Analysis of Continuous Descent Benefits and Impacts During Daytime Operations

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Abstract—This paper presents a case study of modeled arrival operations which utilize descent trajectories optimized for reduced fuel burn and pollutant emissions. Arrival flights descending along optimized vertical profiles are modeled by transforming the descent trajectories of a set of baseline arrival flights, taken from observed radar track data, into descent trajectories at idle throttle. The trajectories of the baseline and modeled arrival flights are described in depth, along with the transformation that connects them. Two implementation scenarios (unconstrained and constrained) of optimized descent procedures during daytime operations are analyzed. In the case of unconstrained optimized descent both the potential benefits and conflicts that result from such operations are quantified. In the case of constrained optimized descent, mitigation strategies are applied which remove the potential conflicts, but also reduce the level of potential benefit. The constrained optimized descent scenario demonstrates that by carefully choosing which level-offs are removed, both benefits can be obtained and conflicts avoided simultaneously. The major conclusion that may be drawn from this study is that procedures for optimized descent arrival operations can be implemented with fuel and emissions savings benefits while avoiding conflicts with other traffic.

Keywords—continuous descent arrival, optimized descent profile, green arrivals, fuel savings, emissions reduction

I. INTRODUCTION

Recent volatility in jet fuel prices and growing environmental sensitivity have stimulated investigation into methods for reducing air transportation fuel consumption, pollutant emissions and noise in the next generation of air traffic management (ATM). Within the descent phase of flight, a concept of operations for reducing these aspects is to redesign flight arrival routes and procedures such that jet aircraft can reduce the application of throttle, and its associated high revolution rate of the jet turbines. By allowing their engines to remain at idle during descent, descending aircraft can minimize the fuel burned, the exhaust gases vented, and the noise generated by the engines. A general term for the broad class of descent routes and procedures which are designed to reduce the application of throttle during descent is Optimized Profile Descent (OPD). The MITRE Corporation’s Center for Advanced Aviation System Development (CAASD) has been tasked by the United States of America Federal Aviation Administration (FAA) to study the feasibility and potential benefit of implementing OPD procedures. The analysis of this study derives from the on-going investigations on OPD procedures at CAASD.

In the most ideal form of OPD, a descending aircraft will not apply any throttle during descent. Instead, the potential and kinetic energy of the descending and decelerating aircraft will be managed optimally. The arriving aircraft will be able to glide down from cruise with its engines set to idle while transferring its kinetic and potential energy into the drag on the airframe. In that case, the fuel burned and pollutants emitted during arrival will be minimized. This is what is generally known as a continuous descent arrival (CDA). However, in actual operations, arriving aircraft are not always able to descend along their aircraft specific optimally efficient trajectory. In the presence of normal traffic levels, such as during daytime operations, constraints stemming from safety and efficiency often require aircraft to use thrust while executing level-offs. These level-off segments, known as arrival shelves, cause the aircraft to burn more fuel than in idle descent.

This study quantifies the benefits attainable from allowing descending aircraft to fly closer to their optimal descent trajectory while avoiding conflicts with non-arrival traffic. This is accomplished by modeling current arrivals as they would be if they had been flown as OPD operations. Briefly, the vertical profiles of baseline arrival flights, taken from radar track data, are transformed into new vertical profiles assuming idle throttle descent segments. The ground tracks and speeds of the arriving flights are left unchanged so that the lateral and longitudinal separations between aircraft are unchanged. This transformation allows focused evaluation of the potential benefits from improved vertical profiles, separated from the potential benefits of shortened ground track. On the interactions between traffic, it allows identification of the potential conflicts between OPD arrivals and non-arrival traffic, but does not address how longitudinal separations between arrivals would change if arrivals were implemented along OPD procedures.
Three main questions are investigated: first, how the proximity of arrival traffic to non-arrival traffic would change if current arrivals were implemented as OPDs; second, what types of compromises in the descent trajectory of the OPD would be required to avoid potential conflicts; and third, what net benefit in fuel savings and emission reductions could be expected assuming those compromises.

