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ASSESSMENT OF ENERGY-EFFICIENT APPROACHES WITH INCREASED GLIDESLOPE ANGLES

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Abstract

In order to tackle aviation's future challenges, aircraft need to fly as energy-efficient as possible. This does not only comprise technical development but also operational means, by which the energy efficiency of the aircraft can be increased through avoiding unnecessary waste of energy. Such operational means can be applied already with today's aircraft and can thus immediately increase the energy efficiency of today's aircraft without extensive technical changes. On the other hand, the further reduction of noise immissions of aircraft in the vicinity of airports is another important factor for future aviation. Increased glideslope angles during final approach are one operational means to reduce the noise immissions from aircraft. However, the increase of the glideslope angle must not negatively affect the aircraft's ability to fly energy-efficiently. In order to investigate the ability of modern transport aircraft to fly steeper approaches energy-efficiently, so-called energy envelopes have been evaluated. For this, a method of backwards simulations of energy-efficient approaches was used. The evaluation was performed for the A320 as representative aircraft type. The variation of fuel consumption and noise within the energy envelope are outlined and discussed. Furthermore, parameters, which influence the shape of the energy envelope, hence the ability of the aircraft to fly energy-efficiently with steeper approaches, are presented as well.

Keywords: increased glideslope angle, energy-efficient approach, energy envelope

1. Introduction

A major challenge for aviation is to reduce its environmental impact [1]. Energy-efficient flying is one key to this, as it can already be applied in today's aircraft operations, without the necessity of extensive technical changes and time-consuming development. By just flying more energy-efficiently fuel, hence CO_2 and other emissions, can be saved directly.

For the terminal maneuvering area, however, the reduction of aviation's environmental impact does not only mean to reduce fuel burn but also to further reduce noise immissions. One operational means to reduce noise is to increase the glideslope angle [2]. Through increasing the glideslope angle, approaching aircraft fly at higher altitudes over a specific point below the final approach path. This aims at reducing the noise level on ground [3]. With steeper approaches, however, the ability of the aircraft to decelerate is reduced. In order to decelerate to the final approach speed pilots might be forced to use airbrakes. The steeper the glideslope angle, the more the airbrakes need to be used. This must be prevented by any means, as the use of spoilers not only increases noise but can also be regarded as energy-inefficient as it is a waste of energy. The use of airbrakes reveals an unnecessary fuel consumption earlier in the flight, which could be prevented if the flight was performed more energy-efficiently.

Today's typical glideslope angle is 3° but some airports already introduced increased glideslope angles, such as e.g., Frankfurt/Main, Germany (EDDF), with a glideslope angle of 3.2° at the northern runway 25R [4]. An extreme example is London City airport (EGLC) with a glideslope angle of 5.5° [5]. However, operations at London City are limited to only some specific aircraft types which are able to fly such steep final approaches (e.g., Avro RJ).

Theoretically, an increased flight altitude would directly lead to a reduced noise level on ground, if the flight state at a given point on the glidepath was not changed by the steeper flight path. However, this is not possible in practice, as the ability of modern aircraft to descend is limited (even with engines in idle) during final approach. In order to keep the airframe noise of the aircraft as low as possible for as long as possible during the approach, landing gear and flaps should be deployed as late as possible and spoilers should not be used at all. In any case, the aircraft has to be fully configured and reach its final approach speed at the so-called stabilization height, which is typically 1,000 ft above ground for instrument approaches. The steeper the glidepath, the worse is the ability of the aircraft to reduce its speed to final approach speed. As a consequence, pilots need to configure the aircraft earlier in order to increase drag, hence improve the ability to decelerate to final approach speed. If the flight path angle is too steep, some aircraft types might even be forced to use spoilers under some conditions, such as tailwind or low aircraft mass. Also, pilots tend to be conservative in their decisions about when to configure the aircraft in order not to risk a go-around because of an unstable configuration at stabilization height. For this reason, there is a risk to reach the final approach speed and configuration way above the stabilization height, which leads to a too early increase of thrust, hence fuel burn and noise increase as well. Both cases, the use of spoilers and reaching the final approach speed too early, resulting in a too early thrust increase, can be regarded as energy-inefficient.

In order not to risk that an increase of the glideslope angle has a deteriorating effect on noise, fuel burn and emissions, the flight performance limitations of the specific aircraft type under the given conditions must be well known und understood. For the designer of approach procedures, it is essential to know which aircraft are able to follow the operational changes and which are not, in order to decide which glideslope angle leads to the lowest noise level on ground and/or the lowest fuel consumption.

From a flight physics point of view, an energy-efficient approach is defined here as one where the aircraft (i) is flown using idle thrust until reaching the stabilization height, (ii) is configured as late as possible so that the final approach speed is reached just at the stabilization height and not earlier, and (iii) no spoilers are used to decelerate the aircraft to final approach speed. These requirements have been chosen here this way, as any violation of one of the criteria would result in a waste of energy. For flying as energy-efficient as possible any waste of energy should be omitted. For this reason, the criteria defined here are a logical consequence of the requirement to fly an approach as energy-efficient as possible.

The requirements as stated above result in a specific speed margin within which the aircraft must intercept the glideslope. With a too low intercept speed the final approach speed would be reached too early, resulting in a too early thrust increase. With a too high intercept speed the final approach speed could not be reached without the use of spoilers. Within the margin of glideslope intercept speeds, the different abilities to decelerate can be considered by a variation of the points where the aircraft is configured.

The specific speed margin at glideslope intercept to allow an energy-efficient approach changes with increasing glideslope angle. The envelope of energy-efficient approaches as a function of the intercept speed and the glideslope angle is introduced here as the “energy envelope”. Within this energy envelope, energy-efficient approaches are feasible. However, fuel consumption and noise change within the energy envelope. Also, the shape of the energy envelope changes with different flying conditions, such as wind, aircraft mass or intercept altitude.

The aim of the presented paper is to give an overview of flight-physical aspects of energy-efficient approaches and the relation to fuel consumption and noise in the context of increased glideslope angles. The paper describes the methods developed to assess energy-efficient approaches and to generate energy envelopes. The used aircraft performance model and the verification of simulation results will be described. Results for the Airbus A320 as example aircraft and different flying conditions are given and the main influencing factors will be described.

2. Approach Calculations

The basis for the evaluation of energy envelopes are approach simulations which fulfill the requirements for energy-efficient approaches as defined in section 1. In order to guarantee that the simulated approaches fulfill these requirements, a specific calculation method is used, which is explained in the following.

2.1 Method

In order to guarantee that the aircraft is always in final approach configuration and has reached its final approach speed when reaching the stabilization height of 1,000 ft above ground, the approach calculations are performed in backwards direction. This means that the simulation is started at the threshold. From there, a linear trajectory of the aircraft is calculated backwards using the final approach speed and the respective glideslope angle until reaching a height above ground of 1,000 ft. Of course, this stable flight segment could be omitted, as it does not influence the energy envelope. This section is only calculated for reasons of completeness. However, the calculation could also be started at the stabilization height.

