Challenges to Modeling Vectored Area Navigation Departures at Dallas/Fort Worth International Airport

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This paper analyzes both air traffic volume and controller motivations while attempting to correlate these factors to the vectoring of area navigation (RNAV) departures at Dallas/Fort Worth International Airport (DFW). One-third of DFW RNAV departures encounter some form of vectoring away from the RNAV routes. The majority of those vectored, about one-quarter of all the departures, are given direct routings that bypass fixes on the route and shorten the distance flown within the DFW Terminal Radar Approach Control (TRACON) airspace. Understanding when and why vectoring occurs gives researchers further insight into the complex dynamics of super dense airspace operations which can be used to improve trajectory prediction for automated decision support tools. This paper describes the development of models aimed at understanding and modeling those instances. The results of these models' development show they are not good predictors of short cuts, as they fail to capture controllers' decision-making criterion for vectoring. The interviews with retired TRACON controllers, however, provided other data to consider or to obtain that might improve the modeling. These interviews also indicate the subjectivity of their decisions to vector these aircraft in clear conditions and highlight the complexity of air traffic in super-dense airspace.

Nomenclature

ARTCC	=	Air Route Traffic Control Center
b_o	=	linear model intercept term
b_i	=	linear model slope, regression coefficients
b_{ii}	=	coefficients for the pure quadratic terms
b_{ij}	=	coefficients for the cross-product terms
D10	=	DFW Terminal Radar Approach Control (TRACON) airspace
DAL	=	Dallas Love Field
DFW	=	Dallas/Fort Worth International Airport
DR	=	Departure Radar
ε	=	error associated with neglecting higher order effects
k	=	number of factors
H	=	heavy aircraft weight class
L	=	large aircraft weight class
NTX	=	NASA/FAA North Texas Research Station
R	=	model response
RNAV	=	area navigation
RNP	=	Required Navigational Precision

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RSE	=	Response Surface Equation
SID	=	Standard Instrument Departure
T	=	Actual Takeoff Time for an RNAV Departure
TRACON	=	Terminal Radar Approach Control
$x_i ; x_j$	=	independent variables

I. Introduction

The Next Generation Air Transportation System (NextGen) calls for the extensive use of trajectory management for aircraft to achieve precision flight paths[1,2]. To understand, develop, and model systems that support these NextGen operations, especially in the terminal area, NASA is analyzing today's terminal operations to gain insight into the expected behavior. This paper analyzes both air traffic volume and controller motivations to correlate these factors to the vectoring of area navigation (RNAV) departures at Dallas/Fort Worth International Airport (DFW). DFW was selected for this case study as these kinds of precise departure procedures have been in daily use there for more than five years.

In clear weather conditions, one-third of DFW RNAV departures encounter some form of vectoring away from the RNAV routes. The majority of those vectored, about one-quarter of all the departures, are given direct routings that bypass fixes on the route and shorten the distance flown within the DFW Terminal Radar Approach Control (TRACON) airspace, designated D10. These divergences primarily result from controllers taking advantage of opportunities in the airborne traffic, similar to direct-to routing in enroute airspace, and are not the result of avoiding loss of separation. During the planning of the RNAV procedures, some of this vectoring was expected and even encouraged, but the number of aircraft affected has grown over time. This means that procedures designed to work in "unused" airspace, or that expand the airspace designated for arrivals, might impact the departure efficiency in an unexpected way.

Understanding when and why vectoring occurs gives researchers further insight into the complex dynamics of super dense airspace operations which can be used to improve trajectory prediction for automated decision support tools. This directs the research toward the elements that will most likely impact operational efficiency. Improving these procedures requires an understanding of how controllers now attempt to achieve the best service. This paper will describe the development of statistical models aimed at understanding these instances when aircraft are taken off their RNAV routes. The statistical models developed using the empirical data from DFW proved to be insufficient predictors of when controllers shortened RNAV departure routes, but information gathered from retired controllers offers important insight to the motivations and considerations behind the vectoring of these aircraft that could improve future models.