Three major insights have followed from this study. First, that approximately 85% of the potential fuel burn and emissions reduction benefit comes from optimizing descent trajectories at altitudes below 20,000 ft above mean sea level (MSL). Second, that arrival shelves in which descending aircraft are passed underneath departure traffic are likely to experience conflicts if the descending traffic is allowed to fly unrestricted continuous descent. Third, that removing a single level-off at the hand-off from en-route to terminal airspace can realize 15% of the full potential fuel and emissions reduction benefit, while avoiding many of the potential conflicts between OPD arrivals and non-arrival traffic.

II. BACKGROUND

Two major international partnerships and many independent research programs are currently underway to investigate methods for reducing fuel burn, emissions, and noise in air transportation. These efforts span two oceans and include collaboration between industry, government, and academia. Spanning the Atlantic Ocean, the Atlantic Interoperability Initiative to Reduce Emissions (AIRE) was formed with the goal to hasten development of environmental improvements for all phases of flight [1,2]. In the Pacific Ocean region, the Asia and South Pacific Initiative to Reduce Emissions (ASPIRE) was formed to extend that goal to flights in Asia and the South Pacific [3].

As part of the initial milestones of the AIRE and ASPIRE programs, field trials of arrival flights utilizing optimized profile descents have been completed, including trans-oceanic flights from Paris to Miami and from Auckland to San Francisco. These trials have demonstrated interoperability and validated the environmental benefits of optimized descents. In addition to the trial flights of the AIRE and ASPIRE partnerships, several trial implementations of regularly scheduled flights have clarified the benefits and operational challenges of implementing optimized profile descents. Three such trial implementations, which are notable for their scale, are a CDA implementation below 6000 ft MSL at London Heathrow Airport [4], an area navigation (RNAV) implementation at Los Angeles International Airport and the United Parcel Service (UPS) implementation at Louisville International Airport [5].

Complimentary to trial flights, investigations of issues related to reducing the fuel burn, emissions, and noise in the descent phase are also conducted through modeling approaches. Some of the issues being studied are: capacity impacts [6]; separation between aircraft [7]; 4-dimensional trajectory management [8-10]; controller workload and acceptability [11,12]; modeling of fuel and emissions [13,14]; modeling of noise [15,16]; traffic flow management [17,18]. The analysis of this study adds to the above cited works by modeling OPD operations in heavy traffic situations. The result gives a direct answer as to how OPD operations would behave if they were done as a part of normal daytime operations.

In addition to the descent phase of flight, research is also on-going into reducing emissions and fuel burned in departure [19], cruise [20], and in surface operations [21]. In these phases of flight the benefit mechanisms are different, but the potential for fuel and emissions reductions can be as great as during descent.

III. METHODOLOGY

The benefits and impacts of OPD implementation during daytime operations are evaluated in this study by modeling current arrivals as they would be if they had been flown as OPD operations. The following section describes in detail how the transformation from baseline to modeled OPD flights is achieved.

A. Description of a Baseline Arrival Trajectory

The ground track of a de-identified arrival flight into Denver International Airport (DEN) in October 2007 is illustrated in Figure 1. This particular arrival entered the terminal airspace from the south east, flew a downwind portion, and landed on runway 16 left (L). The top of descent point along the arrival track is indicated by a red dot near the beginning of the shown segment of track. The runways are visible at the center of the 30 nautical mile (NM) range ring.

![Figure 1: The ground track of a flight arrival into Denver International Airport.](image)

The ground speed, altitude, fuel burn rate and speed brake usage of the flight are plotted in Figure 2. The ground speed and altitude were extracted from the recorded radar track of the flight. The fuel burn rate and speed brake usage were calculated from the flight trajectory information using the total energy model within Eurocontrol’s Base of Aircraft Data (BADA) aircraft performance database [22]. Along the
horizontal axis is the ground track distance prior to the runway threshold in nautical miles (NM). All the quantities are shown on a single graph to illustrate the connection between them. Each quantity is plotted in the following colors and units:

- ground speed is plotted in blue in units of nautical miles per hour (knots);
- altitude is plotted in red in units of hundreds of feet (flight level);
- fuel burn rate is plotted in green in units of pounds weight (lbs) per minute (min);
- and speed brake usage is plotted in orange in units of lbs/min.