From the stabilization height on, idle thrust is applied resulting in a specific deceleration for the specific flight state. Given the current deceleration, the trajectory is calculated further in backwards direction. When reaching the respective flap deflection speed, the flaps are retracted one step. Please be aware that the equivalent of a deployment in reality is a retraction in the backwards calculation. The same applies for the landing gear, which is retracted at a specific procedural position. In this paper the energy envelopes are presented for the A320. For this aircraft type, the standard operational procedure schedules the configuration of the aircraft during approach in a way that the glideslope is intercepted with flaps in Config 2 with gear up, followed by the gear deployment and flap deflections of Config 3 and 4 further down the glide [6]. Generally, the gear can be deployed independently from the setting of Config 3. However, for reasons of noise prevention, the gear deployment should be as late as possible. For this reason, the deployment of the landing gear, Config 3, and Config 4 are clustered here as consecutive events.

The approach is calculated this way until reaching the glideslope intercept altitude. From this point on the altitude is kept constant and the airspeed increases until 250 kts, where the simulation is stopped.

The airspeed at glideslope intercept can be varied through a variation of the airspeed at which the flaps and the landing gear are deployed. This can be varied between the respective maximum flap extension speed (VFE) of the respectively following flap configuration (resulting in the highest intercept speed) and the respective target speed of each flap setting (resulting in the lowest intercept speed). Figure 1 shows these two extreme cases for the A320.

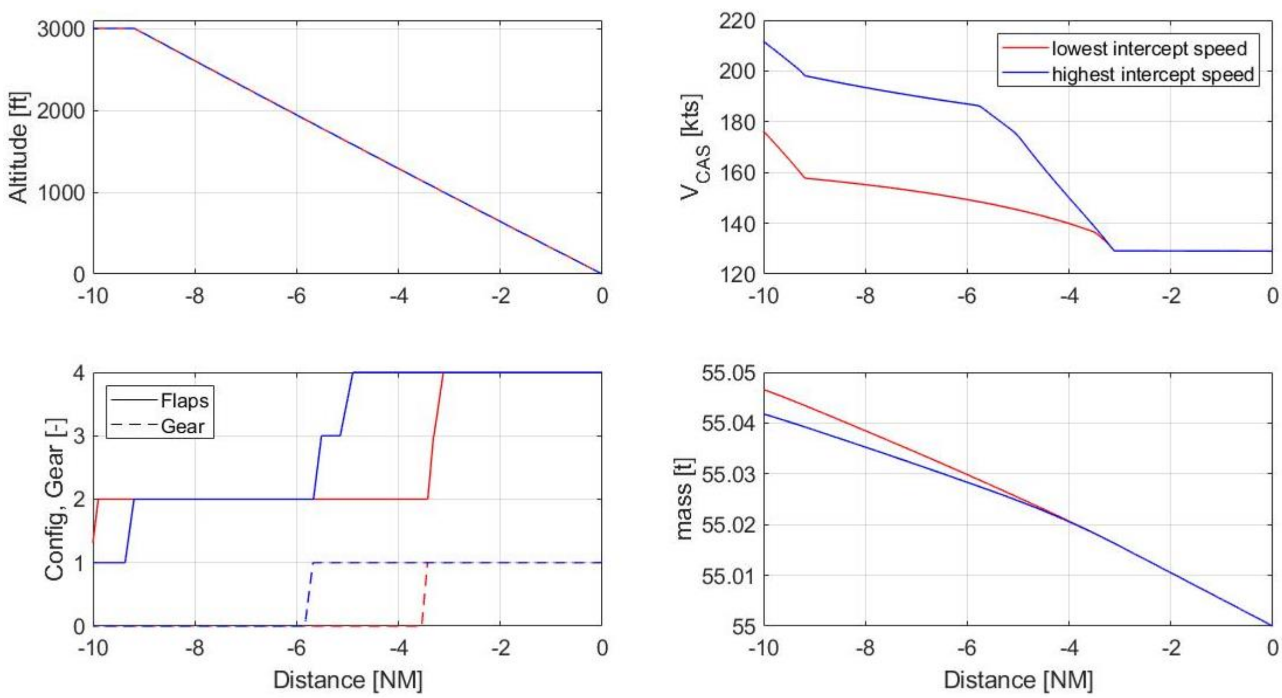

Figure 1 – Energy-efficient approaches with maximum and minimum intercept speed (A320, aircraft mass 55 tons, intercept altitude 3,000 ft, no wind).

By using this method of the backwards calculation, it is assured that the aircraft is always in final approach configuration and at final approach speed at the stabilization height and that the aircraft flies with engines in idle during the whole approach. Using a forward calculation could possibly violate at least the first requirement and would thus lead to a higher computation effort, as the boundaries of the energy envelope would need to be computed iteratively.

In cases in which the aircraft accelerates at any point during the calculations it is assumed that the pilot would use airbrakes in order to keep the speed at least constant. As the use of airbrakes was considered energy-inefficient, such cases are disregarded for the evaluation of the energy envelope.

2.2 Aircraft Performance Model

The most important parameter for the evaluation of the energy envelope is the speed profile during the approach. From the equations of motion the acceleration $\partial V_{TAS}/\partial t$ of the aircraft at each timestep t_i can be determined with the current aerodynamic flight path angle $\gamma_a(t_i)$, the current aerodynamic lift $C_L(t_i)$ and drag $C_D(t_i)$ and the current aircraft mass $m(t_i)$ and total thrust $T(t_i)$ (here always idle thrust) [7]

$$\frac{\partial V_{TAS}}{\partial t}(t_i) = \frac{T(t_i)}{m(t_i) \cdot g} - \frac{C_D(t_i)}{C_L(t_i)} \cdot \cos\big(\gamma_a(t_i)\big) - \sin\big(\gamma_a(t_i)\big). \tag{1}$$

The aerodynamic glide path angle γ_a depends on the actual glide path angle γ and the wind. Apart from this, wind is also considered through the transformation of the airspeed into ground speed, which is required for the calculation of the trajectory. Until reaching the intercept altitude in the backwards calculation, the flight path angle γ is always the negative glideslope angle GSA corrected by a simple function to take the earth's curvature into account using the current distance to the runway threshold $Dist(t_i)$.

$$\gamma(t_i) = \begin{cases} -GSA - Dist(t_i) \cdot 1852/60 & Alt(t_{i-1}) < Alt_{Intercept} \\ 0 & Alt(t_{i-1}) \geq Alt_{Intercept} \end{cases} \tag{2}$$

Please be aware, that due to the backwards calculation the previous timestep of the simulation t_{i-1} represents the subsequent timestep in real flight. The current lift coefficient $C_L(t_i)$ is a function of the current aircraft mass $m(t_i)$, the current altitude-dependent air density $\rho\big(Alt(t_i)\big)$, the current true airspeed $V_{TAS}(t_i)$, and the constant wing area S

$$C_L(t_i) = \frac{m(t_i) \cdot g}{\frac{\rho\left(Alt(t_i)\right)}{2} \cdot V_{TAS}(t_i)^2 \cdot S}. \tag{3}$$

The only parameters left in equation (1) are the thrust and the aerodynamic drag. Generally, any model for thrust and aerodynamic drag can be used for this application. For the Airbus A320, reliable data for aerodynamic drag polars and thrust tables were available from DLR's research aircraft A320 ATRA (Advanced Technology Research Aircraft).

