Deutscher Luft- und Raumfahrtkongress 2016
DocumentID: 420139

# ASSESSMENT OF POTENTIAL FORMATION FLIGHT BENEFITS BASED ON EUROPEAN FLIGHT PLAN DATA

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## Abstract

In this paper potential two-aircraft formation candidates will be identified by comparing the point profiles of all scheduled flights in the European airspace on one specific day. The identification of these formation candidates is performed by calculating the amount of time the flights are planned to fly in close vicinity to each other. The formation candidates will be adapted in order to achieve feasible vertical formation flight profiles and valid formation missions. In a next step, the candidates will be examined by a detailed formation trajectory calculation based on a total energy model. In order to calculate the different mission parameters of the formation the effects of the wake vortices on the following aircraft are included in the trajectory calculation by an aerodynamic model. To assess the potential fuel saving benefit, the corresponding solo missions for all aircraft participating in the formation are being calculated and put in comparison. The formation geometries of the potential formations as well as different parameters such as aircraft types, origins, destinations and durations will be analyzed. It will be shown, that by considering planned point profile data, a considerable amount of opportunities for formation flight exist. Furthermore, based on the calculations the fuel saving benefits will be quantified and compared to the solo flights and it will be shown, that substantial fuel saving benefits compared to flying without formation can be anticipated.

## SYMBOLS

| | |
|---|---|
| $\delta$ | relative formation location |
| $\xi$ | relative length of a route segment |
| $\lambda$ | formation efficiency metric |
| $\Delta F$ | fuel savings |
| $S$ | length of a route/segment (ground) |

## ABBREVIATIONS

| | |
|---|---|
| BADA | Base of Aircraft Data |
| CPACS | Common Parametric Aircraft Configuration Schema |
| ECAC | European Civil Aviation Conference |
| FCA | Formation Cruise Altitude |
| FCS | Formation Cruise Speed |
| FL | Flightlevel |
| ICAO | International Civil Aviation Organization |
| LCV | Long-term Close Vicinity |
| NFE | Network Flow Environment |
| P+ | Formation Begin |
| P- | Formation End |
| RSP | Rendezvous Starting Point |
| SEP | Separation Ending Point |
| STAFD | Standard Formation Definition |
| TCM | Trajectory Calculation Module |

## SUBSCRIPTS

| | |
|---|---|
| *a* | pre formation segment |
| *b* | post formation segment |
| *ben* | segment with formation benefit |
| *form* | formation mission |
| *fw* | follower |
| *F* | whole formation |
| *ld* | leader |
| *ref* | reference mission |
| *rend* | rendezvous segment |
| *sep* | separation segment |

## 1. INTRODUCTION

The aerodynamic formation flight of civil aircraft is known to hold the potential of substantial fuel savings. As it was discovered over one hundred years ago by *Wieselsberger* [1] migrating birds can drastically extend their range by flying in formation [2]. This concept has since then been subject to evaluation (e.g. [3]) and the idea to transfer it to man-made aircraft was analyzed by *Schlichting* already in 1942 [4]. In addition to these theoretical studies several flight tests proved over the time that the concept of formation flight can lead to considerable fuel savings for man-made aircraft [5 - 8]. *Luckner* [9] gives a good overview of the state of the art of formation flight research.

However, an integration of this new operational method into the air transportation system poses many additional challenges and risks. It is therefore necessary to assess the potential fuel savings due to formation flight on a system wide basis as accurate as possible in order to support all affected stakeholders in their decisions about the further development of this new technique. An essential question in this context is the optimal formation routing that strongly influences the benefits that can be achieved by a formation and has been subject to research for some time [10 -14]. Another strong driver for the potential formation benefits is the availability of matching flights. Those flights can be planned or allocated on an ad-hoc basis but all formation flights have in common that they have to be integrated into the regular day-to-day air traffic. One promising approach to achieve this integration is the realization of formation flight without even changing existing flight plans. This approach is reasonable as it can be expected, that in crowded airspaces where many aircraft fly along the same routes at roughly the same time or in structured airspaces such as the North Atlantic region many opportunities for formation flight arise. It is therefore of major interest to assess this inherent formation flight potential for existing flight plans.

Other than previous studies the work presented in this paper therefore deals with the identification and assessment of potential formation flights based on available planned point profile data from *Eurocontrol* for the European airspace. The idea underlying the approach is that if two flights are planned to fly on similar trajectories at close vicinity and at roughly the same time, the resulting planning conflict can be interpreted as the opportunity for formation flight. Instead of resolving the conflict it is translated to a formation candidate for whom the potential fuel saving benefits can be calculated. It will be shown, that for a given time period for the European airspace many of those formation flight opportunities exist that can lead to substantial fuel savings and thus to cost savings and the reduction of emissions.

## 2. APPROACH

### 2.1. General Approach

To answer the above question several steps need to be performed that are shown in FIGURE 1.