The speed and altitude can be read along the left hand scale, while the fuel burn rate and speed brake usage can be read along the right hand scale.

![Graph showing speed, altitude, fuel burn rate, and speed brake usage](image)

**Figure 2: The vertical profile and trajectory of the baseline arrival flight.**

The trajectory of the arriving aircraft in Figure 2 follows from left to right, with a segment of cruise visible to the left (at -150NM) and the runway threshold visible to the right (at 0NM). As in the ground track figure, the location of the top of descent point is indicated by a red dot on the altitude line. Inspection of this particular arrival reveals that it began its descent 135NM prior to landing. Before beginning its descent, the aircraft cruised at flight level (FL) 320 and was burning approximately 75 lbs/min of fuel. After the top of descent point the aircraft began a shallow descent of 1.8 degrees at a half throttle setting which burned between 30-50 lbs/min of fuel. At approximately 70NM from touchdown the aircraft began a steeper descent of 3.9 degrees at idle thrust and utilized a small amount of speed brake to avoid accelerating while descending. At 50NM from touchdown the arriving aircraft leveled-off at 13,000 ft MSL. In order to execute the level-off, the aircraft powered back up to approximately 75lbs/min of fuel burn. For the rest of the arrival the aircraft continued to execute a series of powered level-offs and idle descents.

The trajectory of the described flight arrival contains many level-offs and segments of descent at greater than idle thrust. These level-offs may have been executed due to separation considerations from crossing traffic or airspace constraints. Each non-idle segment during the descent phase is an instance of a potential area for fuel savings and emissions reduction. If those shallow descents and level-offs could be replaced with descent at idle throttle, the potential exists for reducing the overall fuel usage and emissions output during the aircraft’s flight.

**B. Description of a Modeled OPD Arrival Trajectory**

The trajectory of the baseline arrival described in the previous section can be modeled as if it had been flown as an OPD by making two changes. First the cruise segment is extended such that the top of descent point is closer to the runway threshold. Second, the entire descent is executed at idle throttle, with the ground track and speed profile unchanged. The same fuel burn model that was used to compute the fuel burn and speed brake usage in the previous section can be applied in reverse to compute the modeled trajectory of a flight given its fuel burn and speed brake settings. The modeled track that results from that process will be called a modeled OPD arrival trajectory.

The ground track of the modeled OPD track is illustrated in Figure 3. The new top of descent point along the modeled OPD arrival track is indicated by a red dot near the beginning of the shown segment of track. Comparison with Figure 1 reveals that the new top of descent point is approximately 40NM closer to the runway threshold along the flight’s ground track than for the baseline arrival.

![Diagram of modeled OPD arrival trajectory](image)

**Figure 3: The ground track of the modeled OPD trajectory is the same as for the actual track. The new top of descent point is indicated by a red dot.**

In parallel with Figure 2, the ground speed, altitude, fuel burn rate and speed brake usage of the modeled OPD arrival are plotted in Figure 4. As before, the horizontal axis is ground track distance in nautical miles prior to the runway threshold, and all the quantities are shown on a single graph to illustrate the connection between them. Each quantity is plotted in the same colors and units as described in the previous section.

As for the baseline trajectory, the location of the top of descent point is indicated on the altitude line by a red dot, and the trajectory of the modeled flight follows from left to right. Inspection of the modeled OPD arrival reveals a few
Figure 4: The vertical profile and trajectory of the modeled OPD arrival transformed from the arrival flight of the previous section.

differences from the baseline trajectory. First, the cruise segment at FL320 is extended by approximately 40NM, so that the new top of descent point occurs at 90NM from touchdown. During the extended cruise, the aircraft continues to burn approximately 75 lbs/min of fuel. After the top of descent point the aircraft begins a descent of 2.8 degrees at idle throttle setting. As the aircraft descends the rate of fuel burned at idle throttle increases due to the increasing density of air at lower altitudes. At approximately 40NM from touchdown the aircraft executes a short level-off at 16,000 ft, while remaining at idle throttle. This level-off occurs in order to slow the speed of the aircraft. In a real flight, the pilot would at this point pull back on the stick to tilt the nose up slightly and cause the aircraft to slow down. For the rest of the arrival the aircraft continues its continuous idle descent between 2.5–3.0 degrees down to landing.

