# Fuel consumption assessment for speed variation concepts during the cruise phase

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**Abstract**

In recent years, some research studies in Air Traffic Management (ATM) have proposed the idea of adjusting the speed of aircraft for several applications, like for instance, conflict resolution, 4D trajectory management, and airspace capacity and demand balance. In this paper an initial assessment on how this kind of speed variations may affect to fuel consumption is presented. Only the cruise phase is considered and the relationships existing among different variables such as the speed, the flight level, the aircraft mass etc. are arisen. In addition, it is emphasised in what conditions a speed reduction strategy can be implemented without penalising the fuel consumption. Thence, it is shown that there is a range of speeds, lower than the nominal cruise speed, that do not suppose an increase in fuel consumption regarding the nominal block fuel. However, a certain sensibility with the selected Cost Index is identified. High values of the Cost Index allow more speed margin without a negative fuel impact, while low values of the Cost Index reduce the impact on fuel consumption in the case the nominal cruise speed is increased.

## 1 Introduction

The forecast of flights movements in the Eurocontrol Statistical Reference Area (ESRA) for 2030 is between 1.7 and 2.9 times the traffic of 2007 [1]. In the most-likely growth scenario, by 2030, the 11% of actual demand will not be accommodated if the current operational concept is kept [2]. In addition, new challenges that go further than demand capacity management are also arising like, for example, fuel consumption or the environmental impact of aviation.

In recent years, some research studies in Air Traffic Management (ATM) have proposed the idea of adjusting the speed of aircraft for several purposes. For instance, the ERASMUS project, tries to reduce the conflicts by minor speed adjustments or by changes in the Required Time of Arrival (RTA) [3]. There, it has been studied how this concept will impact on the workload of the controllers and some percentages of speed variation have been stabilised in order to avoid controllers perception of the system [4]. In addition, the introduction of new operational concepts by SESAR will open the door to new capacity-demand balance techniques by using accurate speed profiles along the flight plan [5].These

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ideas are mainly based in the forthcoming concepts of 4D trajectories or semi-automated ATM environments. Moreover, speed management is also found in conflict resolution techniques or even in noise abatement procedure design. However, in all theses studies the economic repercussions of the variation on the speed are almost not assessed.

If a change on the aircraft trajectory is done, when solving a conflict or when dealing with a capacity-demand imbalance, it is obvious than more fuel will be burned than initially planned. On the other hand, if speed is reduced as a alternative to the trajectory diversion, in some cases some extra fuel will be saved or spent.

During the year 2008 the price of oil reached prices over $100 per barrel. During this year the most of the airlines reported that fuel costs where in between the 30%-40% of their total expenses. In a world where the fuel consumption is becoming a paramount factor it is important to assess which are the consequences of these changes in the aircraft airspeed. The aim of this paper is to show how variations in speed can impact to fuel consumption and how, in some cases, certain speed reduction strategies can be implemented without penalising the fuel consumption.

In section 2 the context of aircraft operations is presented, summarising briefly some forthcoming concepts that will require speed variations during the flight. In section 3 the assessment of the fuel variations due to speed variations during the cruise phase is done. Two example flights are analysed. Finally, the paper ends with the conclusions and future work in section 4.

## 2 Operational context

In the majority of civil aviation flights, aircraft operators have to trade-off between the fuel consumed and time needed to fly a certain route. Aircraft equipped with Flight Management Systems (FMS) use a *Cost Index* (CI) parameter when optimising the flight profiles. The CI express the ratio between the cost of the fuel and the cost of the time [6]. Thus, a CI set to zero means that the cost of fuel is infinitely more important that the cost of the time and the aircraft will fly at the maximum range speed. On the other hand, the maximum value of the CI gives all the importance to the time, regardless of the needed fuel. In this case, the aircraft will fly at the maximum operating speed (VMO/MMO) with, in general, some safety margins. Airlines can reduce their operation cost by an efficient management of the CI settings among their scheduled flights. Actually, a CI value not only affects to the cruise airspeed but will determine the whole profile of the flight. This means that the optimal flight level may change and that the climb and descending gradients might be different for different CI values.