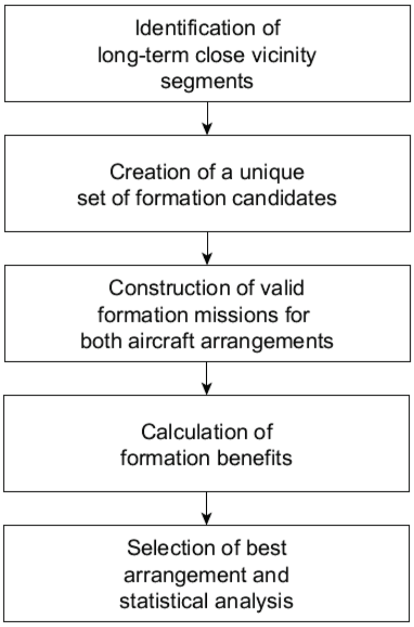

FIG 1.Flowchart of the general procedure used in this study

In the first step, from the available planned point profile data formation candidates are being defined by pairwise comparing the trajectories of the flights in the European airspace and identifying long-term close vicinity segments (LCV-segments). For all these segments a unique set of formation candidates is extracted that can be used to perform the benefit calculation. Unique in this context means, that if one flight has the opportunity to join several other flights to form a formation only one formation is possible. To enable the benefit calculation valid formation missions have to be created for both arrangements of the participating aircraft. A valid formation mission thereby needs to correspond to the assumptions made in this study (see chapter 2.2) and furthermore needs to provide the formation parameters describing the formation geometry. After the benefit calculation is done in a subsequent step the best arrangement of leader and follower is selected and the results are statistically analyzed.

### 2.2. Assumptions

Several assumptions are underlying the studies presented in this paper that are concerning the conduction and modeling of the formation flight.

The general assumptions concerning the operation of formation flight are listed below.

- Two-aircraft formations
- Constant *Formation Cruise Speed* (FCS)
- Constant *Formation Cruise Altitude* (FCA)
- Planned formation flight
- No positional changes
- Course corrections possible

Assumptions that are specific to the study presented in this paper are described in the following.

**LCV-segment limits**

Two points of a point profile are considered in close vicinity when the following three conditions are fulfilled. First a lateral distance below 5 nautical miles that corresponds to the minimum lateral separation defined by ICAO. Second a vertical distance below 0,01 FL ensuring that both flights are on the same flight level. Third and finally a time deviations of less than 5 minutes that corresponds to flights that are considered “on time” by *Eurocontrol* standards is necessary for close vicinity. Furthermore it is assumed that below FL100 flights are generally in the climb/descend phase and not in the cruise flight. Therefore only flights above FL100 are considered in the comparison. A LCV-segment is considered as a formation candidate, when two flights are in close vicinity for at least thirty minutes.

The assumptions described above are summed up in the following list.

- Lateral distance < 5 nm
- Vertical distance < 0.01 FL
- Time deviation < 5 min
- Both flight levels > FL100
- Minimum LCV time > 30 min

**Rendezvous length**

As no reference values for the duration of the rendezvous maneuver exist, the length of this segment needs to be estimated. Therefore the assumption is made, that in the worst case the 5nm of the maximum lateral distance as defined above might need to be covered by the follower in order to catch up with the leader to build a formation. Assuming that the follower accelerates and flies faster than the leader and at the same time the leader decelerates the length of the rendezvous segment $\boldsymbol{S_{rend}}$ is set to 40km what should be sufficient to cover this distance and to enable the rendezvous.

**Separation length**

The length of the separation segment can be considered shorter than the rendezvous segment as the maneuver can be assumed to be less critical and the follower does not need to catch up with the leader. The length of the separation segment $S_{sep}$ is therefore fixed to half the length of $S_{rend}$ in this case to 20km.

## 2.3. Scope

For the study presented in this paper the day of 7th of June in 2012 was evaluated. All flights on this day with a planned departure time between 0:00h and 23:59h were subject to evaluation. Furthermore the geographical locations of the origin and destination airports of the considered flights were limited to the *European Civil Aviation Conference* (ECAC) member states. Altogether for this scope 23836 planned flights were subject to evaluation.

FIG 2. Ground tracks of identified formation missions with resulting formation segments colored in red, other segments in gray

FIGURE 2 shows the ground tracks of all formation missions subject to study. The formation segments are colored in red, other route segments in gray. It can be found, that the formations are equally distributed over Central Europe.

# 3. METHODS

In this chapter the methods used to conduct the study presented in this paper will be described, following the general approach shown in FIGURE 1. The parameters and metrics used in this study will be presented in an additional section at the end of the chapter.

## 3.1. Identification of formation candidates

Formation candidates are identified by analyzing planned point profile data. Two flights are considered a formation candidate if they are planned to fly at close vicinity at roughly the same time for at least thirty minutes. The point profiles are parsed from *Eurocontrol* DDR2 SO6 M1 data to the *Network Flow Environment* (NFE) Trajectory data format [14]. The data thereby consists of aircraft types, departure and arrival aerodrome, intermediate waypoints, the respective coordinates and time. The point profiles are interpolated linearly so that there is at least one point for every minute.

