The Best-speed Diagram for Soaring in Isolated and Aligned Lift

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Abstract

Speed-to-fly theory optimizes the average speed of a glider based on the climb rate in circling flight and on the vertical air motion in straight flight. This paper looks at the optimized average speed when aligned upward motion is available in the straight flight between the circling climbs in isolated lift. The optimized average speed is visualized in a diagram with the climb rate in isolated lift on one axis and the aligned upward motion of the air on the other axis. For aligned upward motion of sufficient strength the pure straight flight mode is faster than the circle-and-glide flight mode. A transition line separates the two flight modes in the best-speed diagram. The diagram is an essential component for the meteorological planning of soaring flights with predictions of isolated and aligned lift.

Introduction

Speed-to-fly theory has been developed a long time ago[1]. A variety of flight instruments like the MacCready ring and electronic speed command devices rely on it and so do pilots. In-flight speed-to-fly information is deduced instantly from the climb rates *measured* in circling and straight flight in order to optimize the average speed. For flight planning, however, *predicted* climb rates are converted to optimized average speed. In this pre-flight application of speed-to-fly theory both the circling climb rate in isolated lift and the aligned vertical air motion in straight flight can be considered. In the initial approach[2] only the predicted circling climb rate in isolated lift was used.

Verifications of predicted climb rates and winds with recorded flight tracks[3] require the conversion of these meteorological variables to the recorded ground speed. Speed-to-fly theory is useful for this conversion as glider pilots tend to optimize speed – particularly in competition flights.

State-of-the-art online self-briefing systems offer interactive tools for flight planning[a,b]. The verification of the predicted soaring weather by the simulation of recorded flights is a standard feature of these tools. The initial version of the flight planning and simulation tool used only predictions of isolated (thermal) lift while aligned lift in straight flight was not considered. Therefore, the flight speeds in aligned lift (wave, rotors, ridge, convective rolls) were under-predicted. This was most obvious for wave flights on cloudy days with hardly any convective updrafts. When Klaus Ohlmann flew from Serres (France) almost to Vienna (Austria) and half-way back to Switzerland in a pre-frontal SW flow[c] on 22 May 2006, the predicted thermal flight distances were negligible all along the 1,336 km flight trace. Even though the majority of soaring flights are made in isolated convective updrafts, the extremely long and fast flights made in aligned lift represented a serious challenge for the meteorological community to come up with predictions of aligned lift.

Techniques to predict aligned lift for soaring will be described in a separate paper. Here we will consider the gain in average speed, if aligned upward motion is available in straight flight in addition to isolated lift. The original speed-to-fly theory provides the answer to this question for weak aligned lift. Strong aligned lift, however, allows for pure straight flight. The transition line between the two flight modes of the classical circle-and-glide flight and the pure straight flight will be identified depending on the relative strengths of isolated and aligned lift.

Graphical method

The optimized speed-to-fly can be obtained graphically from the speed versus sink characteristics of the glider by the tangent from the climb rate when circling (point on the climb axis) to the flight polar[1]. The tangent construction is shown in Fig. 1 for two flight polars A and B. The average speed is less than the speed flown in straight flight between the climbs because of the time spent circling. This average speed is indicated by the intersection of the tangent with the horizontal speed axis (at zero sink/climb) in Fig. 1.

Aligned vertical motion of the air during straight flight shifts the flight polar vertically. In the early days of soaring when gliders were slower and had a higher sink rate than

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[a] http://www.pa.op.dlr.de/ostiv/ … activities/Pfaffstätten/Liechti

[b] http://www.dwd.de/bvbw/generator/Sites/DWDWWW/Content/Luftfahrt/Downloads/Software/jtt/jtt__E,templateId=raw,property=publicationFile.pdf/jtt_E.pdf

