Climb, Cruise and Descent Speed Reduction for Airborne Delay without Extra Fuel

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I. Introduction

In the majority of the situations, Air Traffic Flow Management (ATFM) regulations are issued due to weather related capacity reductions. Considering the uncertainties in weather prediction and other unforeseen factors, ATFM decisions are typically conservative and the planned regulations may last longer than actually needed [1, 2]. At present, ground delay is more preferable than airborne delay (holding) from a safety, environmental and operating cost points of view. However, when regulations are canceled before their initial planned ending time, as occur often [3, 4], the already accomplished delay on ground cannot be recovered, or can be partially recovered by increasing speed, leading to extra fuel consumption.

In order to overcome this issue, a speed reduction (SR) strategy was proposed in [5], which aimed at partially absorbing ATFM delays airborne. Ground delayed aircraft were enabled to fly at the minimum fuel consumption speed (typically slower than nominal cruise speed initially chosen by the airline) performing in this way some airborne delay. At the same time, part of the fuel was saved with respect to the nominal flight. This strategy was further explored in [6], where aircraft were allowed to cruise at the lowest possible speed in such a way the specific range (i.e., the distance flown per unit of fuel consumption) remained the same as initially planned. In this situation, if regulations were canceled, aircraft already airborne and flying slower, could increase their cruise

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speed to the initially planned speed and recover part of the delay without extra fuel consumption [2, 6–8].

In this paper, the SR strategy presented in [6] is extended in such a way that not only the cruise phase is used to perform linear holding, but also the climb and descent phases are subject of optimization to maximize the total amount of airborne delay that can be achieved without incurring extra fuel cost. Three cases are studied: SR only in cruise; SR in the whole flight, but keeping the nominal cruise altitude; and SR for the whole flight while also optimizing the cruise altitude to maximize delay.

II. Methodology
A. Equivalent speeds in climb, cruise and descent

Current on-board flight management systems enable airlines to optimize the aircraft trajectory in terms of direct operating costs by means of the cost index (CI), which represents the ratio between time-based cost and the cost of fuel [9]. The higher CI is, the more importance will be given to the trip time and the faster the optimal aircraft speed will be.

![Graph of specific range as a function of cruise speed](image)

**Fig. 1** Specific range as a function of cruise speed [6].

Typical operating cruise speeds are higher than the MRC (maximum range cruise) speed (i.e. the speed corresponding to CI=0), since aircraft operators also consider time-related costs when planning their flights. Accordingly, the specific range for cruise is lower than the maximum specific range for that altitude. In [6] the authors defined the equivalent speed $V_{crz eq}$ for cruising as the minimum speed that produces the same specific range as flying at the nominal speed $V_{crz nom} = V_{crz ECON}$. 


Therefore, for all speeds between $V_{crz}^{eq}$ and $V_{crz}^{nom}$, as shown in Fig. 1, the fuel consumption will be the same or lower than initially planned while the flight time in cruise will be higher.

Not only is the cruise phase affected by CI, but also climb and descent phases. With CI increasing, the speed of both climb and descent increases, as well as fuel consumption, and the climb profile becomes shallower, while conversely the descent profile turns steeper (see Fig. 2) [10].

![Fig. 2 Climb and descent profiles versus cost index.](image)

Thus, the SR strategy could be extended to the whole flight and not just the cruise phase, in order to increase the amount of airborne delay and even make it appealing for short-haul flights, as climb and descent often represent a considerable percentage of the total trip distance. A similar behavior than in cruise occurs for climb and descent phases when a CI higher than 0 is selected by the operator. In such case, the climb and descent speeds are faster than those of minimum fuel for each phase as a whole, and there exists an equivalent speed $V_{clb/dst}^{eq}$ yielding the same fuel consumption as $V_{clb/dst}^{nom}$.

![Fig. 3 Speed profiles under conventional operation constraints.](image)
For a given aircraft, the theoretical minimal fuel speed $V_{clb\min fuelT}$ is not constant and changes with altitude (and with aircraft mass as long as fuel is burned). This speed is denoted with a green dashed line in Fig. 3, for a hypothetical climb.