II. Background

As part of a broad plan to improve the efficiency of the national airspace system, the Federal Aviation Administration is in the midst of implementing RNAV departure procedures at 35 major airports in the United States[3]. Aircraft that file for RNAV departures must be equipped to fly an RNAV 1 route, which requires a total system error of not more than 1 NM for 95% of the total flight time[4].

DFW began routinely using these procedures in November 2005. The volume of RNAV departure operations following the creation of these procedures validates their utility, and no significant changes have been required. These procedures have reached a state of maturity at DFW, and can serve as a test case of what might occur as other precision operations are implemented throughout the national airspace system.

Previous analyses showed many aircraft executing RNAV departures do not fly within the bound specified by the procedures. In fact, controllers often vector these aircraft to shorten the path flown within D10, or, through handoffs to the Fort Worth ARTCC (ZFW), the aircraft bypass portions of the route while flying direct to fixes outside D10. The number of DFW RNAV departures affected in the course of ten days of clear weather operations was determined[5]. Roughly 33% to 40% of RNAV departures on a typical day at DFW encounter some form of vectoring. This poses a challenge for any automated decision support tool when predicting the future positions of aircraft.

To improve aircraft trajectory prediction of aircraft on RNAV routes, this paper examines the circumstances and possible reasons controllers vector these departures, and develops models to statistically predict how many aircraft will receive vectors. Ideally it would be beneficial to identify which aircraft will receive a vector and use that information as part of the intent information for a trajectory prediction, but starting with this level of modeling can lead to this goal. The work provides a partial understanding of the complex relationships between departure and arrival traffic, and the operations from neighboring airports. The results of this and other studies can guide terminal area research and serve as a benchmark for measuring the performance and efficiency of future concepts with varying levels of precision.

III. DFW Terminal Airspace

D10 is centered on DFW, essentially consisting of a square approximately 60 miles on each side, and controls aircraft within its boundaries up to 17,000 feet. Dallas Love Field (DAL), the closest airport to DFW, is the next largest of more than 30 other airfields within its bounds. Departures from D10 leave through the north, south, east, and west gates (sides) of the TRACON, while arrival traffic passes over fixes on the corners of this square (Fig. 1 and Fig. 2).

Currently, sixteen Standard Instrument Departures (SIDs) define RNAV 1 routes from the departure runway thresholds to the fixes where aircraft transition from D10 to ZFW. Departures from DAL and other airports, as well as propeller and non-RNAV DFW departures, also fly over these boundary fixes, but they receive vectoring from D10 departure controllers and do not use routes that require navigation equipment meeting an explicit Required Navigational Precision (RNP). Based on data collected at the NASA/FAA North Texas Research Station (NTX), approximately 790 departures a day (90% of all departures) from DFW use an RNAV procedure[5].

Each RNAV procedure defines routes for north and south flow airport configurations, that is, the aircraft direction at takeoff, from four potential departure runways. Figure 1 shows the combined routes for the RNAV departures in north flow, and Fig. 2 shows those for south flow. Note that several procedures in each flow direction share common route segments. For example, Fig 2 shows that departures for SOLDO and CLARE use portions of the same route, and also share a fix common to the south gate departures leaving the eastern runway of the airport. Similarly, departures headed for the north gate that leave from the eastern runway use a segment of the route that departures to NOBLY and TRISS use as well. Aircraft on the initial segments of these two sets of routes, starting from the runway threshold, have heading angles fifteen degrees apart.

