cannot be influenced by the flight event itself. On the contrary, all variable direct operating costs can directly be allocated to the flight event. [10]

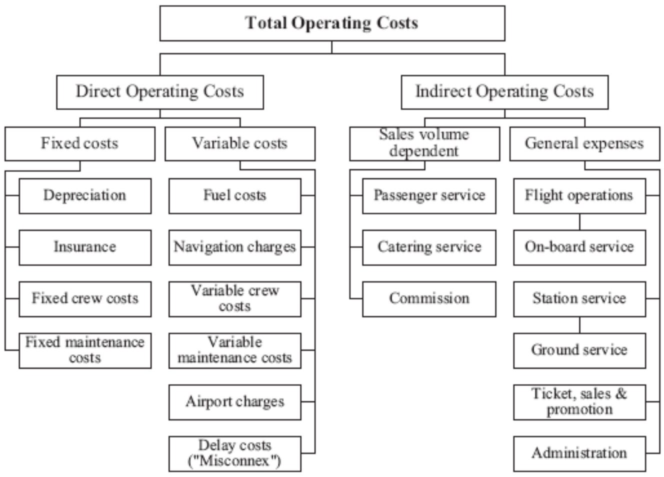

Figure 2. Airline Operating Costs [10]

The variable direct operating costs can be grouped into fuel costs, time-related costs (includes crew, maintenance, and delay costs), ATC charges, and Airport charges. As ATC charges are explicitly addressed by the ICAO KPI *Cost-Effectiveness* and airport charges are independent from flight operations, *fuel and time-related costs remain for the efficiency assessment*. It must be mentioned that environmental costs, e.g. as caused by the emission trading system (ETS) or even based on external cost assessments, are not included here, but their consideration should be discussed for future studies.

The fuel costs of a flight are calculated by multiplying fuel burn (block fuel) with fuel price (typically at the destination airport). The determination of time-related costs is however more complex, as studied in [11], stating that a strong dependency between arrival delays and time-related costs of a flight exists. Figure 3 shows this correlation for an A320 flight with a scheduled flight time of 100 minutes and an on-time departure.

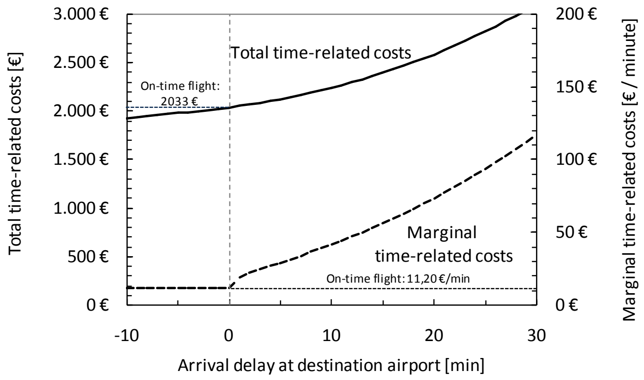

Figure 3. Impact of delay onto time-related costs (example)

The diagram shows both the total time-related costs for the exemplary flight as well the marginal time-related costs. The marginal time-related costs [€ per minute] express the additional time-related costs caused by a flight time increase of one minute. For a flight with on-time departure and on-time arrival the total costs appear to be around 2000 €. Assuming an earlier arrival, e.g. enabled by tailwinds or short-cuts, the total costs can be slightly reduced due to some potential savings of fleet, maintenance, and crew costs (e.g. depended on the payment mechanism for the aircraft crew). Thereby, savings are around 11 € per minute. For delayed arrivals (e.g. due to headwind conditions or queuing at the destination airport), these marginal time costs increase significantly to around 120 € per minute for a 30 minutes delayed flight

With it, it becomes clear that time-related costs strongly depend on the delay situation of a flight. This is already considered by the aircraft operators, who usually adjust the speed in accordance to the estimated delay, respectively the estimated costs caused by the delay. Thereby, the objective is to fly at the most economic (ECON) speed (v_{ECON}), taking into account fuel and time-related costs. As explained in Figure 4, this speed is between Maximum Range Cruise speed (v_{MRC}) and Maximum Operating speed (v_{MO}) or equal to one of them.