To detect LCV-segments planned point profile point-pairs in close vicinity are detected from the interpolated trajectory points. A grid approach is used to avoid comparing all point pairs by limiting the comparison to points in surrounding grid-elements [15]. Close vicinity between trajectory point-pairs is defined as a time difference of less than 5 minutes, a lateral distance below 5 nautical miles and a vertical distance below 0,01 FL (see chapter 2.2). Point profiles with durations of close vicinity for at least 30 minutes are chosen as potential formation candidates. The duration of the close vicinity is defined as the longest interval of two flights (one minute gaps are allowed). In a last step only one formation candidate per flight can be selected. A unique set of candidates with the maximum total duration and without more than one formation per flight is therefore gathered from all potential formation candidates by solving a linear optimization problem. In this approach the binary variables are represented by the formation candidates, the cost function consists of the formation duration for the candidates. The conditions make sure that every flight is in maximum one formation.

## 3.2. Construction of formation missions

The formation candidates that have been identified by the previous steps need to be converted to valid formation geometries as defined in [16]. As a result from the assumptions made in chapter 2.2, the individual missions of the formation members need to be adapted. In this adaption process the LCV-segments are reduced to a constant flight level and separated into a rendezvous- a separation- and a formation segment. Furthermore the dedicated formation points (*Rendezvous Starting Point* (RSP), *Formation Begin* (P+), *Formation End* (P-), *Separation Ending Point* (SEP)) as well as the loadfactors and the Formation Cruise Speed (FCS) are defined. The resulting formation missions are then converted to *Standard Formation Definitions* (STAFD), an XML-based description dedicated to the exchange of formation flight data. The STAFD data format is comparable to the CPACS-Standard developed at DLR [17] and contains all relevant formation information. The STAFD formations can then be used by the *MultiFly Toolkit* developed at DLR to calculate the formation benefits based on the *Base of Aircraft Data* (BADA) version 4 flight performance models from *Eurocontrol*.

### Selection of FCA

It can be observed, that the identified LCV-segments of the trajectories may contain an altitude change. As the assumptions made in this paper contradict a simultaneous altitude change of the formation, these altitude changes have to be removed. Therefore the LCV-segments are reduced to the longest part at a constant flight level. The resulting flightlevels are considered as FCAs accordingly. A distribution of the resulting FCAs is presented in chapter 4.5.

### Construction of Formation Points

As the LCV-segments remaining after the FCA selection represent the longest possible segment for formation flight, it is assumed, that the rendezvous and separation maneuvers have to be conducted within this segments. The first and the last points of the segments can therefore be considered as RSPs and SEPs. To complete the raw formation data and to thereby enable the benefit calculation in a next step the formation begin and the formation end (P+ and P-) are defined, as only in the segment between these points a benefit can be achieved by the follower. These points are computed from the trajectory data according to the assumptions made in chapter 2.2.

FIGURE 3 shows a schematic view of the construction of the formation trajectory from the planned point profile data. The LCV-segment of the trajectory is shown in blue. After the translation to a valid formation mission the red part of the LCV-segment is left to form the formation. The segments for the rendezvous and separation maneuvers (orange) are subtracted from the formation segment at constant FCA and the dedicated points are defined.

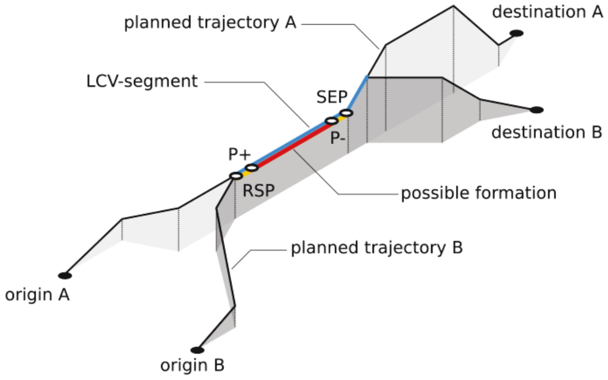

FIG 3.Schematic construction of a formation candidate from a LCV-segment

### Estimation of FCS

The Formation Cruise Speed (FCS) of a formation candidate is initially calculated from the standard cruise speeds of the formation members. The mach numbers of both members are thereby compared and the lower value is selected as initial FCS. This selection should ensure that both formation members can perform the mission. If the formation mission cannot be performed by one of the formation members due to flight performance reasons the loadfactor of that member is being decreased. If the mission still cannot be performed with the decreased loadfactor in a second step the FCS is reduced in order to enable the mission. The distribution of the resulting FCSs is presented in chapter 4.5.

### Estimation of loadfactors

Other than the formation geometry, FCA and FCS the loadfactors are not known from the given planned point profile data or aircraft characteristics and therefore need to be estimated. The estimation algorithm used in this approach is speed optimal. This means, that the highest FCS is selected that allows a completion of the mission (see above). The initial loadfactors are therefore set to 0.825. This value is taken from the *IATA Air Transport Market Analysis* of June 2012 [18] for Europe. If the mission cannot be performed with this loadfactors due to flight performance reasons the algorithm reduces the loadfactor to the lower limit of 0,3 and trials the mission again. If this trial can be performed the highest possible loadfactor is calculated by a stepwise reduction of the loadfactor starting from the initial value. If the trial fails the FCS is decreased and the loadfactor adaption begins anew. The resulting loadfactors are shown in chapter 4.5.