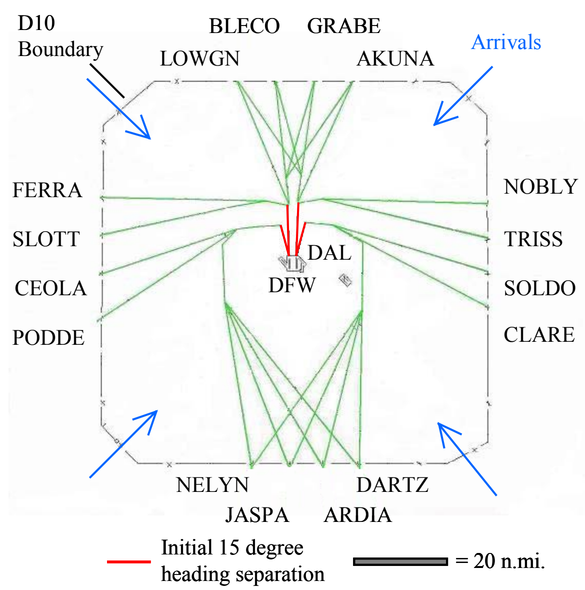

Figure 1. RNAV Departure Routes for North Flow

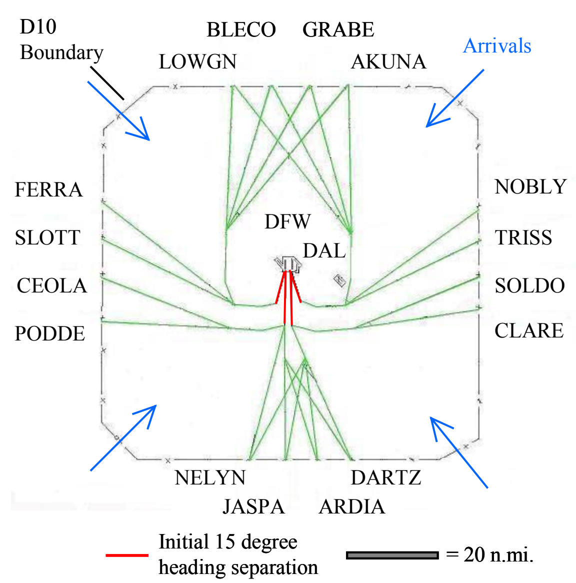

Figure 2. RNAV Departure Routes for South Flow

In periods of high demand, the tower (local) controllers alternate between these sets of RNAV routes for departures from the same runway so that the subsequent aircraft is on a different initial segment than the preceding aircraft; these are termed *divergent heading departures*. In this case, less distance is required between departing aircraft than conventional operations, which in turn reduces the time between departures. Departures from the same runway that have filed the same RNAV route, or have routes with the same initial segment in common, are termed *non-divergent heading departures*. While routes for the western gates from the east side runways (and vice versa)