The aerodynamic drag is modeled here as a function of the current lift coefficient $C_L(t_i)$, the current Mach number $Ma(t_i)$ and the flap configuration

$$C_D(t_i) = f(C_L(t_i), Ma(t_i), CONFIG). \tag{4}$$

Figure 2 exemplarily shows a set of drag polars for different flap and gear configurations and a specific Mach number. Please note that for confidentiality reasons no ticks can be shown on the axes of Figure 2.

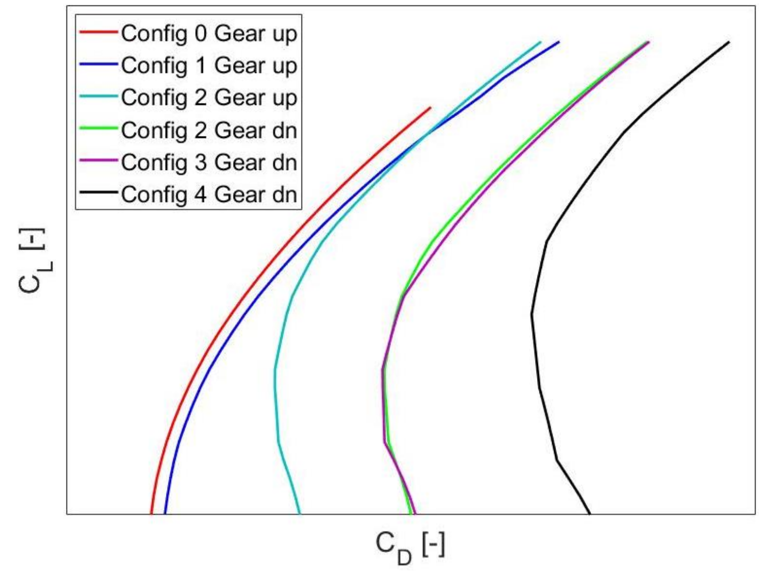

Figure 2 – Drag polars for a specific Mach number and different flap and gear configurations.

The current idle thrust $T(t_i)$ is given by a thrust table. Here, the idle thrust only depends on the current altitude $Alt(t_i)$ and the Mach number $Ma(t_i)$

$$T(t_i) = f\big(Alt(t_i), Ma(t_i)\big). \tag{5}$$

Figure 3 shows the idle thrust table for the A320 as used here. Please note that for confidentiality reasons no ticks can be shown on the z-axis of Figure 3.

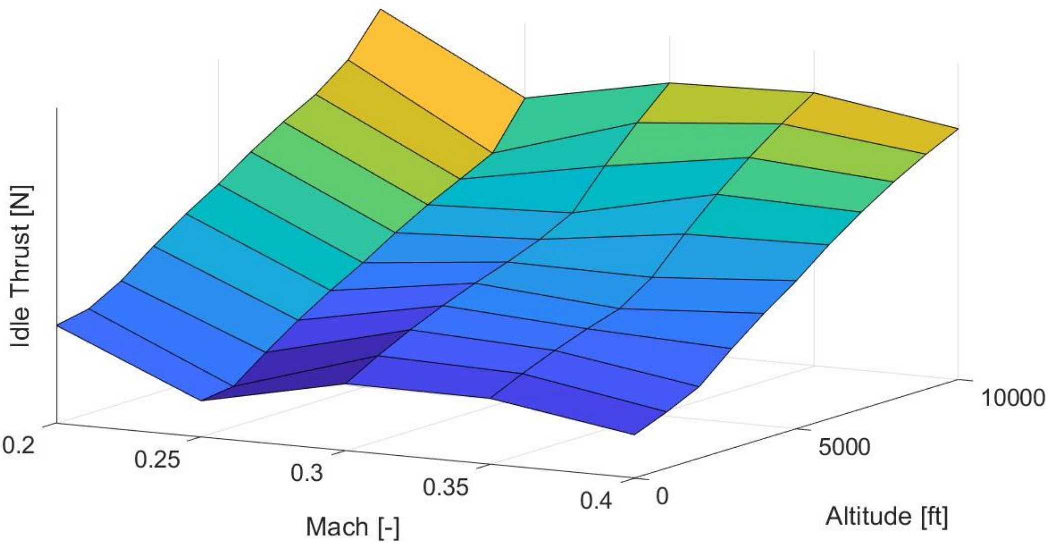

Figure 3 – Idle thrust table.

As stated before, any other aircraft performance model can be used for the presented purpose as well, as long as it provides data on the aerodynamic drag and idle thrust with sufficient accuracy. This means that the aircraft performance model is able to represent the speed profile along the approach of real flights within deviations of only a few knots, as will be shown in the next section.

2.3 Verification

The calculated approaches have been verified against real flight data. Real approaches with A320 aircraft were compared to the calculated approaches using the same conditions in terms of aircraft mass, wind, etc. Of course, the calculated approaches can only be compared to real flight data in case in which the real approaches were also performed with engines in idle.

For the verification of the approach reverse calculation the use of the correct wind is essential. Therefore, the wind information from the flight data is used here. Also, the flaps and landing gear were deployed at exactly the same position as in the real flight. Another important change in the algorithms for the verification purpose is to use the actual flight path angle from the flight data instead of a constant flight path angle that represents the glideslope angle. As in real flight aircraft never fly exactly on the glideslope, changes in the flight path angle inevitably lead to differences in the speed profile if this is not covered correctly in the backwards simulations.

Figure 4 shows an example for the comparison of approaches. The upper row of plots in Figure 4 shows the input values for the aircraft configuration and wind. One can observe that the simulation results (red lines) match the time histories of the real flight (black lines). The lower row of plots in Figure 4 shows the resulting trajectory in terms of altitude, true airspeed and ground speed, as well as the aircraft mass. Please be aware, that the aircraft mass was not recorded with the same frequency as the other signals, for which reason the graph of the aircraft mass shows large steps for the flight data. In the lower left plot, showing the altitude, one can observe the non-linear trajectory of the simulation, which matches the flight data exactly. By using the actual flight path angle, the calculated speed profiles of true airspeed and ground speed fit sufficiently well to the real flight data.

