

Why aircraft will fly more fuel-efficiently on FRIDAY

The FRIDAY route charges method

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Abstract—The Single European Sky is being introduced to improve the efficiency of flight and traffic operations by reforming the air traffic management system. Despite all of these technical advances, airlines choose detours to avoid high route charges. This mechanism is intensified when fuel prices are low. The single unit rate method has been proposed to counter this behavior, but it will introduce other problems for both air navigation service providers (ANSPs) and airlines. For instance ANSPs have to agree on the redistribution of revenues, and some airlines can be confronted with considerable hikes in the route charges. We propose a novel route charges method called FRIDAY (Fixed Rate Incorporating Dynamic Allocation for optimal Yield) that will i). take away the incentive to airlines for detours, ii). keep ANSPs in control of their unit rates, and iii). keep the new route charges for airlines close to the current route charges when introducing FRIDAY. We will show how the FRIDAY method calculates route charges for flights, and revenues for air navigation service providers. Furthermore, we will introduce a numerical method for setting the unit rates for the FRIDAY method. The expected benefits of introducing the FRIDAY route charges method are i). cost, fuel and time savings for airlines, ii). increased predictability, and reductions in traffic risks for ANSPs, and iii). reductions in emissions and CO2 for society.

Keywords: route charges, ANS charges, minimum fuel route, minimum cost route, fuel-efficiency, emissions

I. INTRODUCTION

Route charges (RC) are a considerable cost to airlines. However, RCs are necessary to pay for the Air Navigation Services (ANS) provided. Depending on how the RCs interact with the flight planning process second order effects with respect to airline costs and ANSP revenues can be expected.

International Civil Aviation Organization Doc 9082 [6] provides the general policies regarding these RCs. The basis is that airspace users pay their fair share in the costs of providing the services. The charge for route ANSs should be a single charge per airspace crossed. The charge can be based on distance flown and aircraft weight. Any changes of the

charging system should be introduced gradually, and should be taking into account the consequences for the users and Air Navigation Service Providers (ANSP).

Until 1998 the Most Frequently Used Route (MFUR) method was used as the charging system for the European airspace. The most frequently used route, and not the flight plan route (FPL), is used between a given city-pair as a reference for calculating the RCs along. The RCs are a function of the distances along the MFUR through the charging regions, the maximum take-off weight of the aircraft type, and the unit rates applicable to the charging regions [5]. Due to the independence to the FPL, it was viewed that MFUR did not reflect the charges according to the services provided.

Therefore, the Eurocontrol route charges system (ERCS) was introduced. ERCS is similar to MFUR, but is a function of the distance along the FPL instead of the distance along the MFUR [4].

Delgado [4] showed that ERCS will let airlines make a trade-off between flying a wind-optimal route and evading high RCs by taking a detour. This results in an increase in fuel consumption and emissions when diverting, but a reduction in direct operating costs to flights.

With the introduction of Functional Airspace Blocks (FAB), a connected set of airspace regions, it was contemplated to implement a single unit rate (SUR) within each FAB. With a SUR a FAB acts like a single charging region with one unit rate. Within this single charging region the RC is independent of the flight path. No detours are expected. A major drawback is that airlines may be confronted with a considerable increase in RCs upon transition to SUR relative to when they operated in regions with low unit rates [8].

Bolić et al. considered adding pricing mechanisms to the ERCS to allow for the redistributing of traffic alleviating airspace congestion [1]. Castelli et al. showed that this concept can indeed redistribute traffic [2]. As the underlying route

charging mechanism is the same as ERCS also the associated evading problem remained.

No RCs method is currently known that simultaneously prevents the detour problem, reflects the charges according to the services provided, and can be transitioned to from ERCS without considerable price hikes for airlines.

In this paper we propose an alternative route charging method called FRIDAY ("Fixed Rate Incorporating Dynamic Allocation for optimal Yield") that has the desired properties of ERCS, and does not have the detour problem. The performance of the FRIDAY route charges method will be analyzed during follow-up research. A performance analysis is therefore not part of this paper.