## 3.3. Calculation of formation benefits

The calculation of the formation benefits takes place using a trajectory calculation that simulates the formation benefits using an aerodynamic model as described in [16]. For this calculation an adapted version of the *Trajectory Calculation Module* (TCM) [19] developed at the *German Aerospace Center* (DLR) is used. During the trajectory calculation the strength of the leaders wake vortices is calculated at the position of the follower and the upwinds are modeled by a Hallock-Burnham vortex-pair [20]. The resulting upwind is then averaged over the wing and superimposed on the velocity of the following aircraft.

As the trajectory calculation cannot exactly rebuild the given 4D-trajectory from the planned point profile data the calculated trajectory deviates from the originally planned point profile. This is especially true for the pre-formation and post-formation segments of the formation mission as the trajectory calculation assumes an optimal vertical flight profile for the given mission. Only the formation segment is thereby predefined in terms of altitude and speed. As FCA and FCS are fixed in this segment, the reference mission in this study can be interpreted as the *loose* formation mission, where both aircraft fly in a formation without being in the vortex. The deviation of the calculated trajectories from the planned trajectories however is diminished by the fact that only relative comparisons are applied in this study.

Because of the use of the adapted TCM for the trajectory calculation the aircraft types are limited to the aircraft covered in BADA 4. From the original 605 formation candidates therefore only 510 were assessed in this study (see also TABLE 1).

## 3.4. Assessment of arrangement

For each formation candidate both arrangements of the aircraft within the formation are possible and yield different benefits. Both arrangements are therefore modeled as two separate formations and finally compared in terms of efficiency metric thus achieving the maximum benefit. Altogether 1020 formation missions were calculated.

## 3.5. Parameters and Metrics

A two-aircraft formation can be described by a set of parameters that give basic information about the formation geometry (see [16]). As detours, flightlevel and speed adaptions do not occur in the evaluation presented in this paper only three relevant parameters are remaining. The relative length of the approach segment $\xi_a$ represents the length of the ground track of the pre-formation segment $S_a$ in relation to the overall length of the ground track $S_{form}$. The relation of the length of the formation segment $S_{ben}$ to the absolute length of the ground track is referred to as $\xi_{ben}$. The location of the formation $\delta$ describes the location of the formation segment in relation to the overall mission and can be calculated from $\xi_a$ and $\xi_{ben}$ and therefore is not a genuine formation parameter but can help to better interpret the geometry. $\xi_b$ accordingly represents the length of post formation segment.

$$(1)\quad \boldsymbol{\xi_a = \frac{S_a}{S_{route}} \quad \xi_b = \frac{S_b}{S_{route}}}$$

$$(2)\quad \boldsymbol{\xi_{ben} = \frac{S_{ben}}{S_{route}}}$$

$$(3)\quad \boldsymbol{\delta = \xi_a + \frac{\xi_{ben}}{2}}$$

In addition to these geometric parameters the loadfactors, FCS and FCA are essential to describe the formation.

Beside the parameters describing a formation several metrics can be defined (see [16]) to assess the formation benefits whereof two metrics are being used in this study. These are on the one hand the absolute fuel savings $\Delta F$ as the difference of the fuel used for the reference mission $F_{ref}$ and the fuel used for the formation case $F_{form}$ and on the other hand the fuel based metric $\lambda$ as the absolute fuel savings in relation to the fuel of the reference mission.

$$(4)\quad \boldsymbol{\lambda = \frac{\Delta F}{F_{ref}} = \frac{F_{ref} - F_{form}}{F_{ref}}}$$

All parameters and metrics of a formation can be derived for the *leader* (index *ld*), *follower* (index *fw*) and the *whole formation* (index *F*).

## 4. RESULTS

In this chapter the results of the studies described in chapter 2 and 3 will be presented. This will be done by descriptive statistics mainly using histograms to show the distributions of parameters and metrics. In these histograms the mean values of the parameters are marked by a vertical black dashed line. The general statistical measures are summed up in tables at the ends of the chapters.

### 4.1. Overall statistics

In this chapter general statistics resulting from the calculations are presented. TABLE 1 gives an overview of the global study parameters.

| | **count** |
|---|---|
| Overall flights evaluated | 23836 |
| LCV-segments | 838 |
| Unique formation candidates | 605 |
| Unique formation candidates (BADA 4) | 510 |
| Formation missions | 1020 |
| Successful formation missions | 1000 |
| Unique successful formation missions | 500 |

TAB 1. Statistical overview of flights and formations

From the initial 23836 considered flights 838 LCV-segments were identified that were reduced to a unique set of 605 formation candidates or 1210 flights, representing about 5% of the considered flights. After reducing to BADA 4 aircraft and considering both arrangements 1020 formations were calculated. From these 1000 formations were successfully calculated and the best arrangement option was selected finally resulting in 500 successful formations that were evaluated.

### 4.2. Durations and Route Lengths

For the resulting 500 formations the durations of the LCV-segments are shown in FIGURE 4.

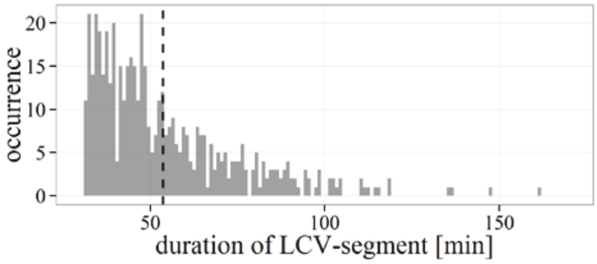

FIG 4. Distribution of durations of LCV-segments in minutes (only durations over 30 minutes were taken into account)

The average duration can be found at 53,65 minutes, the maximum at 161 minutes and the minimum at 31 minutes. The distribution is asymmetric with a positive skew. This can be a result of the assumption that only LCV-segments longer than 30 minutes were selected.