C. Comparison of the Baseline and Modeled OPD Flight Trajectories

The trajectories of the baseline flight and the modeled OPD flight are shown together in Figure 5. The baseline flight trajectory is drawn as a set of thin lines, and the modeled OPD trajectory is drawn as a set of bold lines. Note that since the ground speeds are the same in the baseline and modeled trajectories, there is only a single line for ground speed. Comparison of the two reveals how the fuel burn rates of the two compare at the same locations along the ground track.

In the extended cruise portion of the modeled OPD arrival, the modeled OPD burns fuel at a higher rate than the baseline arrival. The extra fuel is burned to maintain the cruise altitude longer. After the top of descent point of the modeled OPD arrival, the modeled trajectory burns less fuel than the baseline arrival. This is because the modeled OPD descends (by design) with the throttle set to idle. The modeled OPD trajectory does not have any of the level-offs at high throttle that are seen in the baseline arrival. However, there remains a short level-off for deceleration. Overall, the conclusion is that if the considered baseline arrival had been flown as an OPD, it would have burned more fuel in extending its cruise, but would have burned less fuel during its descent. The net fuel burn difference of these two effects is a savings of 220 lbs less fuel burn in the OPD arrival.

D. Discussion of the Transformation

Through the transformation to OPD trajectory, the vertical profile of the descending flight was changed from one with multiple powered level-offs, to one with a single level-off for deceleration. If this transformation is applied to all arrivals into a given airport, it will give a picture of how operations would look if all arrivals were OPD arrivals. Both the potential benefits and conflicts of OPD implementation could be predicted from the method of transforming flights from the baseline to modeled OPD arrivals.

A sample of the baseline to OPD transformation, applied to a set of arrivals from the southeast into Denver International Airport on a particular operational day in October 2007 is shown in Figure 6 and Figure 7, respectively. In each figure, the ground tracks of the flights are shown in the left frame; the

Figure 5: Comparison of the trajectories of the baseline and modeled OPD flights.

Figure 6: The baseline tracks of an operational day of arrivals to DEN from the southeast landing on runways 16L.
altitude profile is shown in the upper right frame; and the speed profile is shown in the lower right frame. Comparison of the two shows that the ground track and speed profiles are unchanged between the baseline and modeled OPD flights, whereas the vertical profiles are different. The modeled OPD flights have extended cruise phases and steeper descents with fewer level-offs.

The fact that the ground tracks and speeds of the arrival tracks are not changed has an implication on the interpretation of the transformation. Specifically, the lateral and longitudinal separations between all aircraft are unchanged. However, since the vertical profiles of all the arrival trajectories are altered, any instances of vertical separation are lost. Given these facts, implementing the transformation described here to all arrival flights into an airport will give a picture of how operations would look if the arrival descents were OPD, with no other changes. An important caveat to the interpretation of this transformation is that this analysis does not tell us how the implementation of OPD vertical profiles could be done. In particular implementing OPD operations may require significant airspace changes, automation changes, and increased collaboration between enroute, terminal and system operations personnel. In that sense this transformation gives us a look at the other end of the OPD implementation process, but does not tell us how we could get there.

IV. CASE STUDY: DENVER INTERNATIONAL AIRPORT

The example flights of the previous sections were actual flight arrivals into Denver International Airport (DEN) in October 2007. The remainder of this study will continue to focus on operations at DEN as a concrete case study. The choice of DEN was not made for any reasons relating to its suitability for OPD operations. Rather, DEN was chosen at random as a typical example of an airport with high volume operations.

The case study of hypothetical OPD arrival operations at DEN will focus on operations in south flow runway configuration. The field elevation at DEN is 5431 ft MSL. As illustrated in Figure 8, these include arrivals on runways 16R, 16L, 17R, and 17L; and departures from runways 08, 25, 17R, and 17L. These runways constitute the majority of arrival and departure operations in south flow runway configuration.