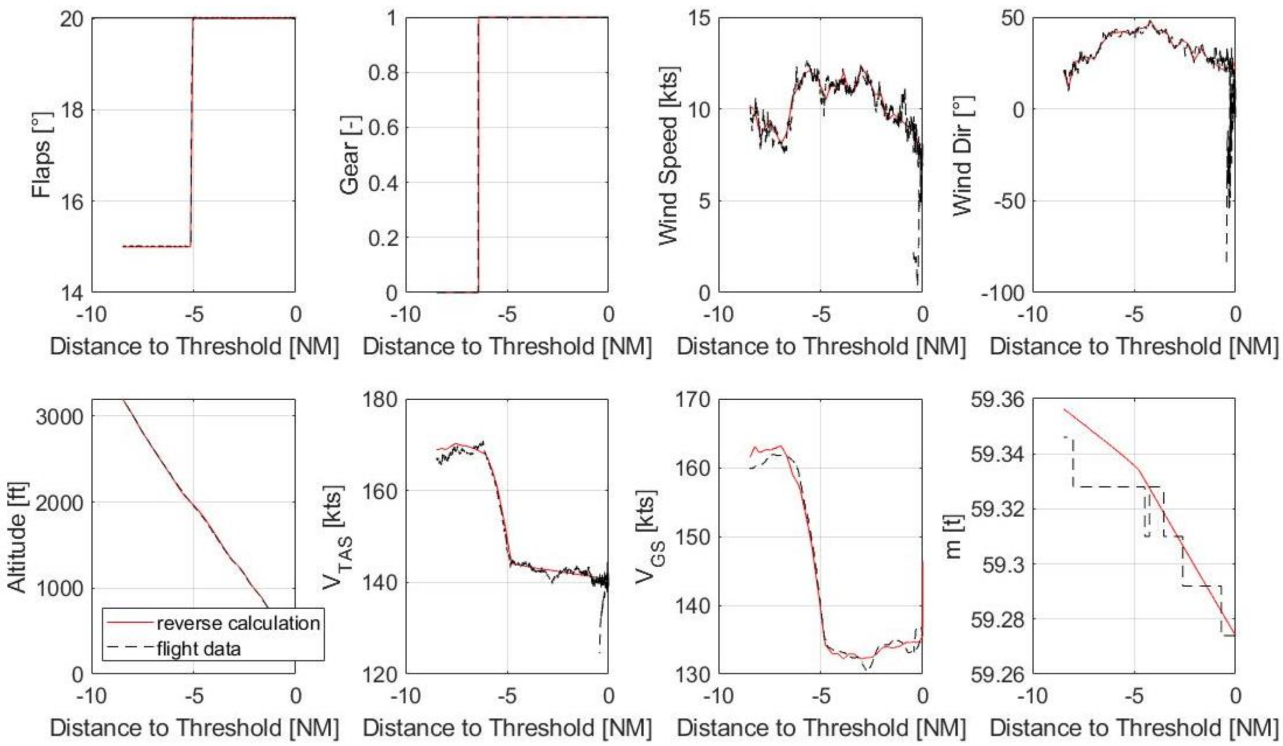

Figure 4 – Comparison of a calculated approach with real flight data for the A320.

Figure 4 clearly shows how well the used calculation method is able to match the flight data. One can see in Figure 4 that, if the flap and gear deployments are aligned sufficiently well with the flight data, the resulting trajectories match sufficiently well, too.

However, the verification of the model results can only be performed using existing flight data. Unfortunately, those available flight data comprise only the common 3° glideslope angle or the increased glideslope angle of 3.2° at runway 25R of Frankfurt/Main airport (EDDF). For steeper approaches no flight data were available, so that the accuracy of the approach calculation for larger glideslope angles could not be verified. However, as accurate flight performance data were used, it can be expected that the results are also acceptably accurate for higher glideslope angles.

3. Energy Envelope

The boundaries of the airspeed at glideslope intercept within which an energy-efficient approach can be performed vary with the glideslope angle. The variation of the glideslope angle results in a speed envelope for energy-efficient approaches, which is called here the energy envelope. One such envelope is shown exemplarily in Figure 5.

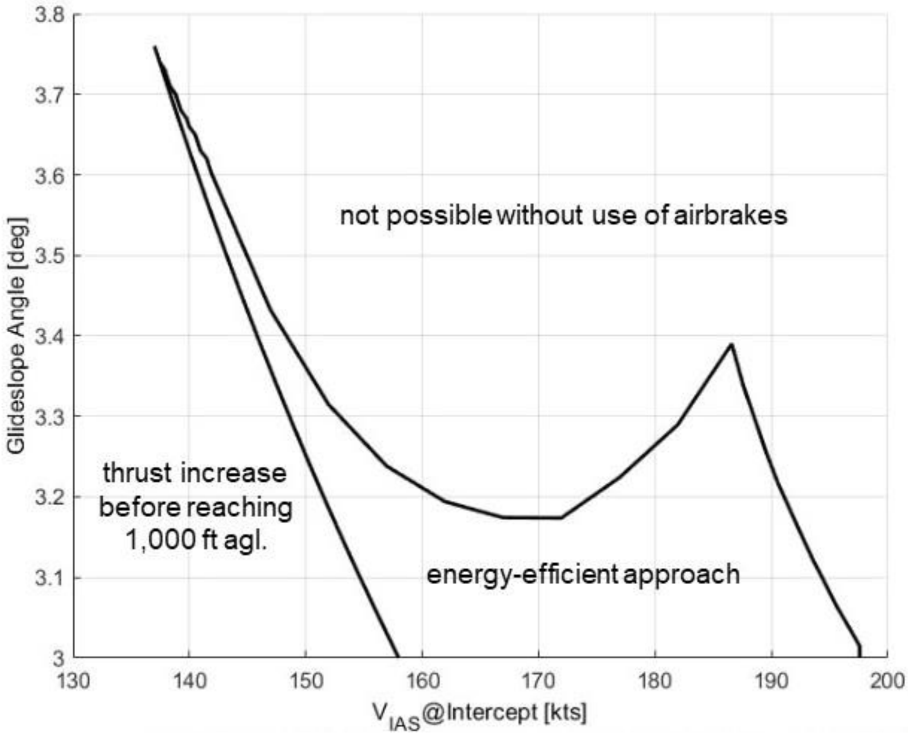

Figure 5 – Exemplary energy envelope for energy-efficient approaches of the A320.

Figure 5 outlines the characteristic shape of the envelope with two peaks at lower and higher intercept speeds. Left of the envelope the intercept speed is too low, resulting in reaching the final approach speed too early, inevitably leading to an unnecessarily early thrust increase, hence fuel burn. On the upper and right side of the envelope the aircraft is not able to decelerate to final approach speed at 1,000 ft above ground without the use of airbrakes.

The belly-like upper boundary of the energy envelope is related to the power curve of the aircraft. For this reason, there are some regions of the glideslope angle where an energy-efficient approach is only possible at high intercept speeds and with low intercept speeds, but not in between (e.g., between a glideslope angle of about 3.2° to about 3.4°).

With a high intercept speed (the right peak of the energy envelope) the lift-to-drag-ratio is not at its best for the given configuration. For this reason, the aircraft is still able to decelerate even with flaps in Config 2 and gear up. The left peak of the energy boundary represents the flight regime at the backside of the power curve. Here, the lift-to-drag-ratio is again lower than its optimum, making it possible that the aircraft decelerates even without the use of airbrakes. However, those low intercept speeds are not desirable as they limit the runway throughput. However, in between the two peaks the aircraft flies at or near its best lift-to-drag-ratio, leading to a worse ability of the aircraft to decelerate. In this region the pilot would have to use airbrakes to prevent that the aircraft accelerates.

The shape of the boundaries of the energy envelope are mostly influenced by the segment with flaps in Config 2 and gear up. This is the longest segment on the glidepath and as it is also the flap and gear configuration with the lowest drag during final approach (remember that in the simulations the glideslope is always intercepted with flaps in Config 2 with gear up) the ability of the aircraft to decelerate is deteriorated in this segment first, in case that the glideslope is too steep. Please note that here the threshold for the use of airbrakes is at a deceleration of 0 kts/s. In reality, pilots might accept a slight acceleration in this segment, as they can get rid of the additional speed by deploying the landing gear a little earlier. However, in the simulations no positive rate of the indicated airspeed was tolerated.