[c] http://www2.onlinecontest.org/olcphp/2006/ausw_fluginfo.php?ref3=24938&ueb=N&olc=olci&spr=en&dclp=27f70cc84861eb8bffea07f87d690dc7

today's high performance ships there was a lot of concern about the best way of flying through *sinking* air. Maximizing the average speed may quickly have to be abandoned for maximizing the flight range (glide slope)[6] when approaching the ground in a sinking airmass. Here we will investigate the effect of *rising* air on the optimized average speed. First, we shift the flight polar upward by about the minimum sink of the glider. This means that the glider encounters aligned reduced sink when flying straight to the next localized updraft in which it will circle. The tangent to the upward shifted flight polar is less steep because of the reduced sink in straight flight. The optimum speed-to-fly in straight flight decreases and the average speed increases. The increased average speed is still below the reduced speed-to-fly in straight flight. The time fraction spent circling is reduced because the ratio of the average speed to the speed-to-fly has increased.

Now we shift the flight polar further upward to the point where the average speed and the speed-to-fly become equal. For flight polar C in Fig. 2 the intersection point of the tangent with the horizontal speed axis is identical to the point where the tangent touches the flight polar. With this amount of aligned lift the speed-to-fly in straight flight is the same as the average speed: the aligned lift is strong enough to allow for pure straight flight without stopping for circling. Note that the aligned upward motion of the air must exceed the minimum sink of the glider, if the climb rate in circling flight is positive.

A further increase of the aligned upward motion of the air leads to a different construction of the optimum speed-to-fly (curve D in Fig. 3). If the glider was flown at the tangent point, the glider would climb in straight flight and the intersection of the tangent with the horizontal speed axis could no longer be the average speed. The average speed can be optimized in this case, if the glider is flown at the intersection of the shifted flight polar with the horizontal speed axis. In this case the glider flies at constant altitude and the optimized average speed is the straight flight speed (no circling).

In Fig. 4 the optimized average speed is shown for an open class glider (best L/D: 54 at 101 km/h, wing loading: 42 kg/m2) as a function of the circling climb rate. The numerical calculations of the optimized average speed were done for a universal flight polar[4] following Irving[5]. Analytical solutions should exist for the empirical flight polar[4]. The uniform upward motion of the air in straight flight was increased stepwise and produced the isolines displayed. The increase in average speed by aligned lift is most pronounced for weak climb rates in isolated lift. In strong aligned lift the circle-and-glide mode changes to the pure straight flight mode. A zero climb rate in isolated lift requires the aligned vertical motion to exceed the minimum sink of the glider (0.45 m/s at 78 km/h).

Phase diagram and order parameter

In Fig. 5 the circling climb rate is displayed along the horizontal axis and the vertical axis represents the strength of the aligned updraft. Here, the black lines in the diagram represent isotachs of the optimized average speed. For the Open class flight polar considered (best L/D: 54 at 101 km/h, wing loading: 42 kg/m^2) an average speed of 100 km/h results either from a circling climb rate of about 2 m/s at zero aligned lift (case A) or from a 0.55 m/s aligned lift at a zero circling climb rate. In strong aligned lift pure straight flight leads to the highest average speed (horizontal isotachs), in strong isolated lift circle-and-glide flight is faster (curved isotachs). The transition line between the two flight modes is linear for circling climb rates exceeding 2 m/s and includes the previously discussed case C.

The optimum speed diagram has the characteristics of a phase diagram: the two flight modes of a glider producing the optimum average speed can be perceived as distinct phases of a system. The time fraction spent circling is the order parameter of the system. The order parameter is positive for the circle-and-glide flight mode and vanishes in the pure straight flight mode. The transition between the two phases is reflected in the behavior of the order parameter: the transition occurs when the order parameter becomes 0.

Figure 6 shows the dependence of the order parameter on the circling climb rate for fixed values of the aligned lift (behavior of the order parameter along horizontal lines in Fig. 5). For the transition to the pure straight flight mode to occur the aligned lift must exceed a threshold (i.e. the minimum sink of the glider). The transition is continuous for climb rates in circling flight exceeding a threshold.