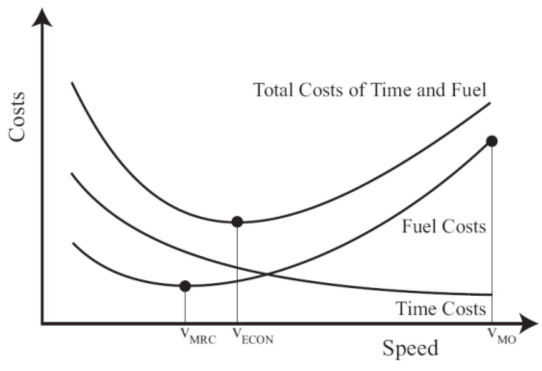

Figure 4. ECON speed calculation based on fuel and time-related costs

The Cost Index (CI) has been introduced to support cockpit crews to fly at the ECON speed for a given ratio of time-related and fuel costs. Generally the CI is given to the cockpit within the briefing package provided by the dispatch and entered into the aircrafts integrated Flight Management System (FMS) as part of the flight preparation. The flight profile calculation (both speed and vertical profile) is then done automatically by the FMS. The CI is defined by the following equation:

$$CI = C_t / C_f \qquad (2)$$

CI ... Cost Index [kg/min] or [100lb/h]

C_t ... Marginal time-related costs [€/min]

C_f ... Fuel price [€/kg]

Looking into detail at the CI equation, the range of feasible cost indices can be identified. In case of nonexistent time-related costs the minimum CI of 0 is applied. If, in contrast, time costs are extremely high and/or the price of fuel negligible, very high values can be achieved. For instance, assuming marginal time-related costs of 11.20 EUR/min for the A320 (see the above example) and a fuel price of 0.60 EUR/kg, a CI of 19 kg/min represents the optimum. The upper limitation of the CI range depends on the particular FMS, e.g. 99 kg/min or 999 kg/min for Airbus aircrafts.

Considering the described facts, the assessment of the impact of trajectory restrictions onto efficiency should be based on the additional costs caused by the restriction and thereby taking into account both fuel and time-related costs.

IV. METHODOLOGY

The current chapter describes the methodology used to quantify the additional costs caused by different trajectory restrictions. It applies a trajectory model for the calculation of the additional fuel burn and additional flight time and converts them into costs.

A. Trajectory Model

The trajectory model used within this study is based on the Base of Aircraft Data (BADA, Version 3.6) [12], but incorporates the following modifications:

- The thrust model was enhanced to allow a differentiation between take-off and climb thrust.
- The drag model was enhanced to take into account the compressibility effect.
- The drag model was furthermore enhanced to take into account the drag that engines cause in idle descent.
- The engine model was enhanced to take into account the impact of true air speed (TAS) on engine efficiency.
- An optimization model was included to enable cost index-based trajectory planning (for both speed and vertical profile optimization).

Within the current paper the analysis is done exemplarily for an *Airbus A320* with *no wind* and *no deviation from the conditions of the International Standard Atmosphere (ISA)*.

The trajectory model was validated using A320 Flight Crew Operating Manual (FCOM) tables, including Integrated Cruise Tables, Climb Tables, Optimum Mach Number Tables, and Descent Tables. The following Figures present validation results for fuel burn during climb, cruise and descent. They compare FCOM tables with both the original BADA 3.6 and the enhanced trajectory model (TM) that is used within the current study.