One can finally observe on Figure 5 that in this specific case for glideslope angles above 3.4° and up to about 3.7° energy-efficient flight is only possible in a very narrow region at the backside of the power-curve. It is theoretically possible to fly such steep final approaches in an energy-efficient way, but only with very low intercept speeds in the region of about 140 kts, which is practically only feasible at airports or in situations with low traffic density. As we will see later, a high intercept speed is not only desirable from the runway throughput point of view but also from the point of view of fuel consumption.

One must keep in mind that the shape of the envelope as shown in Figure 5 corresponds to the chosen procedure to configure the aircraft. As mentioned before, it was decided to follow the Airbus standard procedure to intercept the glideslope with flaps in Config 2 and with gear up. Also, the gear is always deployed right before deploying the flaps to Config 3. For reasons of noise abatement, it was decided here to deploy the gear as late as possible. Of course, the gear can be decoupled from the deflection of the flaps to Config 3 and can be deployed earlier. This would increase the aircraft's ability to decelerate and would change the shape of the envelope at least to some extent.

For the procedure used here that involves the deployment of the gear as late as possible, directly followed by the deflection of the flaps to Config 3 and full, Figure 6 shows the altitudes at which the aircraft needs to be configured, respectively, for a glideslope angle of 3°. The intercept speed range shown on the y-axis corresponds to the envelope boundaries for a glideslope angle of 3° as depicted in Figure 5.

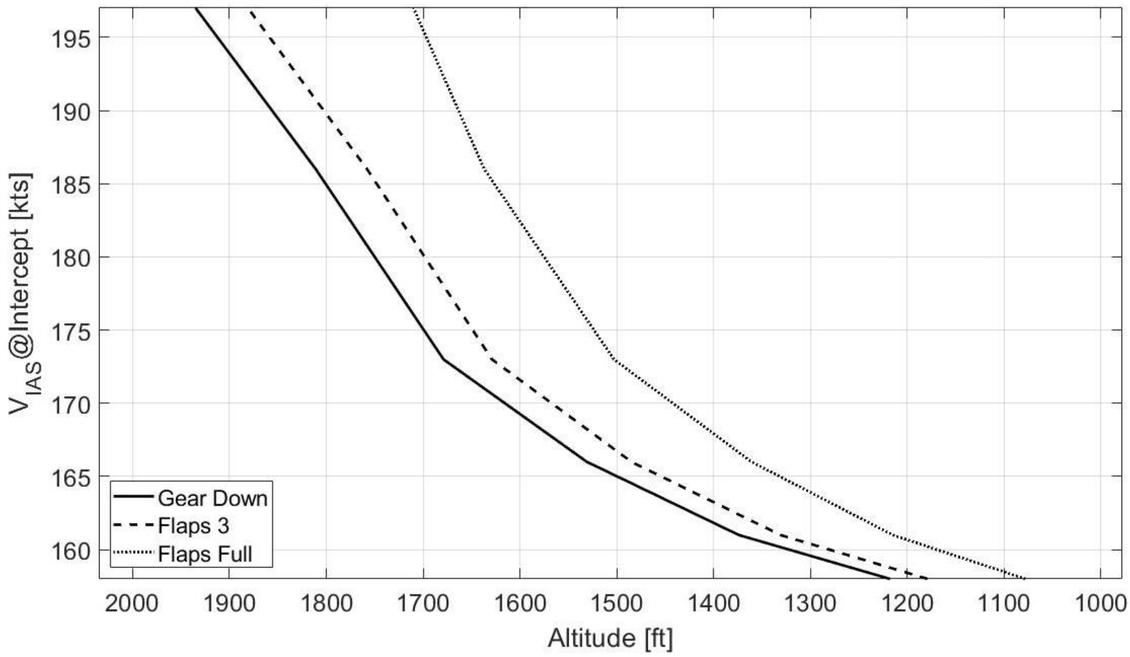

Figure 6 – Exemplary depiction of configuration altitudes within the energy envelope for the A320 and 3° glideslope angle.

It is obvious from Figure 6 that with increasing intercept speed the aircraft needs to be configured earlier, meaning at higher altitudes, in order to reach the final approach speed at 1,000 ft above ground.

Within the energy envelope all approaches can be considered energy-efficient. However, fuel consumption and also noise emissions vary within the envelope. Figure 7 shows the distribution of fuel consumption during final approach within the energy envelope for one example case of the A320 with a gross weight of 55 t, an intercept altitude of 3,000 ft and no wind. The fuel consumption outlined in Figure 7 is derived between glideslope intercept and touchdown.

One can observe in Figure 7 that the fuel consumption decreases with increasing intercept speed and with increasing glideslope angle, leading to the lowest fuel consumption in the upper right corner of the envelope and the highest fuel consumption in the lower left corner.

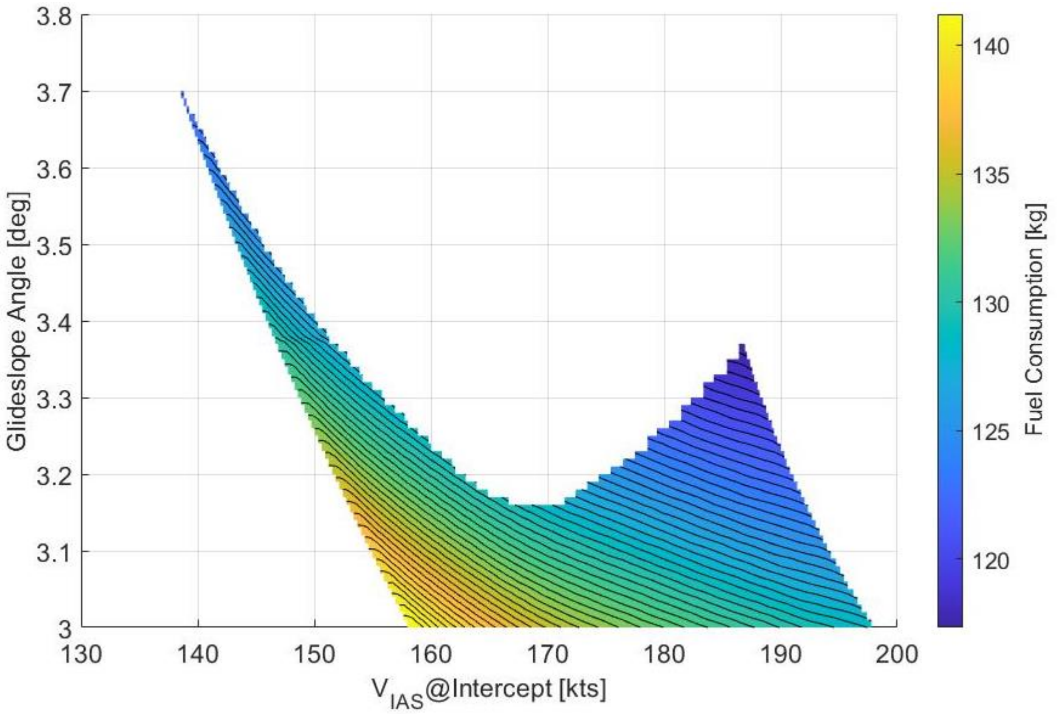

Figure 7 – Fuel consumption during final approach within the energy envelope (A320, aircraft mass 55 t, intercept altitude 3,000 ft, no wind).