As the CI is the main parameter to manage airline operating costs, it is a subject of continuous research. For instance, Cook et al. propose in [7], the concept of a Dynamic Cost Index. This strategy would allow airlines to continuously compute and change the cost index during the flight. Therefore, they will be able to optimise their cost to the uncertainties of a real flight in order to recover, for example, a certain delay.

## 2.1 SESAR operational concept

According to SESAR, the airspace user is the owner of the trajectories and a protocol has been established to develop and modify them. Years before the operation day, the airspace user will develop inside its organisation the Business Development Trajectories (BDT). These BDT will evolve up to a moment when they become available to other users in the Network Operations Plan (NOP). The NOP will distribute all the trajectories to the Network Manager and to the Air Navigation Service Provider (ANSP). At this moment the BDT will become the Shared Businesses Trajectory (SBT).

In case of an imbalance between capacity and demand, a negotiation process will be carried on to reduce as much as possible this imbalance. The airspace users will modify their SBT trajectories to try to fit the capacity constraints. This negotiation process ends when an optimum is obtained. At this point the SBT trajectory become the Reference Business Trajectory (RBT) that the Airspace Users agrees to fly and the ANSP and airports agree to facilitate. The RBT are full 4D trajectories where a time window is attached to each waypoint.

However, the RBT is not a clearance. The trajectory will be cleared by steps and it will be affected by many events like de-conflicting, local capacity management, etc. So, the RBT trajectories can be changed during the flight. The changes will come from the airspace user or from the ANSP to deal with separation, queue management or changes in constraints or in resource availability [5]. As the RBT as attached some time constraints, in case of not achieving one of those constraints, a new renegotiation will be done between the airspace user and the ANSP. This can lead to changes on speed.

## 2.2 Some concepts that require speed management

As previously explained, in the SESAR operational context, the RBT trajectory will be followed by the aircraft and the ANSP will try to respect this initial trajectory. However, due to the uncertainty related with the flight, weather changes, etc. some adjustments may be needed to deal with capacity-demand imbalance, queuing or with conflict resolution. That is the reason why the RBT needs to be cleared as long as the flight evolves. In addition, in the SESAR operational concept new separation modes as the Trajectory Control by Speed Adjustment (TC-SA) are included. The TC-SA will be used to minimise potential conflicts and reduce the workload of the controllers [8, 9].

In the project Contract-Based Air Transportation (CAT), it is proposed a series of time windows constraint that the aircraft will try to satisfy [10, 11]. If the aircraft can not fulfil a constraint window, then a negotiation process will start in order to determine new constraints. This trajectory management is useful but it may be difficult for the aircraft to determine if a time window can be met or not. For instance, if due to a tail wind, the aircraft is flying faster than expected, it could slow down in order to deal with the constraints, but this might lead to a misuse of fuel.