In real operations this speed is not followed, due to operational or ATM constraints. Unlike in cruise where flight is performed at a constant Mach number, the climb is divided into several speed segments. These typically include a speed limitation at low altitudes, typically 250kt IAS (indicated airspeed) below FL100, followed by an acceleration to a constant IAS climb, followed by a constant Mach climb above the crossover altitude. Fig. 3 shows an example for such a climb speed profile (250kt/300kt/M0.78 for this example) with a solid black line and denoted in this paper as $V_{clb\min fuel}$.

Nominal climb speeds for CI greater than zero will lead to climb speed profiles as shown by the red line in Fig. 3 ($V_{clb\nom}$), while $V_{clb\eq}$ denotes the equivalent climb speed profile leading to the same fuel consumption. As for descent, the realistic speed profile is just like the one of climb, but in opposite order that is from constant Mach descent above crossover altitude to the deceleration process at low altitudes.

As the cruise speed reduces, in general, the optimal flight level decreases. Since the equivalent cruise speed $V_{crz\eq}$ is lower than the nominal cruise speed $V_{crz\nom}$, it is possible that the initial planned flight level is no longer the optimal in SR cases. When a new flight level exists, by which the specific range keeps the same or higher while speed reduces more, then it could replace the nominal one. Furthermore, if the new flight level decreases, more fuel can be saved for climb and descent due to the altitude reduction of the TOC and TOD. Thus, the objective of allowing altitude changes is to achieve more airborne delay by the same amount of fuel consumption, namely finding the altitude and speed combination (through trajectory optimization as presented in Sec. II B) that results in that same specific range with the lowest possible speed.

Moreover, worth noting that the equivalent speeds in climb, cruise and descent might be limited by the minimum operational speed (including possible safety margins). In this paper, the Green Dot (GD) speed is adopted as the minimum bound, which depicts the best lift to drag ratio speed in clean configuration. In manual flight, the selected speed/Mach could be set to VLS (lowest selectable speed, the stalling speed at 1.3g) that is lower than the GD speed. Yet, considering the operation
of the SR strategy and aiming at automatic flight, it is more realistic to choose the managed mode
and therefore GD as the lower bound for speed. According to [11] GD speed, below FL200 equals
to \(2 \times \text{weight (tons)} + 85 \text{ (kt)}\), and above FL200, adds 1 \text{kt per 1000ft}.

B. Trajectory optimization of the four cases of study

As discussed above, the equivalent speeds depend not only on nominal speeds, but also the
functions of fuel consumption, which in turn are aircraft performance (such as different types of air-
craft models), atmospheric magnitudes (i.e., temperature, pressure and wind parameters) and flight
status (e.g., aircraft mass which reduces progressively) dependent, and should change continuously
along the execution of a particular flight.

In [6], an approximation was made with regards to these changes by using average values
from the initial and final flight status, such as the mass of aircraft. This could apply for normal
cruise phase which maintains relatively constant changes, but when taking climb and descent phases
involved, it is more accurate to implement the continuous optimization to formulate this optimal
control problem of performing SR within the whole flight phases, as has been studied in [12].

In this paper, optimal trajectories computed with a given CI would be regarded as the *nominal
flights*, and labeled as Case-0. Based on Case-0, different SR strategies will be analyzed, denoted
by Case-1, Case-2 and Case-3:

- **Case-1**: SR in cruise maintaining the nominal flight level;
- **Case-2**: SR in climb, cruise and descent maintaining the nominal flight level; and
- **Case-3**: SR in climb, cruise and descent and optimizing for cruise flight level.

The optimization of aircraft trajectory requires the definition of a model capturing aircraft
dynamics and performances, along with a model for certain atmospheric criteria. In this paper,
a point-mass dynamics model, an enhanced performance model using manufacturer performance
data and the International Standard Atmosphere (ISA) have been considered. For more details, the
readers may refer to [13].