The reader should be aware, that the reduction of fuel consumption only stems from a smaller flying time between glideslope intercept and touchdown. In all approach cases shown in the envelope the engines are in idle until reaching 1,000 ft above ground, hence the fuel-burn in kg/s is always the same until that point. Also, below 1,000 ft above ground the final approach speed is the same for all approach cases shown in the energy envelope as the aircraft mass, wind etc. are the same for all approaches. Therefore, the fuel-burn in kg/s below 1,000 ft above ground is also the same for all cases, except that it is higher than the idle fuel flow. With increasing intercept speed the flying time from glideslope intercept to touchdown decreases, which directly saves fuel. The increased glideslope angle has a similar effect on the fuel burn, as with the same intercept altitude the glideslope intercept point moves towards the runway. This way, the flying time from glideslope intercept to touchdown decreases with increasing glideslope as well.

The values for fuel consumptions discussed before only concern the flight segment from glideslope intercept until touchdown. In any case, an approach with a faster intercept speed requires a later top of descent and therefore consumes more fuel on cruise level. This compensates indeed some of the fuel savings at final approach. Nevertheless, an approach with a faster intercept speed still consumes less fuel than one with a smaller intercept speed, even when the whole fuel consumption from a fixed point before the top of descent to touchdown is considered.

Fuel consumption is only one factor of a flight's environmental impact that varies within the energy envelope. Also, noise is affected by the intercept speed and the glideslope angle. No quantitative results on noise within the energy envelope will be presented here. However, some qualitative conclusions shall be made.

Generally, the approaches with a higher intercept speed should be louder than those with lower intercept speeds. The reason for this is, on the one hand, the faster airspeed, which results in more airframe noise by itself and, on the other hand, the necessity to configure the aircraft earlier with higher intercept speeds, which results in higher noise levels at least in some regions below the glidepath. Apart from this, an increase of the glideslope angle should generally reduce the noise perception on ground because of the higher altitude of the aircraft over a given point in front of the runway. This benefit is at least partly compensated by the necessity to configure the aircraft earlier with higher glideslope angles. Given the same intercept speed, a higher glideslope angle requires an earlier configuration of the aircraft because of the lower ability of the aircraft to decelerate. Nevertheless, past noise assessments for increased glideslope angles revealed that there is still a net benefit in terms of noise, even if an earlier configuration of the aircraft is considered [2].

Approaches with higher glideslope angles should therefore be less noisy than those with lower glideslope angles.

These qualitative thoughts on noise show at least that the noise minimum within the energy envelope is probably not in the same area as the minimum of the fuel consumption. Presumably, the noise minimum lies somewhere in the upper left part of the energy envelope, whereas the one of the fuel consumption lies in the upper right corner. For these reasons, it can be expected that the final approach cannot be optimized with respect to both noise and fuel consumption, but that these parameters have to be traded against each other.

4. Influencing Factors

The shape of the energy envelope is influenced by any factor that influences the flight performance, hence the ability of an aircraft to fly energy-efficiently. Those are e.g., the aircraft mass and the altitude at which the glideslope is intercepted, but also wind.

The aim of the presented work is not to give most accurate values for energy envelopes for a specific aircraft but to analyze and outline the most influencing effects on the ability of modern transport aircraft to fly energy-efficient approaches with increased glideslope angles.

As mentioned before, the aircraft mass is one of the major influencing parameters. Figure 8 shows different energy envelopes for the A320 with different aircraft masses. The aircraft mass denoted here is always the mass that the aircraft has at touchdown.

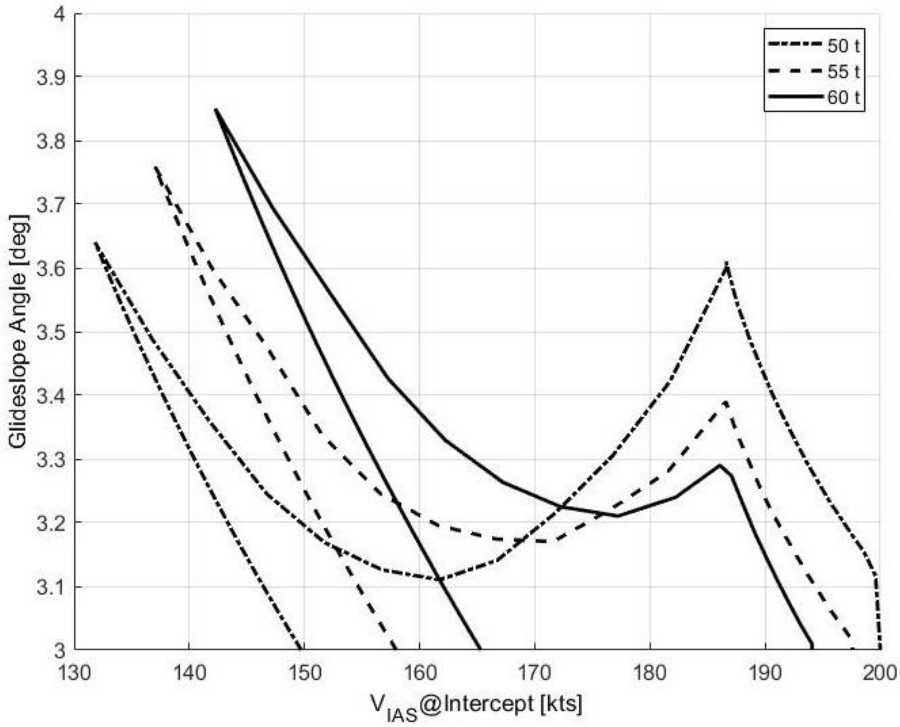

Figure 8 – Influence of aircraft mass on the envelope for energy-efficient approaches for the A320 (intercept altitude 3,000 ft, no wind).

One can clearly see how big the influence of the aircraft mass is on the shape of the energy envelope and on the ability of the aircraft to fly energy-efficient approaches given a specific glideslope angle. Interestingly, the influence of the aircraft mass on the two peaks of the maximum glideslope angle is different. While the left peak at lower intercept speeds increases with increasing aircraft mass, the right peak at higher intercept speeds decreases with increasing aircraft mass. This is an interesting outcome, as it does not support any of the two general opinions, that heavier aircraft can either fly steeper or not – this depends on the intercept speeds, at least in case that the approach is to be performed in an energy-efficient manner. For an intercept speed of e.g., 180 kts the lightest aircraft can fly the steepest glideslope angle, whereas for an intercept speed of e.g., 170 kts the heaviest aircraft can fly the steepest approach.

Another influencing parameter is the glideslope intercept altitude. At the first glimpse, this parameter might not be very obvious to be an influencing parameter, but a change of the intercept altitude changes the shape of the energy envelope and the ability to fly energy-efficient approaches significantly, as can be seen in Figure 9. The major effect from this is the change of air density with increasing intercept altitude, which influences the deceleration rate of the aircraft. The other effect is that with increasing intercept altitude, the distance and flight time between intercept and touchdown is increased as well, resulting in higher required intercept speeds to prevent to reach the final approach speed too early. For this reason, the energy envelope is shifted towards higher intercept speeds with increasing intercept altitude, but it also shrinks in size.