As outlined before, the ERASMUS project tries to strategically reduce conflict generation by adjusting the 4D Business Trajectory on short segment of 15 minutes. To adjust the 4D trajectory, ERASMUS perform minor speed adjustments that are not directly perceivable by the controllers and do not interfere with their actions. It has been estimated that up to an 80% of the conflicts
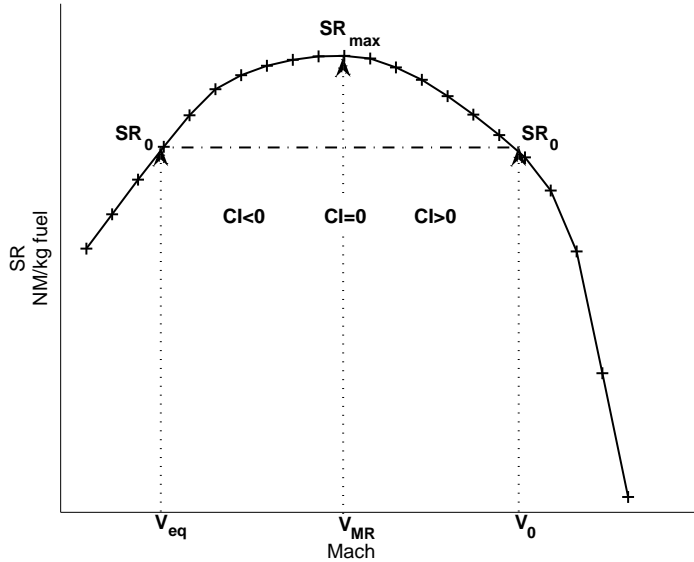
Figure 1: Specific Range (SR) in function of cruise speed.

could be solved without the perception of the controller [3, 12]. In this project, a variation between [-6%,+6%] of the speed is allowed to perform these separations [9, 12]. Moreover, further studies have been done to assess if the variations in speed can be detected by controllers. They show that variations up to a -12% of the cruise airspeed can be done without notice from the air traffic controllers [4].

Finally, recent studies like for instance [13] try to solve air traffic management and air traffic control by using speed control techniques. Their goal is to have sectors without conflicts, thanks to the control of the speeds of the flights. This study uses variation of speed in between [-10%,+10%].

All the results of these studies are interesting and very promising from an operational point of view. However, they usually lack from an accurate assessment on how speed variations may effect the fuel consumption and therefore on the economical impact and the feasibility of the above mentioned concepts.

# 3 Assessment of fuel consumption due to a speed variation

When an airline operator plans a flight at a given cost index (CI), with a given payload and for a given distance, it determines the optimum flight level, the optimum cruise speed and, consequently, the fuel needed for that particular flight. In other words, the fuel consumption is known at a certain level of accuracy.

In Figure 1 it is presented the Specific Range (SR), i.e the amount of Nautical miles that the aircraft can fly with one kilogram of fuel, in function of the speed
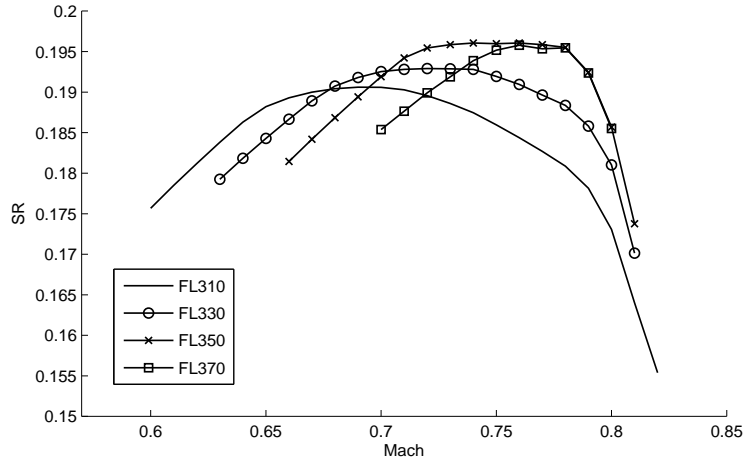
Figure 2: Specific Range (SR) in function of the cruise speed and cruise flight level

for typical air transport aircraft. As it can be seen in the figure, in a normal flight the aircraft will fly at a desired cruise speed, namely $V_0$. On the other hand, the maximum SR is achieved when flying at $V_{MR}$, which is lower than $V_0$ for a positive CI. If speed is decreased below this value, the SR will decrease again. Obviously, speeds below $V_{MR}$ are, a priory, not desirable from an operational point of view and flying to these speeds will signify a negative Cost Index.