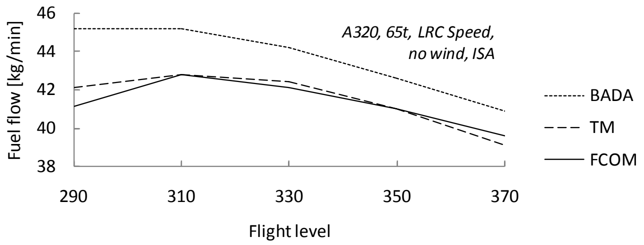

Figure 5. Long Range Cruise (LRC) fuel flow

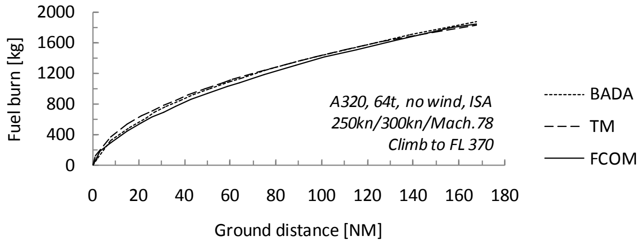

Figure 6. Climb fuel burn

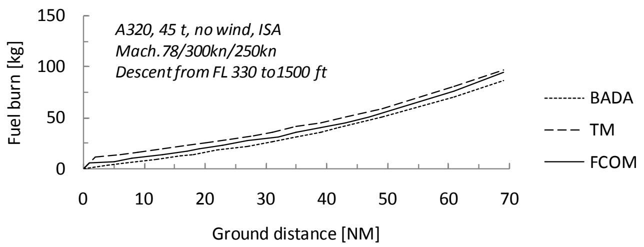

Figure 7. Descent fuel burn

The fuel burn error of the TM is in cruise, climb and descent approximately 1%, which is more precise than BADA 3.6. In particular, the consideration of the compressibility effect and the impact of the TAS on engine efficiency lead to these improvements, which are of importance for the current study. Without them, a modeling of the cost index-based trajectory planning had led to very inaccurate results. This is shown in Figures 8 and 9, which compare the ECON speed as given in the FCOM tables in different flight levels with the modeled results from both BADA 3.6 and the enhanced TM.

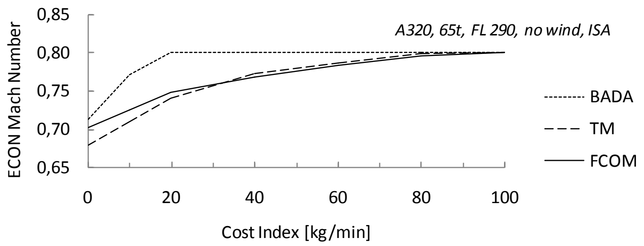

Figure 8. ECON Mach Number in FL 290

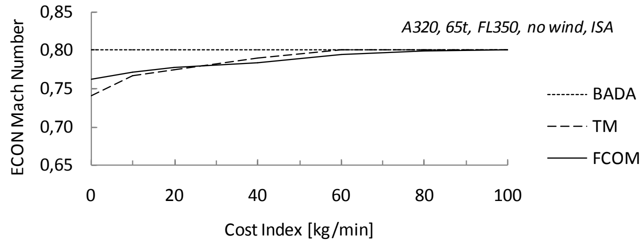

Figure 9. ECON Mach Number in FL 350

B. Additional fuel burn and flight time calculation

Fuel burn and flight time is calculated both for the optimum trajectory (without a restriction) and the actual trajectory (including a restriction). To enable comparability, all conditions, except those affected by the assessed restriction, are set equally. This includes the initial mass of the aircraft, the flight distance, the initial and target altitude, the speed profile as well as environmental conditions (wind, ISA deviation). For instance, the impact assessment of interrupted climb profiles restrictions includes a suitable en-route segment at the optimum altitude to compensate the different top of climb locations.

Based on the results for the actual and optimum trajectory, the additional fuel burn and additional flight time are calculated (difference between the actual and minimum value).