Arrivals into DEN enter the terminal airspace over eight arrival fixes. Each diagonal direction has two fixes. As illustrated in Figure 9, the arrival fix names are: RAMMS and TOMSN from the northwest; POWDR and LARKS from the southwest; QUAIL and DANDD from the southeast; and SAYGE and LANDR from the northeast.

Figure 7: The modeled OPD tracks which are transformed from the baseline tracks.

Figure 8: The runways utilized at DEN in south runway configuration are illustrated. This study will focus on arrivals and departures on the indicated runways.

Figure 9: Sample tracks of arrivals into DEN in south flow runway configuration, showing the arrival fixes.

A. Vertical Separation Zones

Flow tubes which encompass the tracks of arrival and departure flights into and out of DEN in south flow are illustrated in Figure 10. Each flow tube encompasses approximately 90% of the tracks for its flow. The flow tubes of arrival tracks are drawn in purple, and those of departure tracks are drawn in green. The flow tubes of departures tracks from runways 17R and 17L which fly directly south are omitted from the illustration for clarity.
green = departures
purple = baseline arrivals

Figure 10: Flow tubes that enclose the arrival and departure tracks.

Circled on the diagram of flow tubes are locations where arrival flow tubes are above or below departure flow tubes. These are zones where the airspace utilized by arrivals and departures are altitude separated. Since OPD operations are expected to change the vertical profile of arrivals, these locations are potential conflict zones between departures and OPD arrivals. In addition to the interaction zones within the terminal airspace as described here, the results of human-in-the-loop studies have demonstrated additional interactions between descending traffic and crossing traffic in en-route airspace [23]. Implementations of OPD arrivals will need to accommodate both the interactions between OPD arrival flows and departure flows in the terminal airspace, as well those between descending OPD traffic and crossing traffic in the en-route airspace, in order to avoid potential conflicts between OPD operations and other traffic.

B. Observed Level-offs

A sample flow tube for arrivals from the southeast over the DANDD arrival fix to runway 16L is redrawn in Figure 11. This alternative view allows closer inspection of the ground track, vertical profile, and speed profile of the flow tubes. In the figure, dark lines follow the boundaries of the flow tubes. Inspection of the vertical profile in the upper right frame reveals three distinct altitudes at which the tracks exhibit level-offs. For each level-off the corresponding location along the ground track is indicated in the left frame. Specifically, the arrival flow of Figure 11 exhibits level-offs at: 19,000 ft MSL where flights enter terminal airspace; 13,000 ft MSL where the arrivals fly over the departures; and 11,000 ft MSL at the turn onto the base leg. Removal of the level-offs within terminal airspace illustrated here, as well as any other level-offs during descent will be the primary means for obtaining benefit from OPD operations. The flow tubes of arrivals from other directions into DEN exhibit similar behavior as observed in this example.

DANDD to 16L

Level-offs are observed at:
19,000 ft – entry into terminal airspace
13,000 ft – arrival shelf over departures
11,000 ft – turn onto the base leg

Figure 11: The ground track, vertical profile and speed profile of the flow tube boundaries for arrivals from the southeast to runway 16L.

C. Summary of Baseline Operations

The previous two subsections have illustrated the vertical interaction zones between current arrival and departure operations, as well as the level-offs that are observed in current arrival operations. On the one hand, fuel savings and emissions reduction benefits will be obtained by removing the level-offs of current arrival operations. On the other hand, successful implementation of OPD operations will require mitigation of any conflicts which arise between OPD arrivals and other traffic.

V. Analysis

The transformation from baseline to modeled OPD trajectory can be applied to all the arrivals into DEN on a sample set of days to understand how the operations would change if all arrivals were OPD. In particular, the transformation will give estimates of the potential fuel savings and emission reduction benefits, as well as highlighting the potential conflicts between OPD arrival operations and current departure operations.