For fixed values of the circling climb rate the decrease of the order parameter with increasing aligned lift (e.g. cases A, B, C, and D in Fig. 5) is also continuous all the way down to the transition to pure straight flight (C) provided that the circling climb rate is positive. In the absence of isolated lift, however, the transition between the two flight modes becomes discontinuous: for aligned lift below a threshold (the minimum sink of the glider) the order parameter is 1 (the glider circles full time and does not climb), for aligned lift stronger than the threshold the glider can fly straight at constant altitude (the order parameter is zero). A reduction of the circling climb rate to zero will eventually discriminate sharply between full time circling and pure straight flight depending on the value of the aligned lift available (Fig. 6).

Ground speed

The optimized average speed is horizontal and refers to the air in which the glider flies and climbs. In the presence of wind the optimized average speed vector must be combined with the average wind vector to yield the average ground speed vector.

When flying in lift aligned with the wind (e.g. convective rolls) the ground speed is maximized for tailwind and minimized for headwind.

Aligned ridge and wave lift is fixed to the ground and perpendicular or strongly oblique to the wind. Soaring along such ground fixed aligned lift implies that the resulting ground speed vector is parallel to the aligned lift. The optimized average speed vector will be oriented at a crab angle to the desired ground speed vector in order to stay in the aligned lift. In strong aligned lift perpendicular to the wind the pure straight flight mode leads to ground speeds that depend only weakly on wind speed, if the aligned updraft is proportional to the wind speed. An increase in wind speed increases both the glide speed and the crab angle, so that the resulting speed along the ground, fixed aligned lift, remains almost unchanged.

Ground fixed aligned lift oblique to the wind may be found on the downwind side of an isolated mountain peak. On courses oblique to the wind (e.g. across trapped lee waves) aligned lift could be spatially modulated. In such cases the fastest flight track will be different from the shortest one.

Meteorological flight planning

The ground speed is needed for the planning of a flight task as a trajectory in four dimensions (three spatial and one temporal). Meteorological flight planning for gliders requires the prediction of four speed components: the two components of the horizontal wind and two additional components for the vertical wind: the strengths of isolated and of aligned vertical air motion. The two components of the horizontal wind were the first to be predicted by numerical weather models. The strength of isolated lift followed. Predictions of aligned lift are currently being developed. For tailwind, headwind, and crosswind courses optimized ground speed in uniform aligned lift can be computed from such predictions and meteorological flight plans compiled.

Concluding remarks

Speed-to-fly theory provides the optimized average speed of a glider flying in combinations of isolated and aligned lift. Meteorological flight planning can be based on predictions of isolated and aligned lift by applying speed-to-fly theory to optimize the average speed. The optimized average speed can be converted to ground speed by adding the predicted wind properly. With the developed phase diagram of soaring in isolated and aligned lift flight planning is well prepared for the moment, when numerical weather models will predict aligned lift (strength and altitude). The simulation of flights in aligned lift (wave, ridge, rotors, convective rolls) with predicted winds and updrafts will allow for the verification of the predictions. The effects of flight altitude and wing loading on the best speed in isolated and aligned lift have not been investigated in this paper. They will be included in the simulations of flights with predicted weather.

Acknowledgements

Soaring pilots like Klaus Ohlmann (Germany) and Stefan Leutenegger (Switzerland) triggered this work by demonstrating that meteorological flight planning based only on isolated lift fails to foresee the most spectacular flight conditions allowing for the longest flights. Pilot and meteorologist Herbert Leykauf from the German Weather Service (DWD) was challenged by their flights and initiated operational predictions of aligned lift and their use for meteorological flight planning.

I would like to thank the three reviewers for their reports. Their comments made me think about fluctuations in aligned lift and sink and the appropriate reaction in order to optimize speed. More thinking is needed on my side.