C. Conversion into costs

Additional fuel burn and additional flight time are finally converted into additional costs. Thereby, the *fuel price is estimated with 0.60 €/kg* as given in [11]. The variability of the marginal time-related costs is considered by indicating the additional costs as a function of the CI.

V. IMPACT OF TRAJECTORY RESTRICTIONS

A. Lateral trajectory restrictions

As stated above, lateral trajectory inefficiencies are currently expressed as route extensions, indicated in Nautical Miles (NM) or as a percentage value compared to the great circle distance. Figure 10 shows the effects of a *route extension of 20 NM* in cruise (FL 380) on additional fuel burn and flight time. The additional fuel burn is around 100 kg (slightly dependent on aircraft mass). The additional flight time is around 160 seconds.

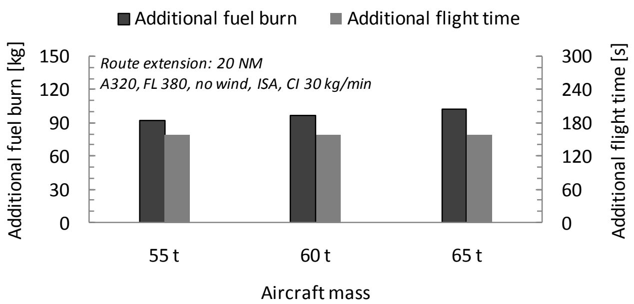

Figure 10. Route extension: Impact on additional fuel and time

Based on these results, Figure 11 shows the additional costs as a function of the CI. Total additional costs increase significantly with increasing cost index due to the higher time-related costs. In case of a CI of 30 kg/min the additional costs are around 110 €, of which around 60 € are fuel costs and around 50 € are time-related costs. For a CI of 0 the additional costs are around 60 €, for a CI of 100 kg/min the additional costs increase to 220 €. It becomes clear that the impact of the aircraft mass on the additional costs is very low compared to the impact of the CI.

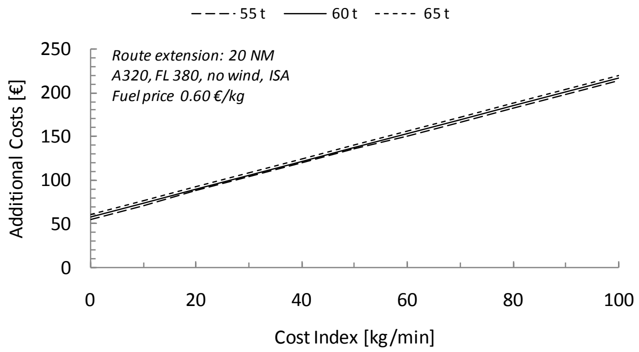

Figure 11. Route extension: Impact on additional costs

In summary, it can be stated that the additional costs caused by a route extension in FL 380 are between 3 € (CI 0) and 11 € (CI 100 kg/min) per NM (A320, fuel price of 0.60 €/kg).

B. Interrupted climb

Continuous Climb Operations (CCO) is "an operation, enabled by airspace design, procedure design and ATC, in which a departing aircraft climbs without interruption, to the greatest possible extend, by employing optimum climb engine thrust, at climb speeds until reaching the cruise flight level" [13]. If CCO is not enabled, additional fuel burn and flight time are caused by interrupted climbs as presented in Figure 12 (horizontal segment of 10 NM).

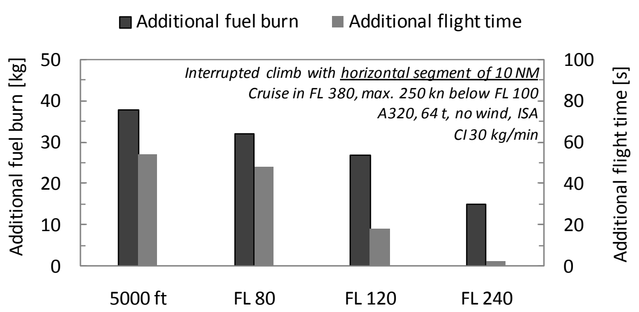

Figure 12. Interrupted climb: Impact on additional fuel and time

Due to the increased drag in low flight levels compared to cruise level, the interrupted climb leads to an increase in fuel burn. Due to the impact of the flight level on TAS also flight time is affected. An interrupted climb with a horizontal segment of 10 NM in 5000 ft leads to additional fuel burn of about 40 kg and additional flight time of about one minute. In FL 240 fuel burn increases by only about 15 kg with almost no effect on flight time.