As seen in the figure, there exists a velocity $V_{eq}$, below $V_{MR}$, that will produce the same SR than the desired cruise speed. Therefore, flying at speeds in between $V_{eq}$ and $V_0$ will produce less fuel consumption than initially planned for the nominal flight at $V_0$.

## 3.1 Influencing parameters

In normal aircraft operations cruise speed $V_0$ is always chosen higher than the maximum range speed $V_{MR}$, i.e. the CI is set to some positive value greater than zero. This means that the aircraft will fly at a SR lower than the maximum SR.

Let $V_{var}$ be a new speed required for some ATM application as discussed in previous section. As it is easily seen in Figure 1, if $V_{var}$ is a value between $V_{eq}$ and $V_0$ some fuel will be earned with respect to the initially planned flight. However, if $V_{var}$ is lower than $V_{eq}$ or higher than $V_0$ some extra fuel will be necessary. Therefore, the range of speeds that allow speed reductions without spending extra fuel depend directly on the difference between $V_0$ and $V_{eq}$.

In turn, this distance depends on the value of $V_0$ but also on the SR curve shape. Figure 2 shows the SR curve in function of the flight level for a same aircraft with the same weight. As it can be seen different flight levels lead to different SR curves and the range between $V_{eq}$ and $V_0$ narrows as the flight level increases. Moreover, this range of speeds is also affected by the weight of the aircraft as shown in Figure 3.

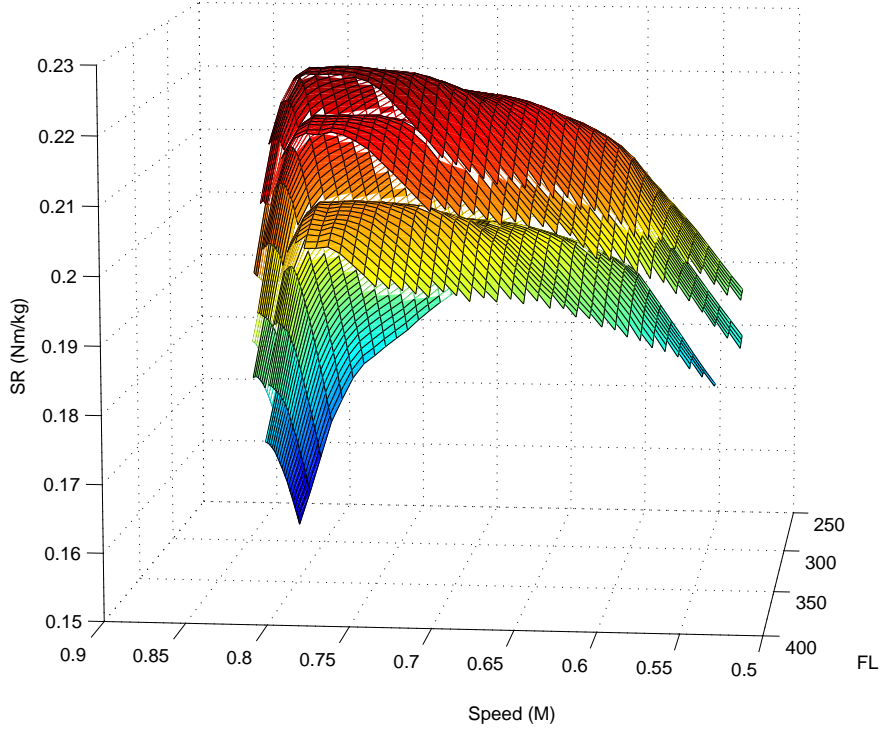Summing up, the available range of speeds depends on the desired initial

5

Figure 3: Specific Range (SR) in function of the cruise speed, cruise flight level and three different aircraft weights

speed $V_0$, the flight level and the weight of the aircraft. In other words, the available range depends on the Cost Index that the airline operator is using. It is important to note that cruise speed and flight levels are not arbitrary chosen. In function of the desired CI, the weight of the aircraft and the length of the flight, the cruise speeds and altitude profiles will be optimally determined. Therefore, it is not possible to further assess the fuel impact of speed reduction strategies without analysing specific flights.