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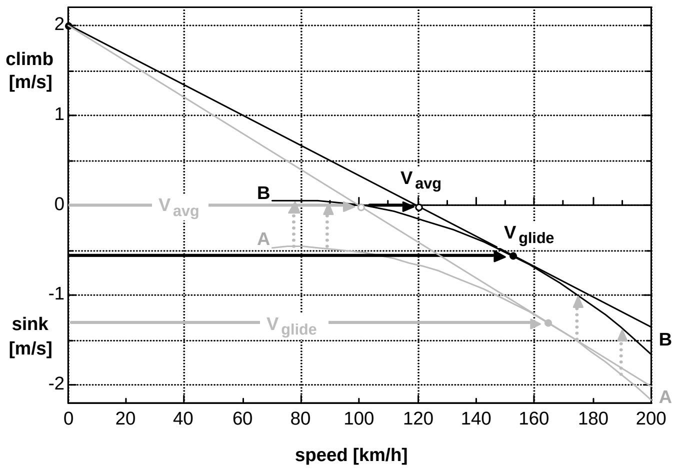

Figure 1 The flight polar in still air (lower grey curve A) with the tangent optimizing the average speed for a particular climb rate (here: 2 m/s) in circling flight. The point where the grey tangent A touches the flight polar indicates the optimized speed-to-fly v_{glide} (and the corresponding sink) in straight flight. The intersection of the grey tangent with the horizontal axis is the optimized average speed v_{avg}. A second flight polar (upper black curve B) is shown displaced vertically. The vertical displacement corresponds to the aligned upward air motion in straight flight. The displaced flight polar B leads to other values for the speed-to-fly v_{glide} and the average speed v_{avg} (black tangent B).

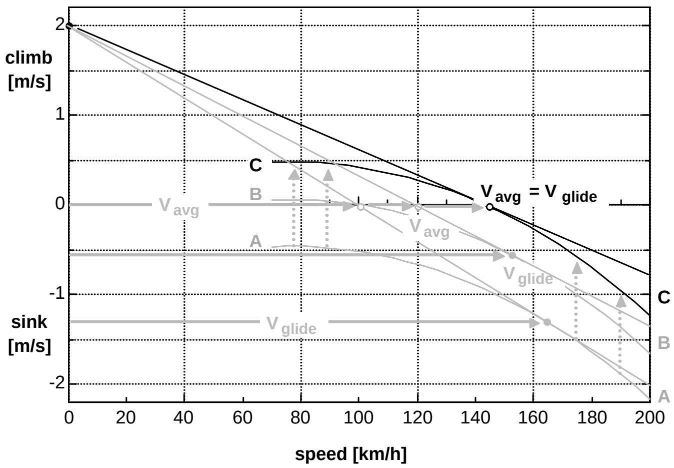

Figure 2 The aligned vertical lift is just strong enough that the speed-to-fly v_{glide} matches the average speed v_{avg} (black curve C). No circling is needed anymore and the glider can fly in pure straight flight.

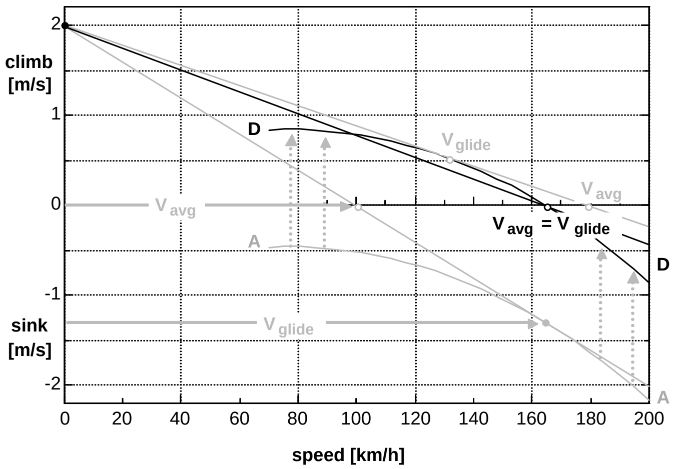

Figure 3 Here the aligned vertical motion is so strong (black flight polar D) that the glider increases its speed-to-fly v_{glide} in order to maintain a constant altitude.