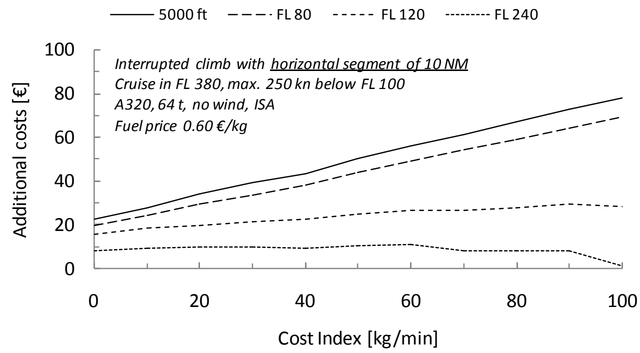

Figure 13. Interrupted climb: Impact on additional costs

Figure 13 shows the impact of an interrupted climb on costs. For horizontal segments below FL 100 the impact increases with the CI due to the speed limit of 250 kn, which causes additional flight time and with it significant time-related costs for high CIs. For horizontal segments above FL 100, the additional costs are almost independent from the CI as the higher time-related costs with increasing CI are compensated (or even over-compensated) by a decreasing difference between the ECON speed in cruise and in the horizontal flight segment during climb.

In summary, it can be stated that the additional costs caused by an interrupted climb are between 0 € (FL 240, CI 100 kg/min) and 8 € (5000 ft, CI 100 kg/min) per NM horizontal segment (A320, fuel price of 0.60 €/kg).

C. Interrupted descent

Continuous Descent Operations (CDO) is „an operation, enabled by airspace design, procedure design and ATC facilitation, in which an arriving aircraft descends continuously, to the greatest possible extent, by employing minimum engine thrust, ideally in a low drag configuration, prior to the final approach fix /final approach point" [14].

The additional fuel burn and flight time caused by interrupted descents are comparable with those caused by an interrupted climb. Minor differences exist due to the typically lower aircraft mass during descent and the differences in ECON climb and descent speeds. Figures 14 and 15 present the according results.