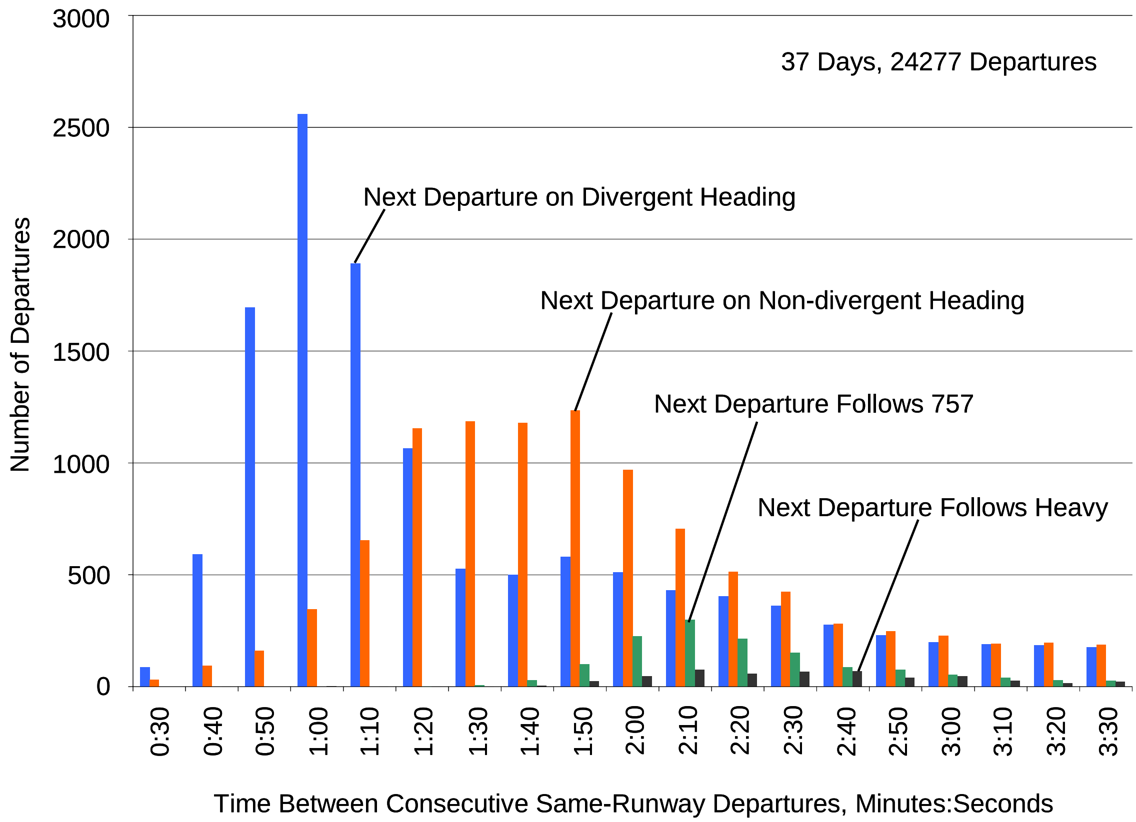

Figure 3. Impact of Divergent Heading Departures on Time Between Departures

exist, they are not used frequently, and differ only in the way aircraft reach the first fix on each route. The impact of divergent heading departures on the time between DFW departures appears in Fig. 3, compiled from 37 clear-weather days of data collected at the NTX. In this histogram, note the peak consisting of large aircraft on divergent heading departures, which occurs with about one minute between consecutive departures from the same runway. As the mix of aircraft entering the departure queue may not have filed departure procedures that allow divergent heading departures, the second-highest peak in Fig. 3 represents those aircraft released on the same initial (non-divergent) heading. Note that this peak is broader and less well-defined, spread over a range from 1 minute 20 seconds to 1 minute 50 seconds. Lastly, standard departure spacing applies to all 757 and "Heavy" aircraft categories (four and five nautical miles, respectively), regardless of the opportunity to use a divergent heading departure. Peak numbers of departures following these kinds of aircraft occur at 2 minutes 10 seconds and 2 minutes 40 seconds, respectively. Note that the differences in the number of aircraft using divergent and non-divergent heading departures become essentially meaningless at this and at higher times between departures, likely indicating that the queue has emptied, and the time between these departures would reflect gaps in departure demand rather than timing for the purpose of airborne spacing.

Past studies have examined a variety of other departure efficiencies resulting from aircraft using RNAV procedures[6,7]. These studies showed the initial benefits to DFW in the first months after the procedures became operational. As D10 controllers gained experience in using these procedures over the years, they have increased RNAV departure vectoring whenever possible to reduce perceived flight-time and distance flown within D10.