The following sections detail those potential benefits and conflicts in three subsections. First the case of unconstrained continuous descent from cruise down to the landing flaps configuration is analyzed. The conflicts that would result from this type of arrival operation and the potential benefits that could be obtained will be estimated. Second, two strategies of conflict mitigation will be described. The decrease in benefit potential from implementing these strategies will be quantified. Finally, a scenario of OPD procedure which avoids the major conflicts of unconstrained continuous descent by utilizing a combination of the two mitigation strategies will be analyzed and the potential benefit in this case will be quantified.
A. Unconstrained Continuous Descent

The case in which arrivals are allowed to execute continuous descent at idle throttle from cruise to landing is referred to as unconstrained continuous descent. The descent trajectories that would result for arrivals into DEN in this case will be modeled from the baseline arrivals by extending cruise and recalculating the vertical descent profiles at idle thrust. This situation is ideal from the perspective of obtaining the maximum benefit by allowing aircraft to fly their most optimum descent. However, it is expected that implementation of this ideal case will cause conflicts between the unconstrained descent and other traffic.

The arrival flow tubes of the modeled OPD arrivals in the case of unconstrained continuous descent are illustrated in red in Figure 12. The baseline departure flow tubes are drawn in green and the modeled OPD arrival flow tubes are drawn in red. Inspection of the modeled OPD arrival flow tubes reveal that they will conflict with the baseline departure flow tubes. The conflicts occur in the vertical separation zones between baseline arrival and departure flows, as described in Figure 10. Since aircraft following OPD descents fly at higher altitudes than baseline arrivals, instances of vertical separation with arrivals under departure flows may be lost. On the other hand, those instances of vertical separation in which the arrivals fly over the departures will not be at risk in an OPD operation since the OPD arrivals will fly higher above the departures. This second situation is also observed in the operations at DEN. In particular, arrivals from two fixes (DANDD and POWDR) which were flying over departures in baseline operations fly further above departures in the modeled OPD operations.

The fuel savings and emission benefits of unconstrained continuous descent from cruise to landing are listed in Table 1. The top four rows are for short-side arrivals from the northern fixes and the bottom four rows are for long-side arrivals from the southern fixes. The fuel savings was computed from Eurocontrol’s BADA aircraft database, as previously described. The emissions savings were computed from a constant multiplier based on fuel burned [24].

Analysis of the modeled OPD arrivals in the case on unconstrained continuous descent has clarified both the conflicts that will arise from this type of operation and the potential benefits that are attainable. The conflicts illustrated in Figure 12 are instances in which modeled OPD arrival traffic shares the same airspace with baseline departure traffic. If those potential conflicts are not mitigated, the result of OPD operations could be loss of throughput as terminal controllers alternately block off airspace for departures and arrivals. In addition to the potential conflict illustrated in Figure 12, field trials and HITL simulations have shown that potential conflicts between OPD arrivals and crossing traffic exists in en-route airspace as well. The potential benefits of unconstrained continuous descent are quantified in Table 1. These numbers are the upper bound of attainable benefit in the most ideal OPD case. If the fuel and emissions savings of all the aircraft arriving to DEN are summed together the total potential fuel savings benefit for arrivals into DEN is an average of 20,000 gallons of fuel per day. The commensurate emissions savings are daily reductions of 200 tons of CO₂ and 100 lbs of SO₂.

B. Conflict Mitigation Strategies

The analysis of the previous section has shown that conflicts will arise between OPD arrivals and departure traffic if the arrivals are allowed to descend optimally without constraint. Although that mode of OPD operation will yield the greatest potential benefit, the conflicts that will arise make unconstrained descent infeasible. Instead, some mitigation strategies will need to be applied to avoid those conflicts. This section describes two conflict mitigation strategies which constrain the descent profiles of arriving aircraft from their optimal profile and their associated reduction of potential benefit.