## 3.2   Application examples

In this section some example flights have been studied in order to determine how variations in speed affect on the SR and, in turn, on the fuel consumption. Two different flights are considered, both with an Airbus A320, and representing two typical routes within the European airspace: Rome-Fiumicino (FCO) to Paris Charles de Gaulle (CDG) and Paris Orly (ORY) to Nice (NCE). Figure 4 shows the optimal cruise speed in function of the desired CI for both routes. As expected, the cruise speed increases as the CI increases. Similarly, Figure 5 shows the optimal cruise flight level (FL) in function of the Cost Index (CI). As it can be seen, for the FCO–CDG flight the optimal cruise flight level oscillates between FL380 and FL390 while for ORY–NCE three different optimal flight
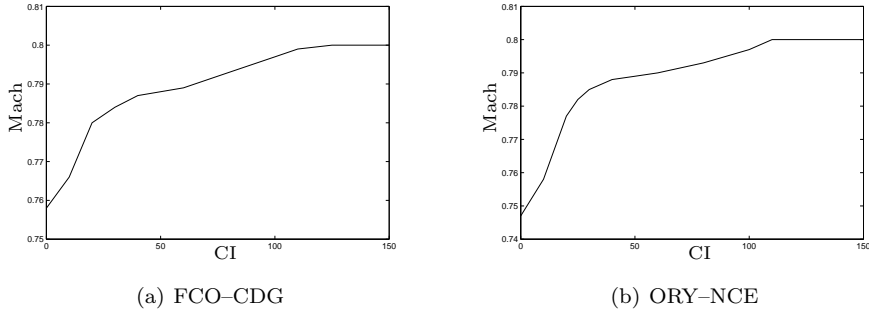
(a) FCO–CDG           (b) ORY–NCE

Figure 4: Optimal cruise speeds
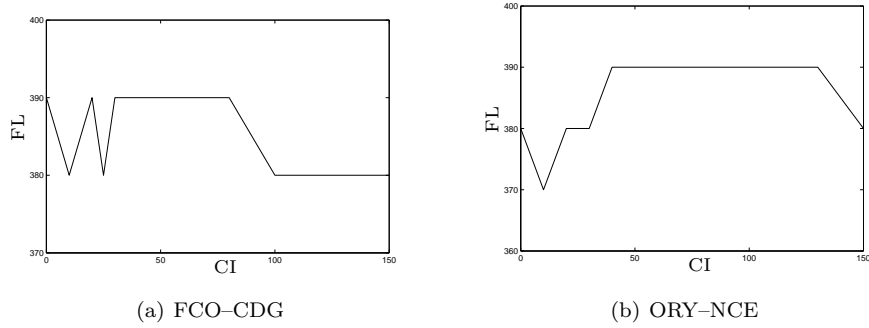


(a) FCO–CDG           (b) ORY–NCE

Figure 5: Optimal flight levels

levels are obtained (FL370, FL380 and FL390).

As shown before, an important parameter is the weight of the aircraft that changes during the flight. However, in this study, as a first approach we have supposed that the weight remains constant during the cruise phase and the actual weight of the aircraft at the middle of this phase is chosen. For the considered flights the actual weight variations during the flight do not suppose a significant change on the presented results.