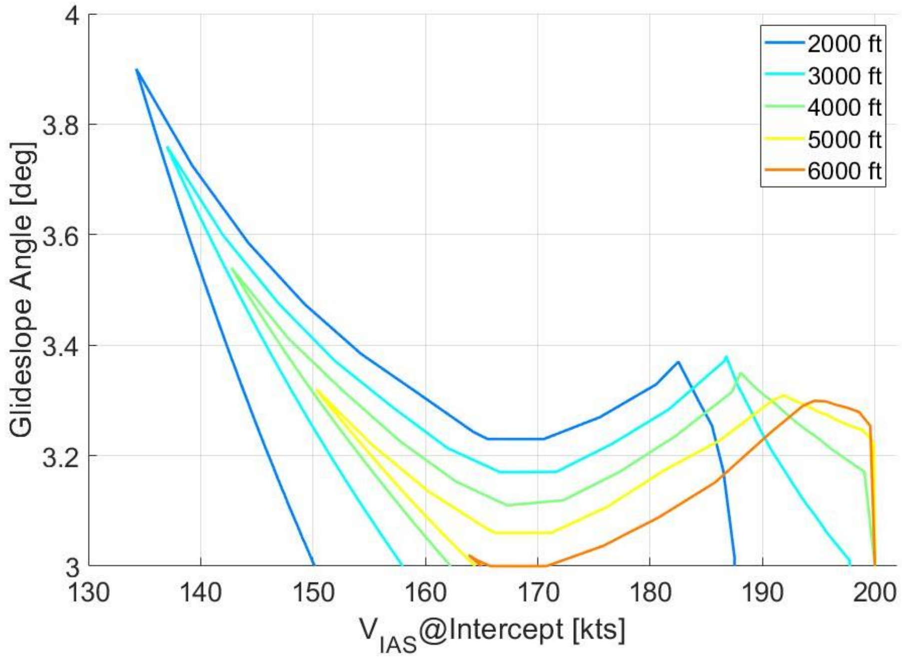

Figure 9 – Influence of intercept altitude on the envelope for energy-efficient approaches for the A320 (aircraft mass 55 t, no wind).

Figure 9 shows that an increasing glideslope intercept altitude leads to a decreasing maximum glidepath angle over a wide range of intercept speeds. Only for high intercept speeds the maximum possible glideslope angle is nearly unchanged, although the right peak of the envelope moves towards higher intercept speeds. However, for an intercept speed of e.g., 180 kts the maximum possible glideslope angle decreases from about 3.35° to about 3.1° if the intercept altitude is increased from 2,000 ft to 6,000 ft.

This means that if it is intended to increase the glideslope angle, the respective intercept altitude should be rather lower than higher than before. Otherwise, the risk occurs that pilots are not able to fly the approaches in an energy-efficient way and that the intended noise reduction from the glideslope angle increase is at least partly reversed by the use of airbrakes in order to reduce the aircraft's speed.

The third and maybe strongest parameter that influences the shape of the energy envelope is the wind. Headwind or tailwind change the ability of the aircraft to decelerate during final approach, hence the wind has a significant influence on the aircraft's ability to fly steeper approaches still in an energy-efficient manner. Figure 10 depicts the energy envelopes for different wind speeds. In this case the wind is always parallel to the flight direction, meaning without any crosswind component. Negative wind speeds are tailwinds, positive wind speeds are headwinds. Please note, that for reasons of simplification, the wind is constant here during the whole approach. This is, of course, not true in reality. However, the effects due to headwind or tailwind as shown here are generally the same, even if the wind speed changes during the approach.

The effect due to wind can be explained by two different reasons. First, as during the final approach the aircraft has to follow the glideslope, it flies with a given flight path angle. Therefore, the wind changes the aerodynamic flight path angle, meaning the flight path angle flown through the moving air. This angle is relevant for the deceleration. With prevailing tailwind, the aerodynamic flight path angle is steeper, resulting in a lower deceleration. With headwind, the aerodynamic flight path angle is shallower, resulting in an increased deceleration, or an improved ability of the aircraft to fly steeper glideslope angles. The second effect is the change of the ground speed due to the wind. As the distance between glideslope intercept and the threshold is constant (for the same glideslope angle), the remaining flight time is changed by the change of the ground speed. This leads to a lower intercept speed in case of tailwind (larger ground speed) even with the same deceleration rate – and vice versa.

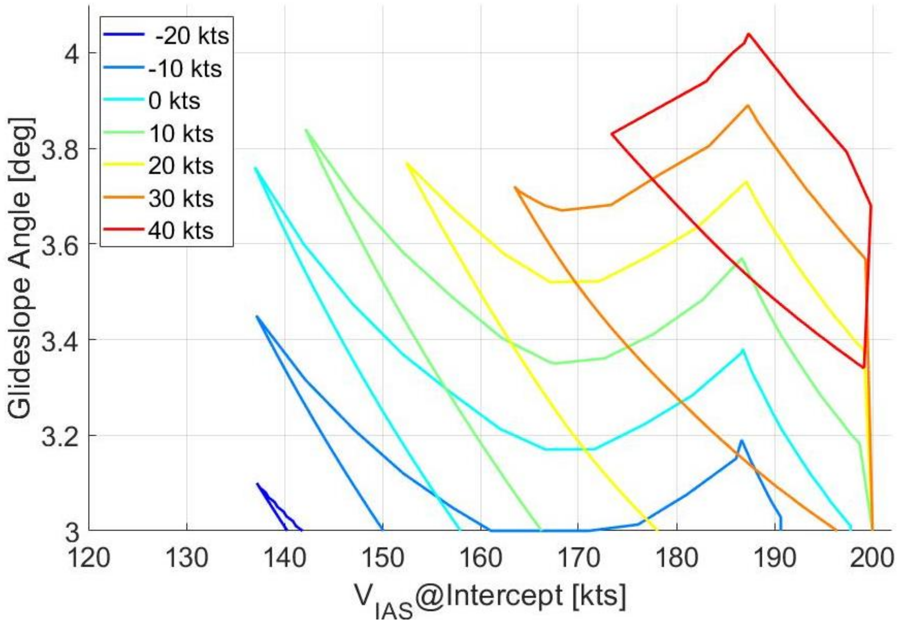

Figure 10 – Influence of wind on the envelope for energy-efficient approaches for the A320 (intercept with flaps in Config 2, aircraft mass 55 t, intercept altitude 3,000 ft).

Figure 10 clearly shows the above-mentioned effects. It is obvious how much the wind increases or decreases the ability to fly steeper approaches. Already with a constant tailwind of 10 kts, the energy envelope shrinks so much that only a narrow region of intercept speeds between somewhat below 180 kts and 190 kts and between 150 kts and 160 kts is possible for the standard 3° approach. Already for a glideslope angle of 3.2° there is almost no possibility to fly energy-efficiently with a constant 10 kts tailwind. On the other hand, Figure 10 shows how effectively headwind increases the possibility to fly steeper approaches. With a constant headwind of 20 kts, a glideslope angle of 3.6° is possible in an energy-efficient way with intercept speeds between 180 kts and 190 kts. With a constant headwind of 40 kts, a maximum glideslope angle of even 4° is possible for still energy-efficient flights. However, Figure 10 also shows that with a constant headwind of about 30 kts it is not possible to fly energy-efficiently at all with a glideslope angle of 3°, at least not if the glideslope is intercepted with flaps in Config 2. In this case the deceleration rate with idle thrust is too large, so that the aircraft always reaches its final approach speed before reaching 1,000 ft. In some of these cases it is possible to intercept the glideslope with flaps in Config 1, allowing to fly the approach energy-efficiently. This gives another energy envelope for glideslope intercepts with flaps in Config 1.