The objective of the optimization for Case-0 is to minimize the cost function consisting of fuel
\(F\) and time \(T\), with different CI values, as Eq. 1, while satisfying the optimization constraints that
model current operational procedures.

$$\min(\sum F + CI \cdot T) \quad (1)$$

The conventional flight profile is divided into several segments where different models and standard operational procedures apply. Fig. 4 summarizes the segments and the corresponding path and event constraints.

Fig. 4 Operational flight profiles divided into specific segments.

For the SR Cases, consider that the basic optimization objective and constraint are as follows:

$$\max(\sum T_{clb}^i + \sum T_{crz}^j + \sum T_{dst}^k) \quad (2)$$

$$\sum F_{clb}^i + \sum F_{crz}^j + \sum F_{dst}^k \leq F_{nom} \quad (3)$$

where $i, j, k$ represent the segments that each phase is divided, as denoted in Fig. 4. $T_{clb}, T_{crz}, T_{dst}$ are the time needed for climb, cruise and descent respectively, and $F_{clb}, F_{crz}, F_{dst}$ denote the fuel consumed for each phase while $F_{nom}$ is the fuel as initial planned in the nominal flight. Note that for Case-1 $T_{clb}$ and $T_{dst}$ are not subject to optimization and are fixed to the nominal climb and descent times, respectively.

Since typically the cruise speed is constant Mach, in order to realize the SR in practice, an extra segment is added in front of each cruise phase allowing speed changes (see $SC_1, SC_{m+1}$ in Fig. 4),
as well as a similar segment \((SC_{m+2})\) at the end of the last cruise phase.

In addition to the flight profile, a flight route must be defined either in Great Circle Distance (GCD) between city-pair airports, or by using ATM service route and published procedures.

To find the optimal solution of the formulated optimal control problem, direct collocation methods \([14]\) are used in this paper, which discretize the time histories of control and state variable at a set of nodal or collocation points, transforming the original continuous (infinite) optimal control problem into a (discrete and finite) nonlinear programming (NLP) optimization problem. The new finite variable NLP problem is solved by using solvers CONOPT (as NLP) and SBB as MINLP (mixed integer nonlinear programming), both bundled into the GAMS software suite. The whole process is briefly presented in Fig. 5.

![Fig. 5 Main process in generating the optimal aircraft trajectory.](image)

III. Illustrative Examples

Results have been obtained from an in-house trajectory optimization tool, firstly with a particular flight AMS-SVQ with CI=150 analyzed in detail, along with its vertical trajectories and speed profiles illustrated specifically. Then, more representative routes are included into comparison and each is further studied with different CI values. Airbus A320, a common two-engine narrow-body transport aircraft is the aircraft type for this simulation. Airbus A320, a common two-engine narrow-body transport aircraft, has been used for this computational experiment.

Some assumptions have been taken: 1) GCD is considered; 2) a passenger occupation (payload factor) of 81% is considered for all flights \([6]\); 3) no wind conditions are considered; 4) alternate and reserve fuel are not included; 5) even flight levels are used (FL260 as the lowest altitude); and 6) cruise step climbs are allowed with 2000ft steps for each flight level.
A. Trajectories of a specific flight: AMS-SVQ with CI=150

The vertical trajectories corresponding to the four Cases of the AMS-SVQ; CI=150 flight are as shown in Fig. 6. The changes when SR is implemented in climb and descent phases can be appreciated in the profile, while the optimal flight level for Case-3 decreases from FL340 to FL320. Comparing the blue dots (Case-2) with the red ones (Case-0), we find the aircraft is climbing steeper (recall that the cruise flight level keeps unchanged for this Case), saving some fuel in the climb phase while also delaying the flight. Conversely, the descent is performed more gradually and flying slower, but burning some extra fuel if compared with Case-0. As for the green squares (Case-3), a decrease in cruise flight level generates even steeper climb and shallower descent trajectories. Table 1 illustrates clearly these changes for all Cases of study.

Fig. 6 Optimal trajectories generated for each Case.