### 3.2.1   Fuel consumption variation

As an illustrative example let us choose a specific CI value for each of the proposed flights as summarised in Table 1. These CI values are representative of what an airline operator would select in a real operation of these routes. As

| Flight | FCO–CDG | ORY–NCE |
|---|---|---|
| Aircraft | A320 | A320 |
| CI | 25 | 60 |
| Cruise Flight Level | 380 | 390 |
| Cruise Speed ($V_0$) | 0.78 | 0.79 |

Table 1: Analysed flights

7

(a) FCO–CDG



(b) ORY–NCE
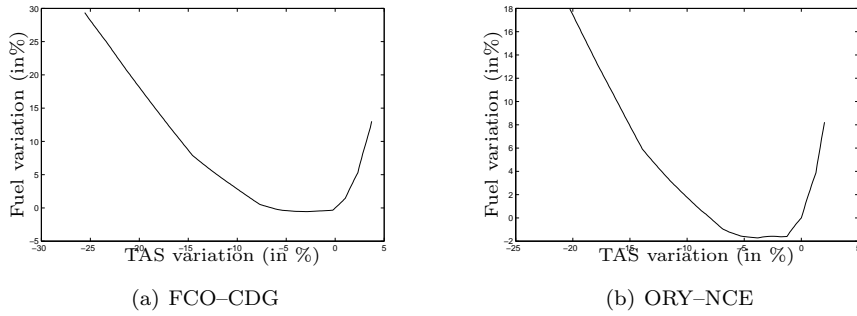
Figure 6: Variation on the fuel consumption in function of the deviation on the cruise speed
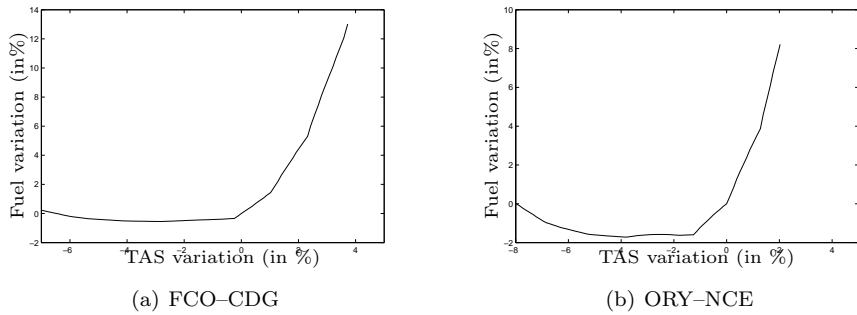


(a) FCO–CDG



(b) ORY–NCE

Figure 7: Variation on the fuel consumption in function of the deviation on the cruise speed. Detailed view around $V_0$

explained before, once the CI is selected the (optimum) cruise flight level and cruise speed are subsequently fixed.

Figure 6 shows, for both analysed flights, the variation on the fuel consumption in function of a deviation in the cruise speed, regarding the optimal cruise speed value of $V_0$. As already commented it is obvious that for $V_{var} > V_0$ the fuel consumption is increased. However the flight time will be reduced. On the other hand, for $V_{var} < V_0$ we have a certain range of speeds where the fuel consumption is equal or less than the initially planned. Figure 7 shows in detail this interval for both flights. For the FCO–CDG case if the speed is reduced up to a -6% of $V_0$, approximately, the fuel consumption will not be penalised and even some small of fuel will be saved. The curves of the SR in function of the speed (and therefore the fuel consumption in function of the speed) become quite flat around the maximum SR values for these flight conditions. Then if $V_{var}$ decreases further, the fuel consumption is seriously penalised as observed in Figure 6. As expected, similar results are obtained with the ORY–NCE flight, allowing in this case maximum variation of a -8% of $V_0$ with no extra fuel required.
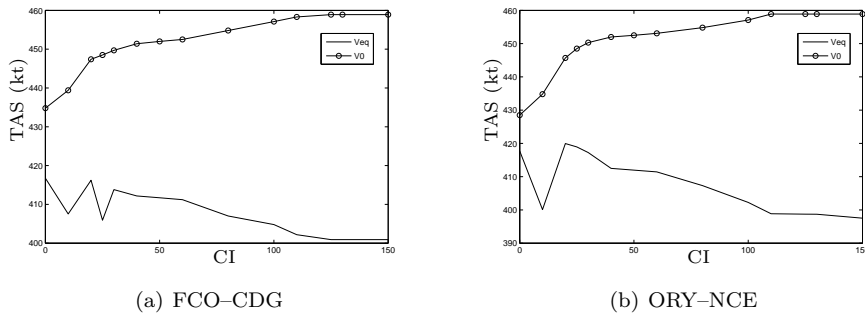
|        |        |
|:------:|:------:|
| (a) FCO–CDG | (b) ORY–NCE |