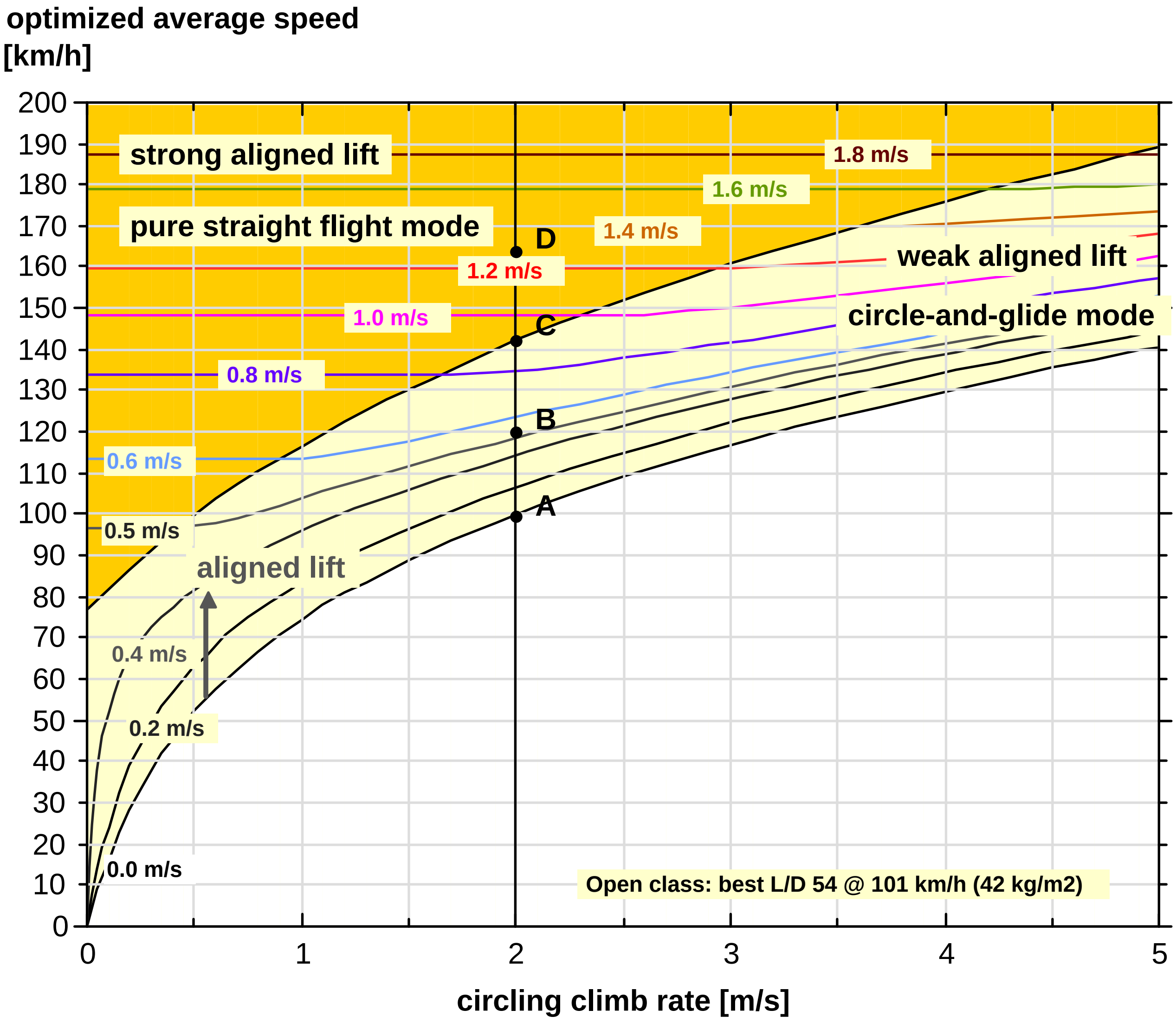

Figure 4 The optimized average speed (vertical axis) for combinations of isolated (horizontal axis) and aligned lift (selected values: aligned updraft increased in steps of 0.2 or 0.1 m/s). The gain in average speed by aligned lift is most pronounced for weak circling climb rates in isolated lift. The calculations were made for an Open class sailplane at sea level. A, B, C, and D correspond to the cases shown in the previous figures.