<table>
<thead>
<tr>
<th>Cases</th>
<th>Climb phase</th>
<th>Descent phase</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fuel (kg)</td>
<td>Time (min)</td>
</tr>
<tr>
<td>Case 0</td>
<td>1685.4</td>
<td>21.5</td>
</tr>
<tr>
<td>Case 1</td>
<td>1685.4</td>
<td>21.5</td>
</tr>
<tr>
<td>Case 2</td>
<td>1415.6</td>
<td>23.3</td>
</tr>
<tr>
<td>Case 3</td>
<td>1064.4</td>
<td>13.7</td>
</tr>
</tbody>
</table>

Table 1 Details of a specific flight for climb, cruise and descent.

<table>
<thead>
<tr>
<th>Cases</th>
<th>Cruise phase</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FL (100ft)</td>
<td>Fuel (kg)</td>
</tr>
<tr>
<td>Case 0</td>
<td>340</td>
<td>4096.5</td>
</tr>
<tr>
<td>Case 1</td>
<td>340</td>
<td>4096.5</td>
</tr>
<tr>
<td>Case 2</td>
<td>340</td>
<td>4196.9</td>
</tr>
<tr>
<td>Case 3</td>
<td>320</td>
<td>4558.8</td>
</tr>
</tbody>
</table>

Compared with the nominal flight (Case-0), Case-1 consumes the same amount of fuel in each phase and achieves 22 minutes of airborne delay when cruising, which accounts for the 22% of the
cruise time and the 17% of the total time.

In Case-2, the fuel consumption reduces 270kg (16%) in climb and the airborne delay is almost 2 minutes in this phase. Since the total fuel consumption is the same for the flight, the 270kg of fuel saved in climb can actually be allocated in cruise (193kg, 5% of cruise) and descent (77kg, 71% of descent), which, in fact, allows to largely increase the time delayed in both phases: 59 minutes (60% of cruise) and 10 minutes (77% of descent), respectively. As a result, if we compare Case-2 with Case-1, it seems that a 193kg (5%) increase of fuel consumption in cruise could exchange for 37 minutes (31%) more time delayed.

Regarding Case-3, when cruise flight level is allowed to change, the new optimal altitude (FL320) allows the aircraft to perform more airborne delay with the same fuel consumption than in Case-0 (nominal Case). Compared to Case-2, 351kg (25%) of fuel are saved during the climb phase, 8kg (4%) of fuel during the descent phase, and 359kg (9%) of fuel are added to the cruise phase, lowering the specific range by 0.006 nm/kg, and further reducing the equivalent cruise speed to produce an even longer (12 minutes) air delay in cruise. Although the flight time in both climb and descent are shorter, the total flight time increases (by 1 minute) due to this extended cruise flight time.

B. Climb, cruise and descent speed profiles

As we can tell from Fig. 7(a), the climb speed profiles of all the Cases have quite similar structures, which mainly include a continuous acceleration process at low altitude, a constant IAS climb, followed by constant Mach climb at higher altitudes. At the end of the climb a small deceleration is observed in order to reach the (reduced) optimal cruise speed. Making Case-0 as the baseline, the difference with Case-1 only lies on the deceleration process at cruise flight level, so they share exactly the same climb speed (see Table 1).

In Case-2 when SR is allowed in climb (and descent), the optimizer chooses a climb speed around 210kt (instead of the 330kt observed in Case-0), as is the minimum speed allowed (GD speed). Due to this lower IAS climb, a higher crossover altitude (around FL320) is obtained to switch to the climb Mach number, which is also lower than the nominal one.

Results show that the climb speed in Case-3 is higher than the GD speed used in Case-2 (see
Fig. 7(a)), but the gained fuel (saved from climb) makes a longer delay time in cruise and descent phases since the total flight time is longer than Case-2 (see Table 1). That means, in this case, part of the delay time of climb is trade in exchange for saving more fuel.