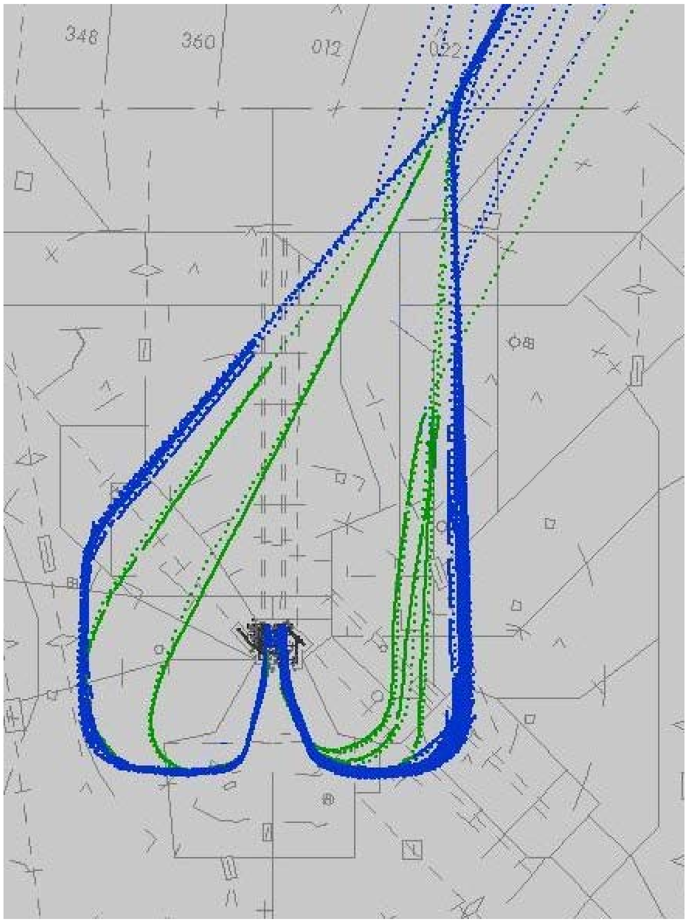

Figure 4. Typical AKUNA Tracks, South Flow

RNAV departure traffic at DFW is a mix of "non-vectored" and "vectored" traffic that presents prediction challenges. "Vectored" traffic in this case means that the aircraft flight plan includes the RNAV departure route, but air traffic controllers alter the route during the execution of the procedure. Figure 4, assembled from a mosaic of ASDE-X (surface and low altitude), ARTS IIIe (D10 radar and flight plans) and Host data (ZFW radar and flight plans), shows typical ground tracks for aircraft using the AKUNA RNAV departure procedure in south flow over the course of a single day. Blue tracks denote flights that stayed on the RNAV route, while green tracks denote those that bypassed fixes on the inside of the route. Six aircraft out of 64 have been vectored before the 90-degree turn in the route originating from the east-side runway. Four tracks out of ten leaving the west-side runway eventually turn inside the route, flying a shortened distance to the D10 boundary. These kinds of tracks that reduce the flight distance will be termed *short cuts* in this paper. While most of the tracks converge on the AKUNA fix on the D10 boundary, a number of aircraft do not pass over it, and cross the D10 boundary at a number of locations. These tracks *bypass the boundary fix*. Departures executing the other DFW RNAV departure procedures show similar vectoring characteristics. Approximately 25% of DFW RNAV departures fly short cuts, while 10% bypass boundary fixes[5]. This paper will be concerned with understanding and predicting the instances of short cuts, as these are the most common form of RNAV departure vectoring in clear conditions.

IV. Initial Analysis

Two methods were used to attempt to understand when controllers vector RNAV departures. The first was to develop a simple linear model that predicts which aircraft will be vectored as a function of DFW departure and arrival traffic volumes. A second attempt used a second order Response Surface Equation (RSE) model, based again on DFW traffic volumes but also including the arrival and departure traffic at Dallas Love Field (DAL). The premise is that the approximate location of these aircraft in D10 either allows or prohibits the vectoring of RNAV aircraft from the route designated in the procedure.

The days used in the 2009 study[5] were selected for their uniformity of departure flow direction and absence of limiting weather phenomena in or near the D10. Ten days were selected for model development, and were comprised of five south flow and five north flow days for a total of approximately 7700 RNAV departures. The days did not feature weather or air traffic constraints that inhibited the flow of traffic. Data available for this study included DFW ASDE-X (surface and low-altitude tracks), D10 ARTS IIIe data, and ZFW Host data. The Surface Operations Data Analysis and Adaptation (SODAA) tool was used for data extraction and analysis[8].