Figure 8: Values of $V_0$ and $V_{eq}$ for different CI

### 3.2.2 Cost Index sensitivity analysis

Being the CI the relationship between the cost of time and the cost of fuel, higher CIs imply higher cruise speeds ($V_0$). This would lead to a wider range of speeds where the fuel consuption is not penalised, as we arleady saw in Figure 1.

In this section we compute for the previous two fights the distance existing between $V_0$ and $V_{eq}$ for different values of the Cost Index. The results are presented in Figure 8 where these two speeds are plotted in function of the CI.

As expected, the higher the CI is the higher the avaiable margin between $V_0$ and $V_{eq}$ is. There are some exeptions where an increment of CI leads to a reduction of the margin between these two speeds. This apparent paradox is due to the fact that when changing the CI not only the cruise speed is changed but also the optimal flight level. Operational flight levels take values that are rounded to the nearest thousand feet and, therefore, this discrete set of feasible flight levels cause these discontinuities in the graphs (see also Figure 5).

As it can be seen in Figure 8, depending of the choosen CI the speed range in which it is possible reduce the cruise speed without afecting the aircraft consumption varies from 17 kt to 57 kt aproximately for the CFO–CDG flight. This corresponds to an approximate variation of the cruise speed of [-12%, -4%]. On the other hand, for the ORY–NCE flight the cruise speed can be reduced around 10 kt to 61 kt which corresponds to a [-13%,-2%] variation. However, for the most common used values of CI these margins will be around the [-6%,-2%].

The variation on the fuel consumption in function of the deviation on the cruise speed, as shown in Figure 6, has been recalculated for different CI values and for both example routes of Table 1. These results are shown in Figure 9 and a detailed view around the cruise speed $V_0$ is given in Figure 10. As it was already seen in Figure 8, we observe again that as CI increases the range of speeds that allow a speed reduction without penalising fuel consumption is wider. On the other hand if the speed wants to be increased above $V_0$, the extra fuel required is higher as CI increases. Moreover, Figure 11 shows the absolute values of this relationship plotting the fuel consumed (in kg) per 1 NM in function of the cruise speed (TAS) in knots.
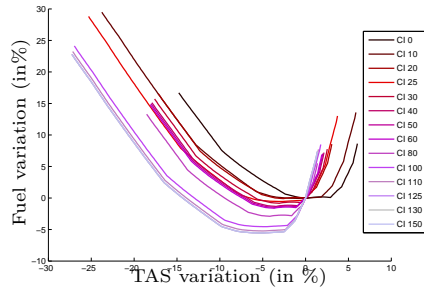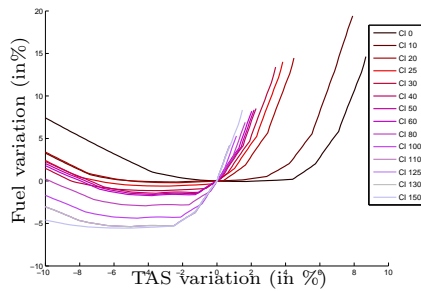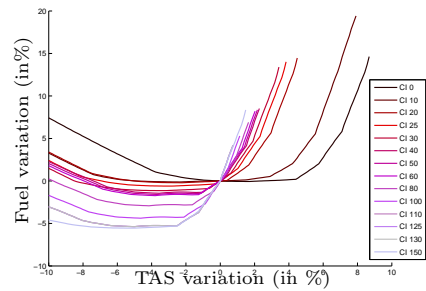
(a) FCO–CDG
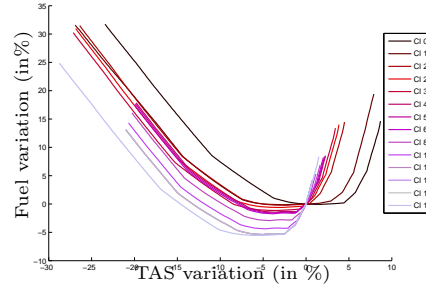
(b) ORY–NCE