When it comes to the cruise phase, if the fuel consumption is fixed in this phase in Case-1, then the cruise Mach decreases from M0.80 to M0.74, while the specific range keeps the same (both 0.188 nm/kg). Unlike, in Case-2 and Case-3, the cruise Mach both reduce directly to the GD speed for each flight level, M0.60 and M0.58 respectively (see Fig. 7(c)).

As for the descent phase, we can see from Fig. 7(b) that Case-2 and Case-3 have no deceleration below FL100 (like in Case-0 and Case-1) simply because the descent speed (around 200kt) is already below the ATC constraint of IAS lower than 250kt below FL100. Meantime, the segments of constant Mach descent are both missing too, since the crossover altitudes lie higher above the cruise flight level due to the lower speed in the constant IAS descent in Case-2 and Case-3.
Normally, the fuel consumed in descent phase accounts for the lowest of the three phases, but the trade-off still generates almost double the descent time in our example (see Table 1). In Case-2, the fuel consumption grows from 107kg to 184kg, reducing the descent speed to the GD speed in descent. Remember that the GD speed is not the same in climb that in descent, since the weight of the aircraft is different (fuel has been burned in cruise).

C. Airborne delay comparison

More specific routes are further included to have a comparison on the amount of maximum airborne delay generated from different SR Cases, including FCO-CDG: 595nm, FRA-MAD: 769nm, AMS-SVQ: 1000nm and STO-ATH: 1305nm, all of which are representative of short and mid haul flights in Europe, and each is further analyzed with CI ranging from 25 to 500 kg/min. Results are summarized in Table 2.

<table>
<thead>
<tr>
<th>Flight Routes (Comp. time)</th>
<th>Case-0</th>
<th>Case-1</th>
<th>Case-2</th>
<th>Case-3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CI (kg/min)</td>
<td>FL (100 ft)</td>
<td>Time (min)</td>
<td>Fuel (kg)</td>
</tr>
<tr>
<td>FCO-CDG 595 Nm (10-15 Sec)</td>
<td>25</td>
<td>380</td>
<td>89</td>
<td>3464</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>380</td>
<td>86</td>
<td>3575</td>
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<td></td>
<td>100</td>
<td>380</td>
<td>85</td>
<td>3641</td>
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<td>150</td>
<td>380</td>
<td>85</td>
<td>3654</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>380</td>
<td>83</td>
<td>3991</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>260</td>
<td>83</td>
<td>4302</td>
</tr>
<tr>
<td>FRA-MAD 769 Nm (10-15 Sec)</td>
<td>25</td>
<td>380</td>
<td>113</td>
<td>4334</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>380</td>
<td>110</td>
<td>4440</td>
</tr>
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<td>100</td>
<td>380</td>
<td>110</td>
<td>4464</td>
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<td></td>
<td>150</td>
<td>340</td>
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<td>4731</td>
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<td>300</td>
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<td>106</td>
<td>5030</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>260</td>
<td>104</td>
<td>5470</td>
</tr>
<tr>
<td>AMS-SVQ 1000 Nm (15-20 Sec)</td>
<td>25</td>
<td>380</td>
<td>144</td>
<td>5482</td>
</tr>
<tr>
<td></td>
<td>60</td>
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<td>6389</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>260</td>
<td>133</td>
<td>6998</td>
</tr>
<tr>
<td>STO-ATH 1305 Nm (20-30 Sec)</td>
<td>25</td>
<td>360</td>
<td>185</td>
<td>7054</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>360</td>
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<tr>
<td></td>
<td>500</td>
<td>260</td>
<td>172</td>
<td>9159</td>
</tr>
</tbody>
</table>

Seeing from the results of Case-0 in Table 2, with the growth of CI, the climb distance increases from CI of 25 to 100 kg/min, and then decreases gradually after greater than 150 kg/min. However,
remember in Fig. 2 that the higher the CI is, the longer the climb distance it should be. This is due to the fact the cases here in the table are resulted from a global optimization for the trajectory as a whole, while the situation in the previous figure is based on a single climb phase. The trade-off of fuel and time among different flight phases (as illustrated by the specific flight in Sec. III A) accounts for the partial inconsistent of these results.