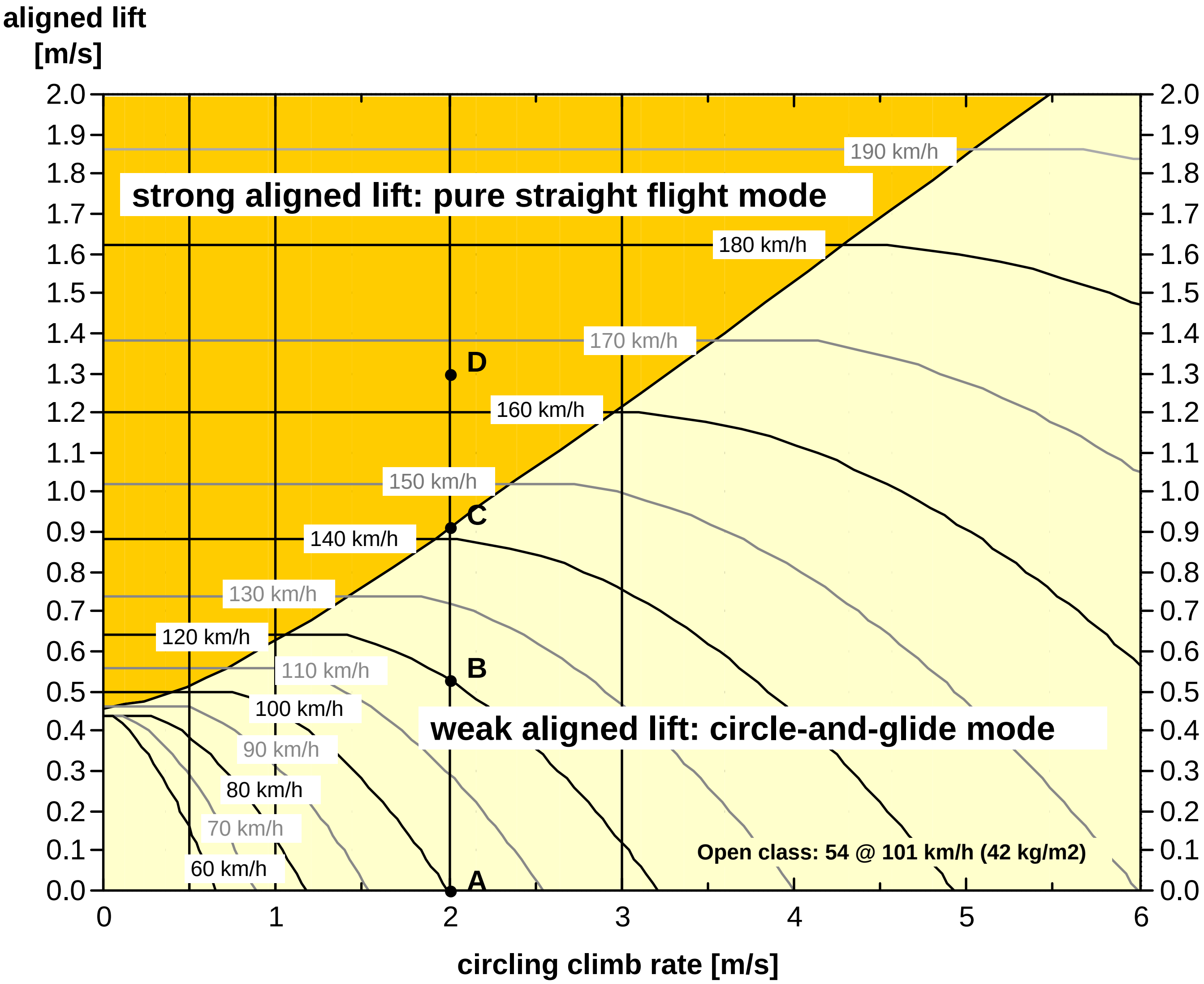

Figure 5 The optimized average speed for all combinations of isolated (horizontal axis) and aligned lift (vertical axis). The transition line separates circle-and-glide flight (bottom) from pure straight flight (top). The calculations were made for an Open class sailplane at sea level. A, B, C, and D correspond to the cases shown in Figs. 1-3.