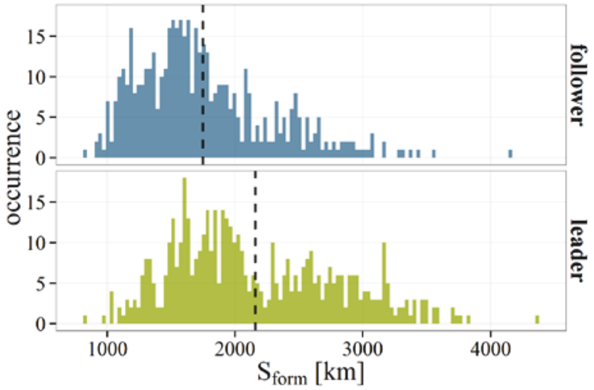

FIG 5. Distributions of absolute route length (ground track) separated for leader and follower

The distribution of the route lengths of the ground tracks of the formation missions $\boldsymbol{S_{form}}$ are shown in FIGURE 5. For the leader in average higher values can be observed. The average formation route length for the leader is 2159 km compared to the route length of the follower with an average of about 1750 km.

### 4.3. Formation Airports

The resulting formation missions can be analyzed concerning the origin and destination airports. FIGURES 6 and 7 show the distributions of the top-20 origins and destinations summed up by leader and follower and ordered by overall occurrence.

It can be found, that some airports accommodate more formation flights than others. This is even true for both directions as can be observed e.g. for LEPA (Palma de Mallorca) and EGKK (London Gatwick).

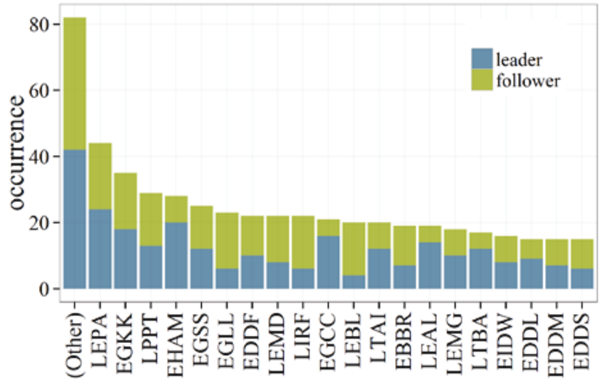

FIG 6. Top-20 origin airports for formations separated by leader and follower and sorted by overall occurrence

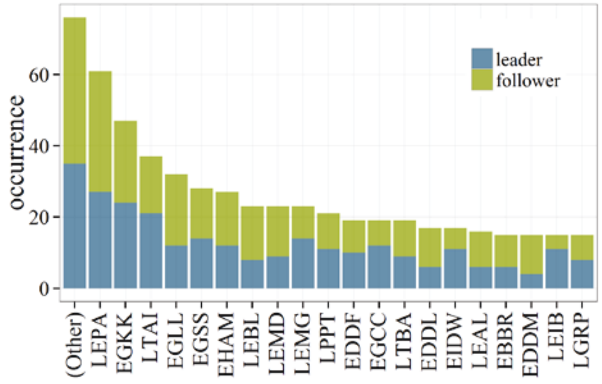

FIG 7. Top-20 destination airports for formations separated by leader and follower and sorted by overall occurrence

## 4.4. Aircraft Types

FIGURE 8 shows the distributions of the aircraft types separated by leader and follower and arranged by the occurrence of formations. It can be found, that the vast majority of the formations is being performed by only five aircraft types with the Boeing B737-800 by far the most frequent one, followed by A320-212 and A319-114.

Generally all aircraft types are used as leader and follower, however it can be found, that the distribution of leaders and followers slightly differs for some aircraft types as it can be found for example for the 737-800 that is more often used as leader than as follower. For the A320-212 and the A319-114 the contrary is the case.

## 4.5. Formation Parameters

The formation parameters give a direct idea of the formation geometry. Therefore it is of major interest to evaluate the distributions of these parameters for the given study. Mean and median values of the parameters can additionally be used to assess formation flight on scenario levels. For the different parameters as described in chapter 3.5 these values are summed up in TABLE 2. Additionally the distributions of the parameters will be presented in the following.

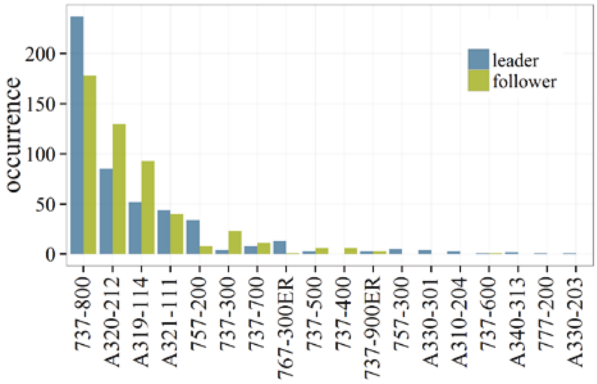

FIG 8. Distribution of aircraft types separated for leader and follower and arranged by occurrence

### Relative lengths of formation segments

The relative length of the formation segment $\xi_{ben}$ is a very important parameter that gives valuable information about the formation geometry. FIGURE 9 shows the distributions of $\xi_{ben}$ for leader and follower.