![Figure 12: Flow tubes of arrival and departure tracks.](image-url)

**Table 1: The average per flight fuel and emissions savings for the case of modeled unconstrained continuous descent into DEN by arrival fix.**

<table>
<thead>
<tr>
<th>Arrival Fix</th>
<th>Fuel Savings (lbs)</th>
<th>CO₂ (lbs)</th>
<th>SO₂ (lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short Side</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RAMMS</td>
<td>132</td>
<td>416</td>
<td>0.106</td>
</tr>
<tr>
<td>TOMSN</td>
<td>139</td>
<td>439</td>
<td>0.111</td>
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<tr>
<td>SAYGE</td>
<td>135</td>
<td>426</td>
<td>0.108</td>
</tr>
<tr>
<td>LANDR</td>
<td>141</td>
<td>445</td>
<td>0.113</td>
</tr>
<tr>
<td>Long Side</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>QUAIL</td>
<td>292</td>
<td>921</td>
<td>0.234</td>
</tr>
<tr>
<td>DANDD</td>
<td>228</td>
<td>719</td>
<td>0.182</td>
</tr>
<tr>
<td>POWDR</td>
<td>264</td>
<td>833</td>
<td>0.211</td>
</tr>
<tr>
<td>LARKS</td>
<td>261</td>
<td>823</td>
<td>0.209</td>
</tr>
</tbody>
</table>
1) Delayed Initiation

The first conflict mitigation strategy described here is targeted at avoiding the conflicts between descending OPD aircraft and crossing traffic in en-route airspace. This type of conflict can be avoided most simply by restricting aircraft from beginning their idle throttle descent above a certain altitude. For example, the continuous descent portion of an OPD arrival can be restricted to begin below some OPD initiation altitude. Above that altitude the arriving aircraft would follow normal ATC procedures, including any step-downs that are issued by the en-route air traffic controllers. This strategy is illustrated in Figure 13.

![Figure 13: The conflicts between OPD arrivals and crossing traffic in en-route airspace can be avoided by restricting continuous descent below an OPD initiation altitude. Above that altitude would be normal operations including step-downs.](image)

The decrease in potential benefit from implementing this strategy is quantified in Figure 14. Each line plots the potential fuel savings for a particular aircraft type arriving over the DANND arrival fix to runway 16L. Along the horizontal axis is the OPD initiation altitude. At the far right is the case in which the continuous descent portions can begin at flight level 400, which in effect means that aircraft may execute unconstrained continuous descents. As the OPD initiation altitude is lowered the level of potential fuel savings decreases. When the OPD initiation altitude has been lowered to flight level 250, approximately 85% of the potential fuel savings remain.

![Figure 14: The potential fuel saving benefit for a sample of aircraft types are plotted versus OPD initiation altitude for arrivals over the DANND fix to runway 16L.](image)

2) Early Termination

The second conflict mitigation strategy is targeted at avoiding the conflicts between descending OPD aircraft and departure traffic in terminal airspace. This type of conflict can be avoided by requiring aircraft to end their idle throttle descent portions when they reach a certain altitude. For example, continuous descent portions of an OPD arrival can be required to end at an OPD termination altitude. Below that altitude the arriving aircraft would follow normal ATC procedures, including any level-off shelves to go under or over departure traffic. This strategy is illustrated in Figure 15.

![Figure 15: The conflicts between OPD arrivals and departure traffic in terminal airspace can be avoided by restricting continuous descent above an OPD termination altitude. Below that altitude would be normal operations including arrival shelves.](image)

The benefit reduction from implementing this second strategy is quantified in Figure 16. As before, each line plots the potential fuel savings for a particular aircraft type arriving over the DANND arrival fix to runway 16L. Along the horizontal axis is the OPD termination altitude. At the far left is the case in which the continuous descent portions can extend down to the field elevation (i.e. an unconstrained continuous descent). As the OPD termination altitude is raised the potential fuel savings decreases. When the OPD termination altitude has been raised to flight level 150, approximately 70% of the potential fuel savings is no longer available.

![Figure 16: The potential fuel saving benefit for a sample of aircraft types are plotted versus OPD termination altitude for arrivals over the DANND fix to runway 16L.](image)
C. Constrained Continuous Descent

The conflict mitigation strategies described in the previous section help to avoid conflicts with crossing traffic in en-route airspace and departure traffic in terminal airspace. Combining those two strategies an OPD procedure can be designed which gives a lower level of potential benefit, but also avoids conflicts which will make it infeasible. Specifically, if the OPD initiation altitude is set to flight level 250 and the OPD termination altitude is set to flight level 150, the resulting OPD procedure will avoid both low and high altitude conflicts. This constrained continuous descent OPD procedure is illustrated in Figure 17.