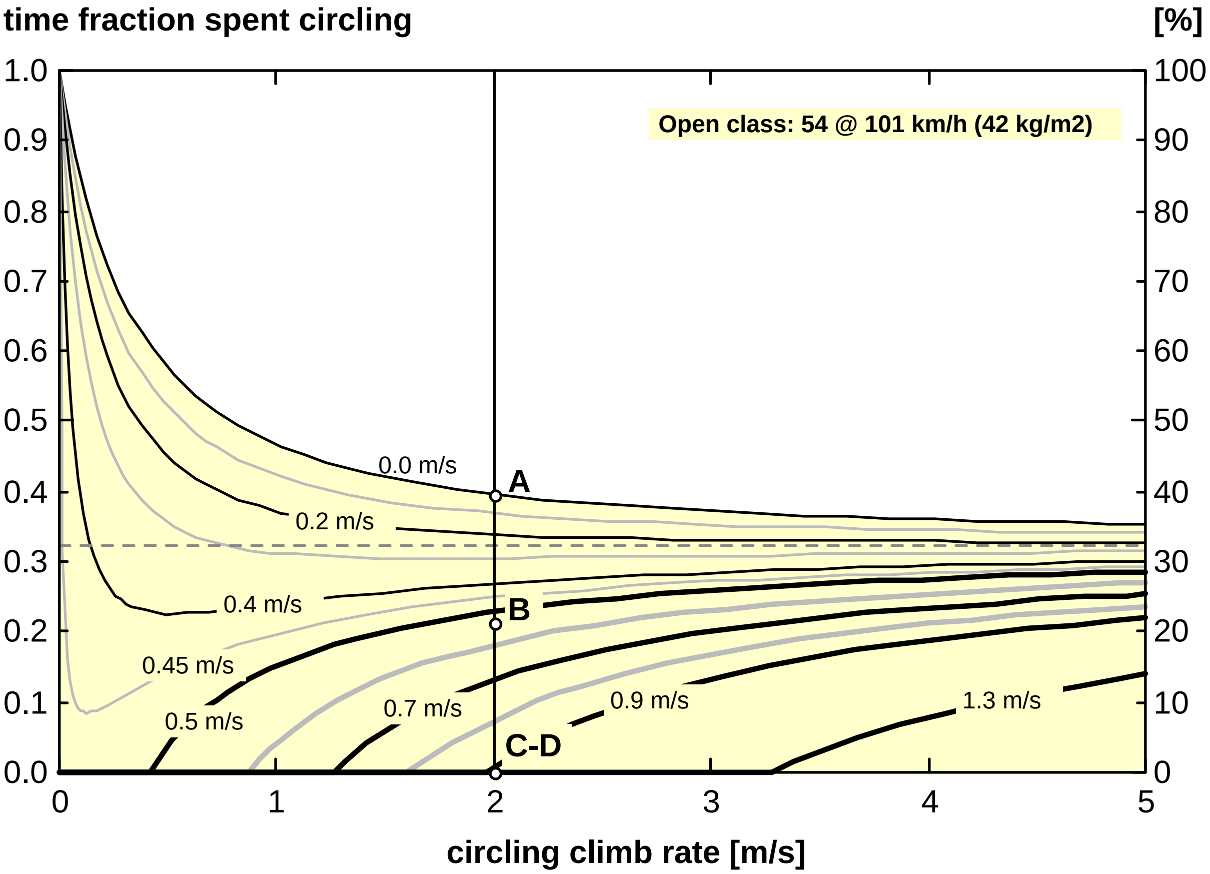

Figure 6 The time fractions spent circling (vertical axis) for combinations of isolated lift (horizontal axis) and aligned lift (selected values: aligned updraft). In the absence of aligned lift the time fraction spent circling stays above a threshold (32%). Weak aligned lift reduces the circling time fraction mainly in weak isolated lift. Strong aligned lift allows for (fast) straight flight with no circling at all, if isolated lift is weak to moderate. A, B, C, and D correspond to the cases shown in Figs. 1-3.