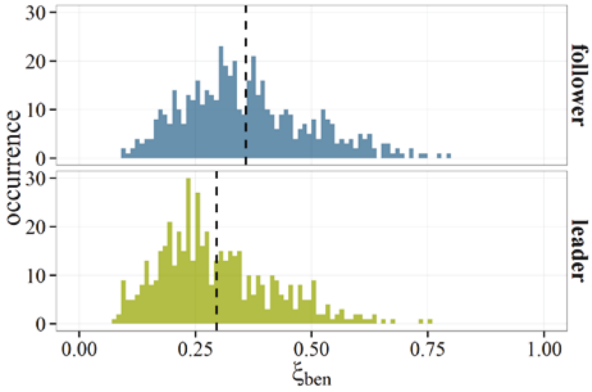

FIG 9. Distribution of relative lengths of formation segments ($\xi_{ben}$) separated by leader and follower

It can be found, that the distribution of $\xi_{ben}$ is asymmetric with a positive skew. The means are located at 0,296 for the leader and 0,359 for the follower. In average the follower therefore flies slightly longer in formation with respect to the overall mission than the leader. The average relative length of the formation for both members accounts for about 30,9% of the whole mission length. Other studies, for example regarding the North Atlantic [21], yield higher values. This shows, that the average formation segment length can vary with the scenario and is characteristic for the scope under evaluation.

As leader and follower fly on the same formation segment, the absolute lengths of the formation segments of leader and follower are identical as it can be seen in FIGURE 10. Basically the same asymmetric distributions can be observed as for the relative segment lengths. The average length of the formation segment $S_{ben}$ amounts to 538 km with a maximum at 2406 km and a minimum at 241 km.

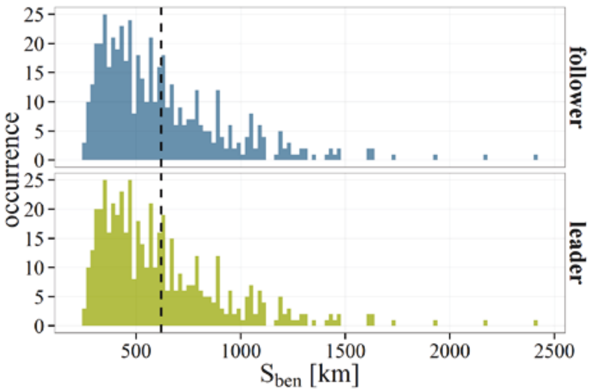

FIG 10. Distribution of lengths of formation segments (ground tracks) separated by leader and follower

### Relative lengths of pre formation segments

The relative length of the pre formation segment $\xi_a$ describes the length of the route segment before the formation phase begins. The distributions of $\xi_a$ are shown in FIGURE 11.

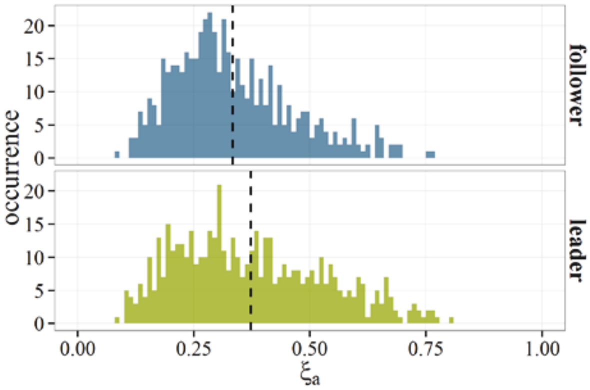

FIG 11. Distribution of relative lengths of pre formation segments ($\xi_a$) separated by leader and follower

Same as for $\xi_{ben}$, $\xi_a$ shows an asymmetry in the distribution with a positive skew. However in contrast to $\xi_{ben}$ the values of $\xi_a$ for the follower are slightly lower. The means are located at 0,373 for the leader and at 0,333 for the follower. The distribution of $\xi_b$ is not presented here as it can easily be derived form the other parameters.

### Formation locations

The formation location $\delta$ describes the relative position of the formation segment in relation to the overall ground track. $\delta = 0,5$ indicates, that the formation segment is right in the middle of the mission, $\delta < 0,5$ indicates a shift of the formation to the beginning and $\delta > 0,5$ to the end of the mission.

FIGURE 12 shows a symmetric distribution of the formation location with the means at around 0,521 for the leader and 0,513 for the follower. This means, that the formation segments are in average located almost in the middle of the formation mission.