Figure 11 outlines the two energy envelopes for glideslope intercepts with flaps in Config 1 (dashed envelope) and Config 2 (solid envelope) for two cases with strong headwinds (30 kts and 40 kts). One can observe the envelopes for the Config 1 intercepts below the ones for Config 2 intercepts. However, the gap between the envelopes for Config 1 and Config 2 is also obvious, and this gap even increases with increasing headwind.

One example shall illustrate the difficulties, which can be observed in Figure 11. For the extreme case of 40 kts headwind and given an intercept speed of 190 kts, a 3° glideslope angle is possible in an energy-efficient way with a glideslope intercept with flaps in Config 1. With increasing glideslope angle and still an intercept speed of 190 kts, the ability of the aircraft to decelerate in the Config 1 segment of the final approach is degraded. At a glideslope angle of almost 3.2°, the boundary is reached where the aircraft does not decelerate anymore in Config 1. From this point on, with increasing glideslope angle, the aircraft requires speed brakes in order not to accelerate. However, if the glideslope was intercepted here with flaps in Config 2, the deceleration rate of the aircraft was too large, resulting in reaching the final approach speed too early. For this reason, no energy-efficient flight is possible here. Only with a glideslope angle of about 3.5° (in the exemplary case of an intercept speed of 190 kts) it is again possible to fly energy-efficiently but with a glideslope intercept in Config 2. This is possible up to a glideslope angle of almost 4°, above which the aircraft needs to use air brakes in any case.

For the extreme case of a constant headwind of 40 kts, Figure 11 also shows that no energy-efficient solution exists, for example, for a glideslope angle of about 3.3° (given this aircraft mass and intercept altitude).

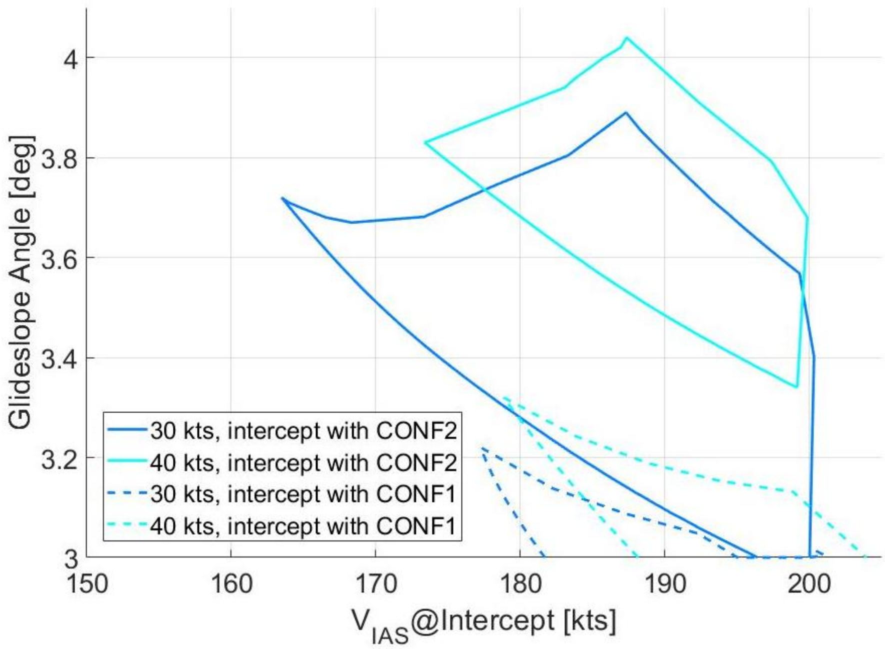

Figure 11 – Influence of strong headwind on the envelope for energy-efficient approaches for the A320 (intercept with flaps in Config 1 or Config 2, aircraft mass 55 t, intercept altitude 3,000 ft).

Figure 11 reveals the great influence that wind has on the possibility to fly approaches in an energy-efficient manner. It also shows, that for some extreme cases no energy-efficient solution might exist. Of course, applying a constant wind along the glidepath is not realistic. However, it was intended to show the most influencing effects on energy-efficient flight in a simplified way. In reality, with changing wind along the glide, it is even harder or maybe nearly impossible for pilots to always fly energy-efficiently without any kind of assistance system. The outcome of the presented work even more justifies the introduction of any kind of energy assistance system in order to enable energy-efficient flight with increased glideslope angles.

5. Conclusions

In order to assess the ability of modern transport aircraft to fly energy-efficient approaches with increased glideslope angles, energy envelopes have been evaluated by using a backwards simulation of idle approaches. The results of the approach calculations have been verified against real flight data and show an acceptable level of conformity. However, the verification could only be performed for approaches with glideslope angles of 3° and 3.2°. As accurate flight performance data from DLR's research aircraft A320 ATRA were used and the comparisons to real flight data showed a sufficient accuracy, it can be expected that the results are also acceptably accurate for higher glideslope angles.

The fuel flow varies within the energy envelope and shows a minimum at high intercept speeds and high glideslope angles. The variation of noise within the envelope could not be assessed quantitatively, but qualitative considerations indicate that the minimum noise within the energy envelope will at least not be in the same region as the minimum fuel consumption. For this reason, fuel consumption and noise probably need to be traded against each other in order to find an approach balancing both noise and fuel consumption.

The parameters that influence the shape of the energy envelope, such as aircraft mass, glideslope intercept altitude or wind have been varied in order to show the sensitivity of approaches with increased glideslope angles against these parameters. The envelopes show that the influence of the aircraft mass on the maximum energy-efficiently achievable glideslope angle depends on the intercept speeds. While for high intercept speeds lighter aircraft can fly steeper approaches, heavier aircraft can fly steeper approaches at lower intercept speeds. The energy envelopes also show that it is favorable to have lower intercept altitudes at higher glideslope angles as a higher intercept altitude decreases the maximum energy-efficiently achievable glideslope angle. The variation of wind reveals the strong influence of wind on the ability of aircraft to fly approaches energy-efficiently. The analysis of the variety of influencing parameters underlines the need for any kind of energy assistance systems, which can enable pilots to fly energy-efficiently even with increased glideslope angles and under the various and changing conditions in real flight.

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Copyright Statement

Nomenclature

ATRA	Advanced Technology Research Aircraft
DLR	German Aerospace Center
Alt	altitude, m
C_D	drag coefficient, -
C_L	lift coefficient, -
CAS	calibrated airspeed, m/s
$CONFIG$	flap configuration, -
$Dist$	distance to the runway threshold, NM
g	gravitational acceleration, m/s²
GS	ground speed, m/s
GSA	glideslope angle, °
IAS	indicated airspeed, m/s
m	mass, kg
Ma	Mach number, -
S	wing area, m²
t	time, s
T	thrust, N
TAS	true airspeed, m/s
V	velocity, m/s
VFE	maximum flap extension speed, kts

γ flight path angle, °

γ_a aerodynamic flight path angle, °

ρ air density, kg/m³

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