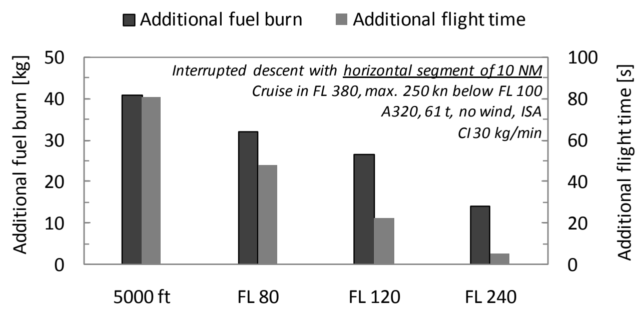

Figure 14. Interrupted descent: Impact on additional fuel and time

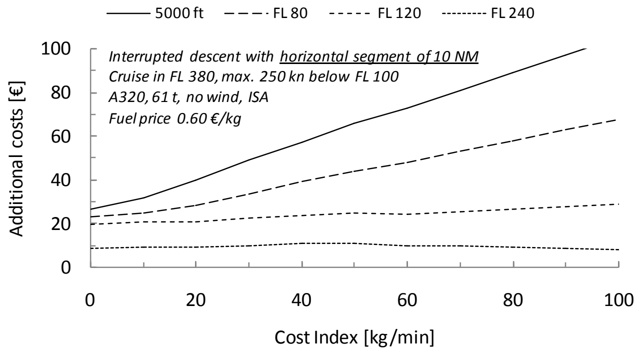

Figure 15. Interrupted descent: Impact on additional costs

Also for the interrupted descent it becomes clear that due to the speed limit of 250 kn below FL 100 additional costs for horizontal segments in low altitudes significantly increase with higher CIs. However, it must be stated that interrupted descents are often used to merge arrival traffic. Hence, if the additional flight time is used to absorb delay, the additional time costs should rather be associated with the delay absorption than the interrupted descent.

D. Flight level cappings

About 12 % of flights in Europe are affected by flight level cappings [15], defined in the Route Availability Document (RAD) [16] for selected city pairs. They restrict the maximum flight level that can be filed in the flight plan. Flight level cappings contribute to a reduced traffic complexity, but cause additional costs to airspace users.

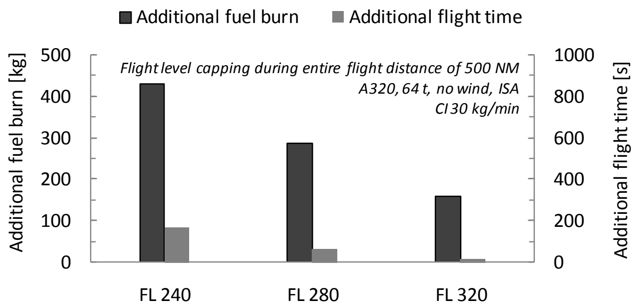

Figure 16. Flight level capping: Impact on additional fuel and time

Figure 16 presents the impact of a flight level capping for a flight with a total distance of 500 NM. In case of a maximum FL 240, the additional fuel burn is around 430 kg. The additional flight time is about 3 minutes. However, for higher CIs from about 50 kg/min, the level capping goes along with even a slight decrease in flight time due to the higher TAS compared to the optimum cruise flight level (FL 380).

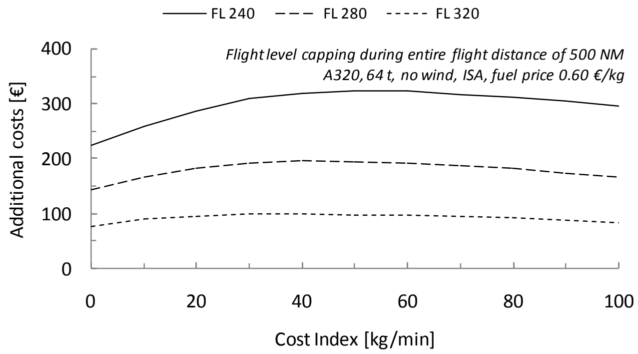

Figure 17. Flight level capping: Impact on additional costs

The additional costs caused by a flight level capping (see Figure 17) are almost independent from the CI due to the described effects on TAS. Nevertheless, especially in case of a level capping in FL 240, the caused costs of about 300 € are high in comparison with the other presented trajectory restrictions. For example, in case of a CI of 30 kg/min, only a route extension of 60 NM causes the same additional costs.

E. Speed restriction below FL 100

For flights below FL 100 a maximum speed of 250 kn Indicated Air Speed (IAS) is defined in the ICAO Annex 11 (for all flight in airspace classes D and higher as well as VFR flights in airspace class C) [17]. With it, for example turn radiuses are limited supporting ATC to manage traffic in high density airspaces. However, especially during climb this causes a significant deviation between actual and optimal speed profiles. For instance, in case of a CI of 30 kg/min, the ECON climb speed is around 310 kn IAS and hence 60 kn higher than the defined limit. Figure 18 shows the effects on additional fuel burn and flight time.