In section II we will describe the general route charging problem and its relationship to the flight planning problem. In section III the FRIDAY route charges method is introduced. Section IV describes how unit rates can be set for multiple charging zones. Section V discusses the method and expected benefits. Finally, in section VI initial conclusions are drawn in respect to the performance of FRIDAY in comparison to ERCS and SUR.

II. FLIGHT PLANNING AND ROUTE CHARGES PROBLEM

A. Notations

a	specific flight
b	first parameter of weight factor p
C	cost coefficient of flight
c	second parameter of weight factor p
d, D	distance factor for ERCS, FRIDAY
h	altitude
i, j	specific charging zone
J	cost function of flight
m	aircraft mass
p	weight factor
r, R	route charge for ERCS, FRIDAY
t	off/on block time
u, U	unit rate for ERCS, FRIDAY
v	true air speed

Three types of indices are used. With the index a it means that it is for a specific flight, with index i or j it means that it is for a specific charging zone, and with the combined index ia or ja it means that it is for a specific charging zone and flight.

B. Eurocontrol route charges system

The Eurocontrol route charges system (ERCS) as implemented in Europe is a function of three basic factors [10]:

1. Distance factor
2. Aircraft weight factor
3. Unit Rates for each charging zone.

The distance factor d_{ia} is based on the great circle distance to be travelled by aircraft a within each charging zone i . The distance is measured between points which are either entry or exit points of the charging zone, or the departure or arrival airport. The points are placed along the last filed flight plan. The distance in a radius of 20 km around the airport is not taken into account as this is considered to be covered by the terminal area charges.

The aircraft weight factor is a function of the maximum take-off weight of the aircraft according to the aircraft flight manual.

The number of service units is a function of the distance factor and weight factor. The unit rate u_i is a fixed charge per service unit for a charging zone. The unit rate is set for a fixed period.

The total charge r_a for a specific flight $a \in \{1, \dots, m\}$ (m = number of flights) is the summation of all separate charges r_{ai} within each charging zone $i \in \{1, \dots, n\}$ (n = number of charging zones).

$$r_a = \sum_i r_{ia} \quad (1)$$

The individual charge is a function of the number of service units and the unit rate for the charging zone.

$$r_{ia} = d_{ia} \cdot (b_i \cdot MTOW_a)^{c_i} \cdot u_i = d_{ia} \cdot p_{ia} \cdot u_i \quad (2)$$

where $MTOW_a$ is the maximum take-off weight of flight a , and b_i and c_i are parameters used for calculating the weight factor p_{ia} . Within the European airspace the parameters are uniformly $b=1/50$ and $c=0.5$. ICAO's policy is that the weight factor must be less than proportional to the weight of the aircraft ($0 < c_i < 1$) [6]. The distance multiplied with the weight factor is expressed in service units.

The total revenue within a charging zone is the summation over all flights of the route charge within the charging zone:

$$r_i = \sum_a r_{ia} \quad (3)$$

C. Flight plan optimization

Airlines use the flight planning process to generate routes that are optimized in respect to the direct operating costs. The main factors influencing the direct operating costs are the off blocks period, the fuel consumption and associated fuel price, and route charges [9]. The associated cost function J_a can be defined as:

$$J_a = \int_{t_{0a}}^{t_{1a}} [C_{ta} + C_{fa}g(h, m, v)] dt + \sum_i d_{ia}p_{ia}u_i \quad (4)$$

where C_{ta} is the cost coefficient of the off blocks period with t_{0a} and t_{1a} being the off and on blocks times

respectively, C_{fa} is the cost coefficient of the fuel consumption, $g(h, m, v)$ is the rate of fuel consumption depending on the altitude h , mass m and true air speed v . The summation is the route charge from (2).

When we assume that the route charge is not taken into account for the optimization then the cost function is simplified to the integral part. A trajectory can be calculated for this cost function. The associated cost with this trajectory is the minimum cost possible for this integral for the given boundary constraints. This trajectory has still an associated route charge.