In Case-1, it is obvious that the achievable airborne delay increases with the growth of flight route distance (i.e., the cruise distance in this case, as climb and descent phases are fixed in Case-1 in line with the nominal flight). Specifically, for each flight route, the higher CI the nominal flight chooses, the more airborne delay the flight will achieve (through the SR strategy) in general. However, we may also notice a reduction trend within the CI scope of 100 and 150 kg/min. It is because for those CIs, extra fuel is consumed in climb and descent to obtain higher speeds during the two phases, such that less fuel is left (given the total fuel kept constant) for the cruise phase, and thus a reduced amount of delay is generated.

As for Case-2, the airborne delay increases significantly only after climb and descent phases are included. If we compare the percentage that climb and descent normally account for in a flight, with the percentage that cruise has, we may find that for those short-haul flights, the distances of climb and descent may account for up to 50% while time nearly 50% too, but for the mid/long-haul flights, both distance and time percentages could reduce to about 20%. Nevertheless, most of the airborne delay in Case-2 increase to almost 3-fold of the ones in Case-1, which, as discussed in Sec. III A, is due to the fact that adding climb and descent makes it possible to re-allocate the fuel consumption in each phase, as long as the total fuel consumption remains unchanged.

When the cruise flight level is allowed to change, as Case-3, the airborne delay further increase but not so remarkable as from Case-1 to Case-2 (see Table 2). The main reason is that the specific range curves for different cruise flight levels are quite close within the low cruise speeds. As a result, the speed reduction from altitude changes, i.e., Case-2 to Case-3, will not be as large as the reduction from nominal speed to equivalent speed, i.e., Case-1 to Case-2. Typically, the new flight level would be lower than the original, but since the step interval is 2000ft, which is a discrete change due to operation constraints, some flights just keep unchanged as Case-2.
Fig. 8 Airborne delay achieved in climb, cruise and descent phases.

Fig. 8 illustrates the amount of airborne delay each phase contributes to, where in some cases negative values are observed. Worth noting these negative values are all in the climb phase of Case-3, in which the optimal cruise flight levels are lower than the nominal ones. Therefore, the altitude reduction of TOC shortens climb time, leading to a negative airborne delay.

However, this does not apply to the descent phase, given that an altitude reduction on TOD occurs as well. Since the fuel consumption in climb is typically much higher than that in descent (maximum climb thrust versus idle thrust), while the ranges of speed remains almost the same, the trade-off of fuel and time differs notably, and thus the descent phase should have a higher effect in generating airborne delay by SR with the same amount of fuel.

Finally, if the cruise flight level is not allowed to change from the nominal (Case-2), the airborne delay realized in climb can be as much as that in descent phase which keeps almost stable with regards to different CI, as shown in Fig. 8, and thus less airborne delay are generated from the cruise phase if compared with Case-3, so as to keep the total fuel consumption unchanged.
IV. Conclusions and Further Work

This paper extends previous research on linear holding strategies in cruise phases to absorb part of the ATFM delays by allowing SR on climb and descent phases too. Three different variants are analyzed, and the maximum airborne delay trajectories are computed by means of numerical optimization using an in-house trajectory generation tool, which relies on accurate performance models derived from manufacturer data.

Compared with previous works, a remarkable increase of the maximum airborne delay that can be realized without extra fuel consumption is observed. Results suggest that there exist differences on the trade-off between fuel and time in various flight phases (even in flight segments within a particular phase), and therefore including climb and descent into the SR strategy would enable the optimizer to utilize these differences to maximize the achievable time increase. Besides, the characteristics of trajectory variance resulted from performing the SR strategy has not been analyzed in this paper, and deserves a further work by including more simulation experiments.

Further work will also focus on exploring the effects of this SR strategy for the whole flight in realistic operations, as done for instance in [2]. Considering that the ATFM regulations (and the associated delays) are typically issued in response to adverse weather conditions, the wind and non-standard atmospheres, which always have great impacts on real flights, should be further taken account in regard of the application of the proposed SR strategy.

References