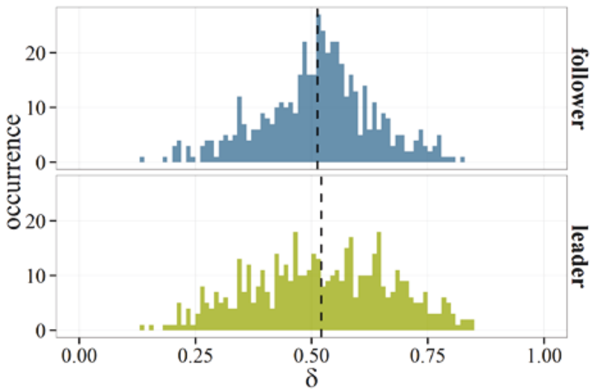

FIG 12. Distribution of location of the formation segment δ in relation to the overall mission separated by leader and follower

### Loadfactors

As the loadfactors of the formation members are not known from the planned point profile data, they are estimated during the calculation using the method described in chapter 3.2. The distributions of the resulting loadfactors are shown in FIGURE 13.

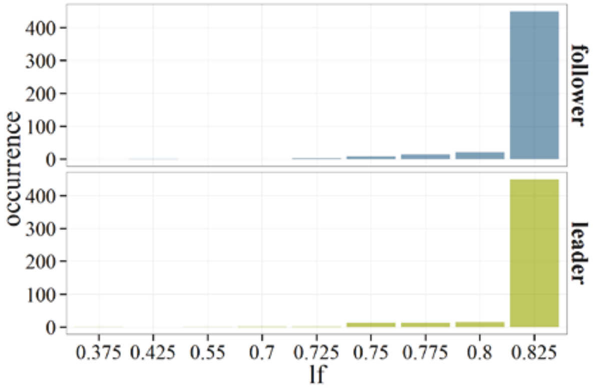

FIG 13. Distribution of the estimated loadfactors separated by leader and follower

It can be found, that the loadfactors in general range from 0,7 to 0,825 with outliers at 0,375 and 0,425. The average loadfactors can be found to be around 0,818 for the leader and 0,82 for the follower. For both leader and follower in 50 formations or about 10% of the cases the loadfactors were adapted by the adaption algorithm described in chapter 3.2.

### Formation Cruise Speeds

The formation cruise speed is subject to change by the described algorithm and therefore is evaluated within this study. FIGURE 14 shows the distribution of FCSs for all calculated missions. It turned out, that during the calculation in no case the FCS was adapted as described in chapter 3.2. This means, that at least half of the considered aircraft operate at their standard cruise speeds as defined in BADA.

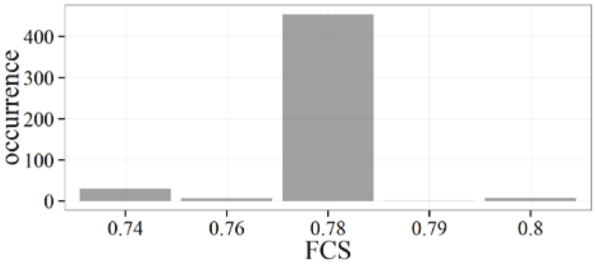

FIG 14. Distribution of formation cruise speeds (FCS)

**Formation Cruise Altitudes**

The formation cruise altitudes of the formation missions are determined by the available planned point profile data and therefore are not altered within this study. The distribution of the formation cruise altitudes is shown in FIGURE 15.

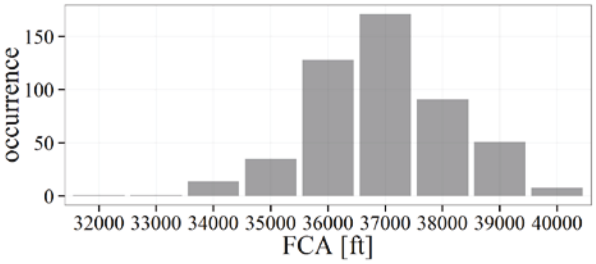

FIG 15. Distribution of formation cruise altitudes (FCA)

The flightlevels range from FL320 to FL400 with a peak at FL370 and are basically normally distributed over the covered range.

**Average and mean values**

The following TABLE 2 holds the mean, median, minimum and maximum values of the formation parameters.

| parameter | unit | mean | median | min | Max |
|---|---|---|---|---|---|
| $\xi_{ald}$ | - | 0,373 | 0,347 | 0,088 | 0,800 |
| $\xi_{afw}$ | - | 0,333 | 0,310 | 0,086 | 0,766 |
| $\xi_{benld}$ | - | 0,296 | 0,270 | 0,080 | 0,760 |
| $\xi_{benfw}$ | - | 0,358 | 0,335 | 0,093 | 0,794 |
| $\delta_{ld}$ | - | 0,521 | 0,520 | 0,136 | 0,844 |
| $\delta_{fw}$ | - | 0,513 | 0,520 | 0,133 | 0,825 |
| $lf_{ld}$ | - | 0,818 | 0,825 | 0,375 | 0,825 |
| $lf_{fw}$ | - | 0,82 | 0,825 | 0,425 | 0,825 |
| FCA | ft | 36940 | 37000 | 32000 | 40000 |
| FCS | - | 0,77 | 0,78 | 0,74 | 0,8 |
| $S_{form\,ld}$ | km | 2159 | 2008 | 825 | 4363 |
| $S_{form\,fw}$ | km | 1750 | 1645 | 825 | 4145 |
| $S_{ben\,ld}$ | km | 538 | 618 | 241 | 2406 |
| $S_{ben\,fw}$ | km | 538 | 618 | 241 | 2406 |

TAB 2. Mean, median, minimum and maximum values of the formation parameters

### 4.6. Potential benefits

The benefits of a formation can be assessed using the metrics described in chapter 3.4. In the study presented in this paper the leader does not achieve a change in the fuel consumption, as the reference mission corresponds with the formation mission and therefore is not subject to evaluation.