![Figure 17: The conflicts between OPD arrivals and other traffic in both en-route and terminal airspace can be avoided by restricting continuous descent to only between 25,000 ft MSL and 15,000 ft MSL. Outside this range would be normal operations including step-downs and arrival shelves.](image)

The average per flight fuel savings and emission benefits from constrained continuous descent between 25,000 ft MSL and 15,000 ft MSL are quantified in Table 2. The potential fuel and emissions savings benefits are listed for each arrival direction separately. Comparison with Table 1 shows that the potential benefits from constrained continuous descent are lower than those of unconstrained continuous descent, as expected. If the fuel and emissions savings from all the arrival fix directions are summed together the total potential fuel savings benefit for arrivals into DEN is 3,000 gallons of fuel per day. The associated emissions savings are daily reductions of 30 tons of CO$_2$ and 15 lbs of SO$_2$. This level of potential benefit is reduced to only 15% of the potential benefit in the most ideal case. However, the potential conflicts with other traffic are also reduced.

The constrained continuous descent OPD procedure described here has mitigated potential conflicts between arriving traffic and other traffic by keeping many of the level-offs usually executed by an arriving flight. Inspection of the level-offs enumerated in Figure 11 reveals that between 25,000 ft MSL and 15,000 ft MSL only one major level-off has been removed. That level-off is the one executed at the terminal boundary as aircraft are handed-off from en-route to terminal controllers.

<table>
<thead>
<tr>
<th>Arrival Fix</th>
<th>Fuel Savings (lbs)</th>
<th>Emissions Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAMMS</td>
<td>27</td>
<td>85</td>
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<td>DANDD</td>
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<td>LARKS</td>
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<td>128</td>
</tr>
</tbody>
</table>

Table 2: The average per flight fuel and emissions savings for the case of modeled continuous descent constrained to between 25,000 ft MSL and 15,000 ft MSL into DEN are listed by arrival fix.

In order to avoid potential conflicts between OPD arrivals and crossing traffic en-route, a mitigation strategy was proposed which involved delaying the initiation of continuous descent until the arriving aircraft has descended below a specified altitude. Above that altitude, descending aircraft would execute step-downs as in normal operations to avoid conflicts with crossing traffic. Similarly, in order to avoid potential conflicts between OPD arrivals and departure traffic, a mitigation strategy was proposed which involved terminating continuous descent operations below a specified altitude. Below that altitude aircraft would execute level-offs as in current operations to avoid conflicts with departure traffic.

Those two conflict mitigation strategies were combined in the second implementation scenario. The continuous descent portions of the trajectories in this second scenario were constrained to begin at 25,000 ft MSL and end at 15,000 ft MSL. These choices for the OPD initiation and termination altitudes avoid conflicts with both crossing and departure traffic. However, the benefits attainable from this scenario at DEN were found to be reduced to only 15% of the potential benefit in the unconstrained continuous descent case. Specifically, the attainable benefits were found to be daily savings of 3,000 gallons of fuel, and daily reductions of 30
tons of CO₂ and 15 lbs of SO₂. Although the first scenario (of unconstrained continuous descent) yielded the greater potential benefit, it is clearly infeasible since it causes conflicts with crossing and departure traffic. Alternatively, the second scenario avoids those conflicts but still offers an attractive level of potential benefit.

The major conclusion that may be drawn from this study is that OPD arrival operations can be implemented with real measureable benefits while avoiding conflicts with other traffic if the OPD arrival procedures are carefully designed. In particular, OPD arrival operations do not need to be implemented to the maximum extent in order to yield beneficial fuel and emissions reductions. A constrained and limited implementation of OPD arrival operations is sufficient. The constrained continuous descent scenario has shown that by carefully choosing which level-offs are removed, both benefits can be obtained and conflicts avoided simultaneously.

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