To find an optimal trajectory for the given cost function the problem could be viewed in theory as a multi-objective optimization problem [3]. The two objectives consist of both the integral (i.e. time and fuel part) and the summation (i.e. route charges part) component of (4). Multi-objective optimization theory states that when a Pareto optimal solution is found then it is not possible to improve one of the objective function parts without affecting any of the others negatively.

Hence the associated route charge costs at the minimum time/fuel point can only be reduced when accepting an increase of the cost of time and fuel. Therefore the route for overall minimum cost is normally not the same as the route for minimum time and fuel costs.

Now it is the question if it is possible to design a route charge method that does not lead to deviation from the minimum time/fuel trajectory, and that simultaneously will decrease average direct operating costs. Furthermore, the route charge must still allow ANSPs to recover the full costs of providing their services.

III. FRIDAY ROUTE CHARGES METHOD

A. Method description

An increase in the cost of time and fuel as a result of including the cost of route charges in the overall cost function can only be prevented when:

1. the route charge has its minimum always at the optimal time/ fuel trajectory, or
2. the route charge is independent of the chosen trajectory.

The first option is not practical as this presumes knowledge about the time and fuel cost function to Air Traffic Management (ATM) for each specific flight. This information is not available to ATM, and airlines are not eager to provide this business sensitive information. We therefore do not consider this option.

The second option can be any charge that is not dependent on the filed route. The independent charge we propose is a route charge that is calculated along the great circle distance (blue dashed line in Fig. 1) between the origin and destination airport, and not using the files route (green dotted line in Fig. 1).

The great circle line is subdivided into sections crossing several charging zones. The route charge is calculated using the section lengths along the great circle line, the weight factor, and the unit rates of the intersected charging zones along the great circle line. This fixes the total route charge the airline has to pay for a given city-pair and aircraft type.

The route charge for a section of the great circle line is calculated in the following way (the parameters that are different from the ERCS method are indicated by use of a capital letter):

$$R_{ia} = D_{ia} \cdot p_{ia} \cdot U_i \quad (5)$$

where D_{ia} is the distance covered by the great circle line from origin to destination crossing the charging zone i . U_i is the unit rate applied in the charging zone. The total route charge to be paid by aircraft a is:

$$R_a = \sum_i R_{ia} \quad (6)$$

This individual route charge is close to the Eurocontrol route charge in (2). The total distance covered is in most cases within a few percent of the actual distance flown. The weight factor is the same, and the unit rate can also be set close the unit rates used with the Eurocontrol route charge. How to calculate the unit rates is discussed in section IV.

Setting up the route charge in the proposed way does not relate the route charge to the services provided by the actual charging zones that are passed. The actual route can pass through a charging zone that is not covered by the independent route charge at all. Therefore, we propose to proportionally divide the collected charges over the ANSPs of the charging zones actually crossed (orange line in Fig. 1). In other words, it is proportionate to ERCS. S_{ia} is the share or portion the crossed charging area is allocated.

$$S_{ia} = \frac{r_{ia}}{r_a} = \frac{d_{ia} \cdot p_{ia} \cdot U_i}{\sum_j d_{ja} \cdot p_{ja} \cdot U_j} \quad (7)$$

The summation in the denominator is the total route charge

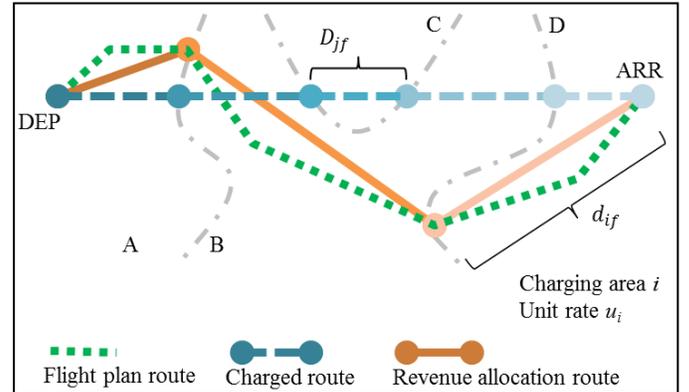


Fig. 1 The aircraft f flying along the green planned route is charged based on the blue great circle line. The revenues are distributed to the charging zones based on the orange line.

when the route charge would be calculated using ERCS. The nominator is the route charge within a specific charging zone using ERCS.