A. Evaluation of a Linear Model

The intent of this linear model is to simply predict if an RNAV departure will receive a short cut. Given the total number of aircraft that filed for a particular RNAV departure procedure and the flow direction of the airport, the model would predict the percentage that will receive a short cut.

The first method investigated assumed that the number of vectored aircraft could be represented by a linear regression model of the form:

$$R = b_o + b_i x_i \tag{1}$$

Where:

R is the dependent parameter (response) of interest, in this case, the percentage of vectored aircraft, either short cut or that bypassed a boundary fix;

b_o is the intercept term;

b_i is the slope; and

x_i represents the independent variables.

The 2009 study[5] showed a trend between RNAV vectoring on the basis of flow direction and filed RNAV procedure. The prediction of the number of departures receiving short cuts or bypassing boundary fixes was attempted on the basis of the number of aircraft filing for each of the sixteen RNAV departure procedures and the flow direction of the airport. An initial investigation attempted to associate the percentage of departures vectored with a measure of average time between departures as the independent variable. The results, relying on the form shown in Equation 1, proved too random, meaning that the model failed to capture what was truly driving or preventing vectoring.

B. Evaluation of a Second Order Model

A more extensive analysis followed, involving a greater number of independent variables to attempt to capture D10 traffic situations that might correspond to periods when the number of DFW RNAV departure short cuts increased or decreased. This would attempt to correlate the short cut or on-track status of each RNAV departure in the ten days of data to the other air traffic in D10 at that time. This started with a review of D10 controller responsibilities to determine which variables might be key to understanding the timing of these short cuts.

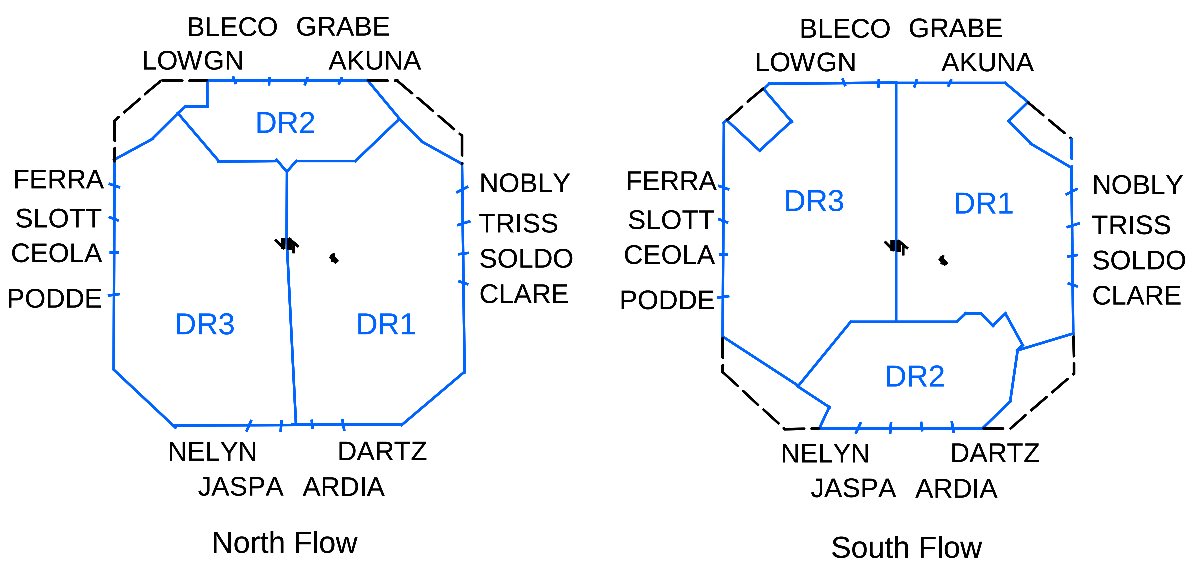

Figure 5. Approximate Departure Radar (DR) Boundaries for D10 in North and South Flow