Figure 9: Variation (in %) of the fuel consumption with respect to the planned block fuel, in fucntion of speed variations
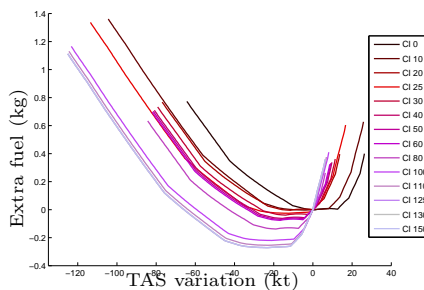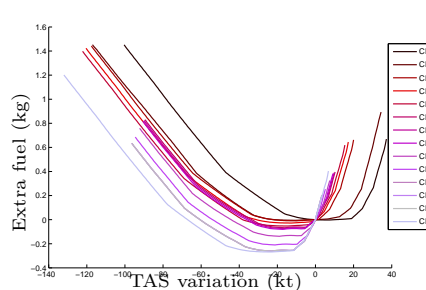


(a) FCO–CDG

(b) ORY–NCE

Figure 10: Variation (in %) of the fuel consumption with respect to the planned block fuel, in fucntion of speed variations. Detailed view around [-10%,10%] of cruise speed variations



(a) FCO–CDG

(b) ORY–NCE

Figure 11: Absolute variation of the fuel consumption per 1 NM, with respect to the planned block fuel, in fucntion of speed variations

# 4   Conclusions and Futher work

In this paper an assessment is done analysing the effects that variations on the cruise speed have into the fuel consumption when dealing with conventional air transport aeroplanes. Some of the nowadays research in the Air Traffic Management domain suggest speed variations as one of the key enablers for a wide range of applications (ranging from conflict resolution to aircraft flow management). Speed variations during the cruise phase have a direct impact in fuel consumption. It is clear that in a normal operation an increase of the cruise speed will lead always to an increase of fuel consumption. However, a speed reduction may lead sometimes to save or expend more fuel. Due to the close relationship existing among optimal flight levels, optimal cruise speeds, the weight of the aircraft, the lenght of the flight and the desired Cost Index it is difficult to arise a general figure of fuel efficiency valid for all flights. In this paper we have shown how these parameters influence in the fuel consumption and two example flights have been analysed. We have identified that the desired Cost Index has a big influence in the variations of fuel consumption due to variations of speed during the flight phase. The higher the Cost Index is the wider the range of velocities which permit to fly without burning extra fuel is. We have shown that for a typical flight within the european region with a typical Cost Index setting the maximum speed reduction that can be acheived during the cruise flight without penalising the fuel consumption is around the 7%. However, a relative high sensibility to different CI is present and this percentage on speed reduction can go up to 15% when high values of CI are used. On the other hand, for low values of CI the margin is reduced but the negative impact of increasing the cruise speed is also reduced. Nowadays alternatives to future speed reduction techniques involve on-ground delays, holdings or re-routings which lead also to an extra cost per flight for the airliners. Therefore, speed variation solutions may be also competitive, from an economical point of view and the presented results open the door to this kind of techniques in the future ATM system. However, fuel consumption should always be present when dealing with these new concepts. The authors envisage a further coparison study between ATM solutions. In addition it is planned to include the analysis of more flights and different aircraft.

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