The total amount each route charging zone is allocated over all flights is:

$$R_i = \sum_a R_a S_{ia} \quad (8)$$

This route charge method has been called FRIDAY. FRIDAY is an acronym for Fixed Rate Incorporating Dynamic Allocation for optimal Yield. This title reflects the two main ideas behind the route charges method: 1. fixed rate for flights to prevent route deviations as a result of the charges, and 2. the dynamic allocation of the total revenue between the charging zones overflowed.

B. Example applying FRIDAY

In Fig. 2 an example of charges calculated by the FRIDAY method is given based on the route in Fig. 1. The blue bar indicates the total route charge to be paid by the flight. The right most orange bar indicates what the flight would have paid using ERCS. The proportions from this bar are used to calculate the shares of the servicing ANSPs from the actual paid (blue bar) amount by the flight. This is indicated in the middle orange bar.

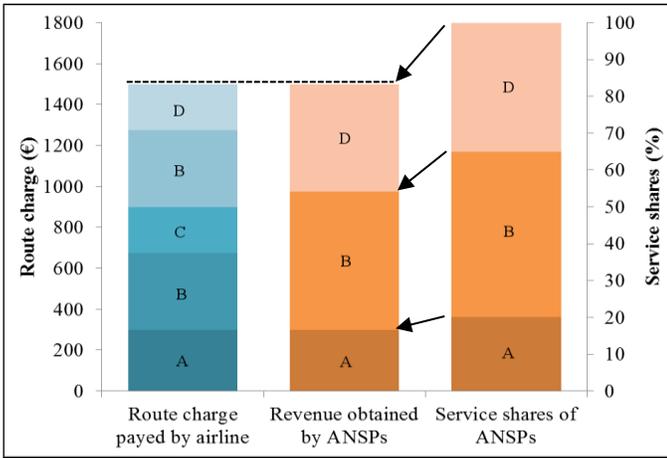


Fig. 2 The revenue obtained by the ANSPs is determined by the route charge paid by the airlines and the proportion of services provided.

IV. DETERMINING UNIT RATES

A. Eurocontrol route charge system

ANSPs have to set periodically, usually yearly, their unit rates. For the Eurocontrol route charge the unit rates are set such that the periodic costs c_i of providing the air navigation services equals to the expected amount of service units within that period multiplied with the unit rate.

$$c_i = u_i \sum_a d_{ia} (u_1, \dots, u_n) p_{ia} \quad (9)$$

Estimating the amount of service units can in practice be done by taking the actual amount of service units from a previous year and adding an expected growth percentage. This gives a reasonable estimate. Still errors can be introduced due to:

- Deviations in the traffic growth, weight factor, and the city pairs, and
- Actual routes filed: routes can deviate due to variations in wind conditions and due to unit rate differences between charging zones.

B. FRIDAY route charge method

For the FRIDAY route charges method setting the unit rate is not trivial as there is a limited dependency with the unit rates of the other charging zones. The cost for each charging zone must be set equal to the expected revenue:

$$c_i = \sum_a \frac{\sum_k D_{ka} p_{ka} U_k}{\sum_j d_{ja} p_{ja} U_j} d_{ia} p_{ia} U_i \quad (10)$$

When is assumed that the weight factor is the same in all charging zones, as is the case in Europe, the equation is simplified to:

$$c_i = U_i \sum_a \frac{\sum_k D_{ka} U_k}{\sum_j d_{ja} U_j} d_{ia} p_a \quad (11)$$

In the simplest case with the assumption of free routing and no wind, aircraft will all fly the great circle route from origin to destination ($d_{ia} = D_{ia}$). The cost equation is in this case even further simplified to:

$$c_i = U_i \sum_a D_{ia} p_a \quad (12)$$

C. Numerical method

The unit rates can in the simple case (12) directly be calculated when the service units of all expected flights in the charging zone are summed.