The three D10 Departure Radar (DR) positions are designated DR1, DR2, and DR3[9]. Because of the shape of the sectors and the location of DFW at the center of D10, as shown in Fig. 5, two of the three D10 departure controllers take control of DFW departures after they leave the airspace of the local controllers. DR1 handles departures headed for the east gate of D10, and the two eastern fixes on either the north gate (in south flow) or the south gate (in north flow). Similarly, DR3 is responsible for all departures using the west gate of D10, as well as the two western fixes of either the north or south gate, depending on flow direction. The north-south line that divides DR1 from DR3 passes through and equally divides DFW airport, parallel to the most heavily used departure runways. DR2 is responsible for the south gate departures in south flow and the north gate departures in north flow. Note that these positions are responsible for not just the DFW departures, but also departures from DAL and all the regional airports within the boundaries of D10. Also note that, given the sector geometry, DR1 and DR3 take handoffs of all the DFW departures (RNAV and non-RNAV) from the local controllers. Based on the way aircraft are short cut, as shown earlier in Fig. 4, the vast majority of the short cuts are issued by DR1 and DR3.

From this division of traffic and responsibility, it follows that examining departures on the basis of the side of the airport where each departure originated should correlate well to the workload of the DR1 and DR3 controllers. As few departures that originate from west side runways use the east gate (and few east side runway departures fly west), the expectation would be that east side departure volume would have some correlation to the ability of DR1 to grant short cuts, and west side departures would have a weak (if any) correlation with these short cuts. To capture this demand, the number of departures from each side of the airport before and after each RNAV departure were totaled, on the basis of defined time segments. These categories and the time segments appear at the beginning of Table 1.

The time segments are defined relative to the takeoff time of each RNAV departure. For example, for an RNAV departure taking off from the runway at time T, the number of aircraft that left the east and west sides of DFW within five and ten minutes before and after T were counted. Counting aircraft that preceded an RNAV departure roughly represents the number of aircraft for which the departure controller already has responsibility when that RNAV departure takes off. Likewise, the aircraft following the RNAV departure represents demand that the departure controller anticipates. The overall bound of ten minutes approximates the amount of time departures use to transit the DR1 and DR3 sectors, and should therefore capture the time during which the traffic could affect the controller's decision to short cut an RNAV departure.

As mentioned in the description of D10, DFW arrivals fly from the corners of D10 toward DFW at its center. Departures from DFW are held at or below 10000 feet as the arrivals cross at a minimum of 11000 feet above them. While the structure of D10 keeps these flows of traffic separated, a controller's decision to short cut might be influenced by the positions of these arrivals relative to the RNAV departure. Given flow directions and the DR1 and DR3 sector boundaries, the DFW arrival traffic was categorized for this analysis by the corner of D10 that each aircraft overflew. Five-minute time increments were again used, but (as shown in Table 1) the overall span of the times examined was shifted compared to the departure groups. The "arrival time" for each aircraft was its threshold crossing time at DFW airport. Therefore, unlike the departure demand, aircraft that arrived before an RNAV departure takes off at time T cannot be a factor for DR1 and DR3 in granting a short cut. The departures that might influence these controllers are those entering or are traveling through D10 at time T. As arrivals may take up to 20 minutes to fly through D10, the bound for the arrival traffic counts was likewise set to 20 minutes.