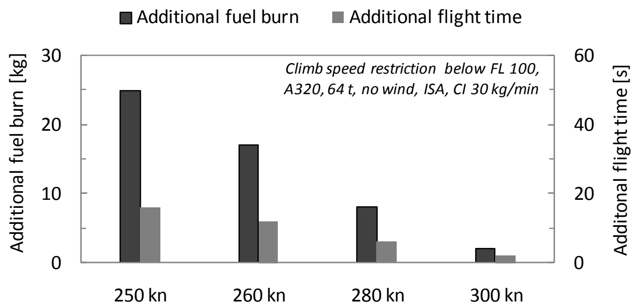

Figure 18. Speed restriction below FL 100: Impact on additional fuel and time

The speed limit of 250 kn causes additional fuel burn of around 25 kg and increases flight time by around 15 seconds. Assuming higher speed limits, these values are consequently lower. Figure 19 shows the according effects on additional costs.

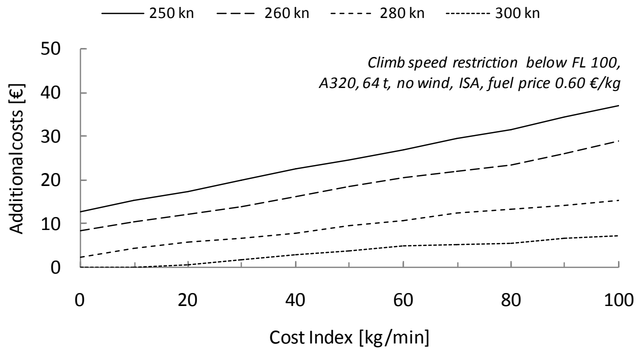

Figure 19. Speed restriction below FL 100: Impact on additional costs

The additional costs increase significantly with higher CIs, caused by the increasing difference between optimum (ECON) and actual (limited) speed and the moreover increasing time-related costs. For a speed limit of 250 kn the additional costs are between 15 € (CI 0) and 40 € (CI 100 kg/min) per flight (A320, fuel price 0.60 €/kg).

F. Departure delays

Delays at the departure airport cause additional costs to airspace users due to the direct impact of delays on the flight time. Thereby, it is assumed that the flight time begins with the Target Off-Block Time (TOBT) as requested by the airspace users. In general, two types of departure delays exist: Pre-departure delays at the stand and additional time in the taxi-out phase. The effect on additional fuel burn is assumed with 120 kg/h at the stand (Auxiliary Power Units only) and 630 kg/h during taxi (stationary ground) as given in [18].

Delay absorption at the stand contributes to fuel savings. This principle, the so called pre-departure sequencing (or departure metering), is one of the elements of the Airport Collaborative Decision Making (Airport CDM) concept [19]. However, due to uncertainties in the push-back and taxi-out process, it is not recommended to absorb the complete delay at the stand, as otherwise unnecessary gaps may reduce runway throughput and cause additional delays. It is rather recommended that the pre-departure sequencing strategy must be chosen cautiously in dependence on the fuel and time costs for airlines. Based on a simulation of outbound traffic at Frankfurt Airport [20], Figure 20 shows the effects of different pre-departure strategies on additional fuel burn and total delays.

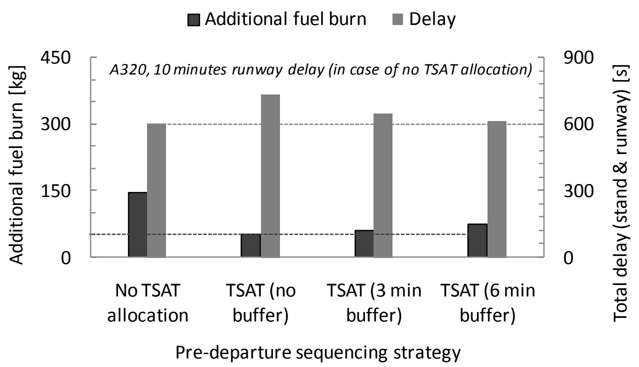

Figure 20. Departure delays: Impact on additional fuel and time

Assumed is a delay at the runway of 10 minutes in case that no stand delay is given (no Target Start-Up Approval Time, TSAT, is allocated). Additional fuel burn in this case (due to queuing at the runway) is about 150 kg. If the complete delay of 10 minutes is absorbed at the stand, the fuel burn can be reduced to about 50 kg. However, due to stochastic effects the delay at the runway cannot be avoided completely. Hence, total delay increases to about 12 minutes.