If can be found from FIGURE 16, that the distributions of $\lambda$ are asymmetric with a positive skew. As it can be expected, the range of the values for the follower is higher than the range for the whole formation as for the whole formation the fuel savings need to be split on both leader as well as follower.

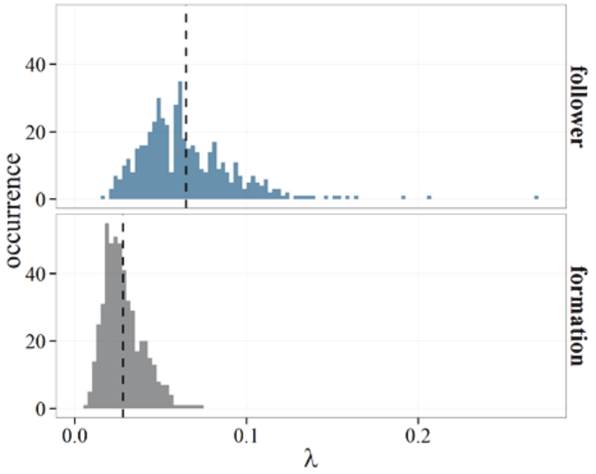

FIG 16. Distributions of formation efficiency metric separated by follower and the whole formation

The average values for $\lambda$ are at 0,0648 for the follower and 0,0281 for the whole formation. The highest values can be found at 0,269 for the follower and 0,074 for the whole formation.

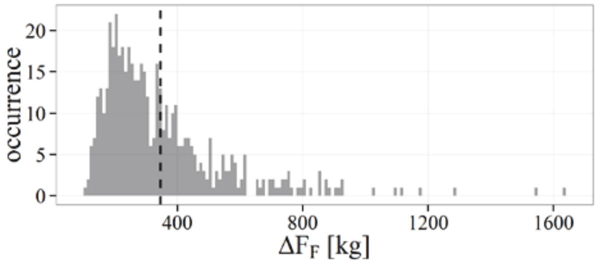

FIG 17. Distribution of absolute fuel savings for the whole formation $\Delta F_F$

FIGURE 17 shows the distribution of the average fuel savings $\Delta F_F$. The values spread from 108kg to 1638kg of saved fuel with an average at 346kg. The potential fuel savings of all formations as resulting from the calculations sum up to about 173000kg of fuel.

**Average and mean values**

The following TABLE 3 holds the mean, median, minimum and maximum values of the benefit metrics.

| metric | unit | mean | median | min | max |
|---|---|---|---|---|---|
| $\lambda_{fw}$ | - | 0,0648 | 0,0601 | 0,0158 | 0,2691 |
| $\lambda_F$ | - | 0,0281 | 0,026 | 0,0071 | 0,074 |
| $\Delta F_F$ | kg | 346 | 290 | 108 | 1638 |

TAB 3. Mean, median, minimum and maximum values of the metrics used for the evaluation

## 5. CONCLUSION AND OUTLOOK

In this paper possible formation missions were identified based on planned point profile data for the European airspace and assessed in terms of potential fuel savings. It could be shown, that a considerable amount of formation flight opportunities in Europe exist as about 5% of the daily traffic is planned with a long-term close vicinity segment (LCV-segment) longer than 30 minutes. It was shown, that a substantial amount of fuel savings can be anticipated if these formation flight opportunities would be put into practice. The average fuel savings in this case would account for about 346kg per flight and sum up to roughly 173000kg in total for the day subject to evaluation. In terms of relative fuel savings in relation to the flights without formations up to 7,4% fuel savings can be reached for the whole formation and up to 27% for the follower. In average for the whole formations fuel savings of about 2,81% and for the followers of about 6,48% with respect to the missions without formation flight were calculated. For the geometry parameters it could be found, that the average formation segment length accounts for around 31% of the whole mission with the leader showing slightly shorter segments than the follower. The average absolute length of the formation segments amounts to 538km. Furthermore the formation segments were found to be in average situated in the middle of the mission. Concerning the aircraft types it was shown, that most of the identified formations are served by only 5 different aircraft types and that some aircraft types are used more often as leader and others more often as follower. With respect to origin and destination airports it was found, that some airports exist that accommodate more formations than others.

As the presented study only covers a limited geographic area it can be expected, that worldwide much more opportunities for formation flight exist and that higher fuel savings can be expected. It is therefore necessary to expand the scope to larger scenarios including longer time periods not only to prove that the results can be repeated. Also the trajectory calculation has to be adapted to better simulate the planned point profiles and thus leading to more realistic results. Finally the selection of the unique set of formations can be included in an optimization loop thus selecting an even better set of formation candidates yielding higher potential fuel savings.

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