This set of unit rates can be used as a starting set $U_{iq} \forall i$ (with iteration counter q being 0) for finding the optimal set of unit rates $U_i' \forall i$ for the general FRIDAY method in (11). Except for the unit rates all other parameters are fixed, and nondependent on the unit rates. Equation (11) can therefore be used for defining a system of nonlinear equations: $f_i(U_1, \dots, U_n) = 0 \forall i$. The unit rates can then be estimated using a generic numerical method for solving systems of nonlinear equations. This can be for instance the Newton method using difference formulations [7].

No performance analyzes has been performed yet to verify the feasibility of the numerical method. This will be done in follow-up research.

V. DISCUSSION

To understand the consequence of switching from ERCS to FRIDAY it is best to first envision what would happen if route charges would be abolished.

A. *No route charge scenario*

In such an extreme scenario of elimination of route charges the first order effect will be that most flights will start to fly optimal trajectories in respect to time and fuel (emissions) within the charging area. Also secondary order effects can be expected. As could be seen in (4), flight planning methods for optimal time and fuel are less complex than minimum cost methods. The used heuristics will in general find solutions close to the global optimum more easily for the minimum time and fuel problem than for the minimum cost problem. This will result in some small, but additional fuel and time savings upon the switch. Another secondary effect is that currently airlines sometimes have to file an updated flight plan upon flow measures. This will mostly result in increases in the route charges. This practice of additional financial punishment upon a flow measure will be absent.

For ANSPs it is trivial that in this extreme scenario no costs can be recovered, but there are also a number of positive secondary order effects. First of all, there is less need for pilots requesting “directs” to be able to reduce the effects of the detours in their minimum cost flight plan. The predictability, the deviation between the filed flight plan and actual flown trajectory, will therefore improve. Traffic concentrations in areas with low unit rates can also be reduced.

B. *FRIDAY scenario*

The impact of the FRIDAY route charges method is similar to the scenario without route charges. There are some additional effects, though. For an airline the FRIDAY route charge is mostly close to the common route charge. This difference is smaller than in case of the common unit rate vs. the common route charge. This helps with the acceptance by airlines of an updated route charges method.

For the ANSPs there is a need to work together on setting the unit rates using the FRIDAY method. This is due to the limited dependency between the unit rates as can be seen in (10). The basics for the numerical method for setting the unit rates at the right level, is described in section IV. Furthermore, there will be no competition anymore between ANSPs through the unit rates. ANSPs can only attract more traffic by improving the efficiency of their airspace.

VI. CONCLUSIONS

We have proposed an improvement to the common route charges method we called FRIDAY (Fixed Rate Incorporating Dynamic Allocation for optimal Yield). Like with the common unit rate method aircraft will tend to fly their minimum time and fuel trajectory, and will not try to fly longer routes to evade route charges. This will reduce overall emissions of traffic. But unlike the common unit rate, FRIDAY will keep ANSPs in control of their own unit rates, and will keep the FRIDAY route charges for airlines closer to the common route charges currently experienced. We have described calculation techniques for the FRIDAY method, both for the airspace users

and ANSPs. Furthermore, we have introduced a numerical iteration method for setting the unit rates for the FRIDAY method. In the discussion we showed that the main benefits are cost, fuel and time savings for the airlines, emission reductions for the society, and increased predictability, and reduction in the financial exposure to traffic risks for the ANSPs.

How to incentivize ANSPs to keep unit rates low using FRIDAY is still an unaddressed question. This will need to be addressed in the follow-up research.

Further quantitative research will be needed to show the actual performance of the FRIDAY route charges method in a practical setting, and to show that the discussed benefits are feasible.

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