In case of the application of suitable buffer times (minutes of delay that are planned to be absorbed at the runway), the slight increase of additional fuel burn can be overcompensated by the total delay reduction. According to [20], a buffer of 6 minutes is considered to be the optimum. Figure 21 shows the effects of departure delays on total costs and thereby compares different pre-departure sequencing strategies.

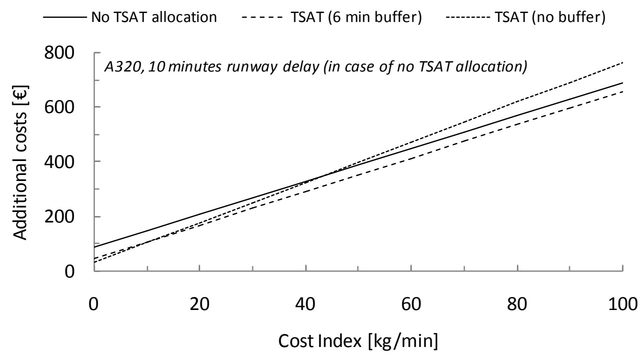

Figure 21. Departure delays: Impact on additional costs

The impact of departure delays on additional costs strongly depends on the cost index, as time-related costs play the major role, whereas the fuel costs have minor impact. For instance, with a CI of 30 kg/min, each minute of departure delay causes approximately 25 € additional costs. By the application of a pre-departure sequencing strategy, which includes a suitable time buffer considering the uncertainties of the outbound process, these additional costs can be reduced by about 30 to 40 € per flight in case of a departure delay of 10 minutes.

VI. SUMMARY

Within the current paper, a quantification of the additional costs caused by several trajectory restrictions was given. Thereby, identical efficiency metrics (additional fuel burn, additional flight time and additional costs) have been used for all kinds of restrictions, including horizontal, vertical and speed profile restrictions as well as delays. With it, and this is in particular the key motivation for using costs as an efficiency metric, the impact of different restrictions becomes much more comparable.

Especially due the fact that interdependencies with other key performance areas (such as safety, capacity) exist, inefficiencies can never be avoided completely. However, in order to maximize efficiency, a better understanding of restriction impacts based on a consistent metric supports decision makers in all planning phase (from airspace planning to air traffic control advisories) to identify restrictions fulfilling the requirements (e.g. maximized utilization of capacities) and thereby causing the lowest costs to airspace users.

The impact of route extensions on additional costs was quantified as between 3 € and 11 € per NM for an A320 and a given fuel price of 0.60 €/kg. Moreover, it was shown that also vertical profile restrictions contribute to significant additional costs. For instance, a flight level capping to FL 240 for a flight with a distance of 500 NM causes approximately 300 € additional costs (A320, fuel price 0.60 €/kg). Although these restrictions appear relatively seldom (12% of flights) and only for short flight distances, their further avoidance can strongly contribute to efficiency improvements.

As a further conclusion it can be stated that the impact of delays on additional costs must be considered. It was shown that for a cost index of 30 kg/min, one minute of departure delay causes around 25 € additional costs. Hence, the effects of measures that contribute to a reduction of horizontal and vertical profile restrictions must carefully be assessed in order to avoid negative effects on efficiency, if on the other hand delays increase excessively. Finally, it was also shown that measures to absorb unnecessary delays efficiently contributes to significant costs savings for airspace users.

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