Table 1. Aircraft Counts for Correlation to RNAV Departure Short Cuts

Aircraft Traffic Category	Interval for Counting Aircraft Relative to RNAV Departure Time T
DFW East Side Runway	Departing 10 to 5 minutes before T
DFW West Side Runway	Departing 5 to 0 minutes before T
	Departing 0 to 5 minutes after T
	Departing 5 to 10 minutes after T
D10 Northeast Corner	Arriving at DFW 0 to 5 minutes after T
D10 Southeast Corner	Arriving at DFW 5 to 10 minutes after T
D10 Southwest Corner	Arriving at DFW 10 to 15 minutes after T
D10 Northwest Corner	Arriving at DFW 15 to 20 minutes after T
DAL	Departing 10 to 5 minutes before T
	Departing 5 to 0 minutes before T
	Departing 0 to 5 minutes after T
	Departing 5 to 10 minutes after T
	Arriving at DAL 0 to 5 minutes after T
	Arriving at DAL 5 to 10 minutes after T
	Arriving at DAL 10 to 15 minutes after T
	Arriving at DAL 15 to 20 minutes after T

DAL is the second busiest airport in D10 and is relatively close to DFW. The merging of DAL departures with DFW departure flows, and the airspace the DAL arrivals might deny to DFW RNAV departures that could be short cut, cannot be ignored. Therefore, counts for all DAL traffic were also determined. The same time windows were used as DAL and DFW are only seven miles apart, and so the timing of departure and arrival traffic relative to short cut opportunities would be similar. In total, each RNAV departure had 32 traffic counts associated with it, based on the categories outlined in Table 1.

As a standard first order linear regression model of departure vectoring failed to provide an acceptable quality of fit, a second order regression model called Response Surface Equation (RSE) model was investigated. RSE is of the form:

$$R = b_o + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} x_i^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} b_{ij} x_i x_j + \varepsilon \tag{2}$$

Where:

R is the dependent parameter (response) of interest.

b_o is the intercept term.

b_i are regression coefficients for the first order terms.

b_{ii} are coefficients for the pure quadratic terms.

b_{ij} are the coefficients for the cross-product terms.

$x_i ; x_j$ are the independent variables.

k is the number of factors.

ε is the error associated with neglecting higher order effects

RSE assumes that for any model the error, ε, should be normally distributed as N(0,1), that is, a normal distribution of mean = 0 and a standard deviation of 1.

The statistical modeling software JMP was used to predict the RSE coefficients for short cuts for three cases (SOLDO departures in north flow, SOLDO departures in south flow, and AKUNA departures in north flow) in an initial evaluation. SOLDO was used because it is the most commonly filed RNAV departure, and has a large difference in the number of flights receiving short cuts as a function of flow direction. AKUNA shows less variation with flow direction and is more typical of departures heading for the north or south gate of D10. The quality of fit is estimated using the coefficient of determination (or root mean square) $\boldsymbol{R}^2$; which was approximately equal to 0.4 in each case. This result compares poorly with an ideal fit of $\boldsymbol{R}^2 = 1$.

A screening of the independent variables was done to determine the contribution of each variable to the chance of an RNAV departure receiving a short cut. The JMP software was used to create Pareto charts for this purpose. These verified one expected result: the contributions of certain independent variables to SOLDO short cuts did change depending on flow direction due to airspace and airport geometry. In particular, the Pareto plots (Fig. 6 and Fig. 7) show that departures and arrivals at DAL have a bigger impact on SOLDO short cuts in south flow configuration compared to north flow. The charts show the orthogonal estimates for each category listed in the left-hand column. The values show the relative contribution of each variable to the response (i. e., SOLDO short cut). Negative values indicate that the corresponding contribution of the parameter is inversely impacting the response. In other words the higher the value of the parameter "DFW dep 5 to 0 min prior" (i. e., the heavier the traffic), the less likely there will be a short cut. The higher the orthogonal value, the more influence this parameter has on predicting short cuts. Note that, while the relative contribution for the values in both flow directions are quite small, the impact of "DFW dep 5 to 0 min prior" in south flow is over twice as large as that of north flow (–0.06555 compared to –0.0273). In north flow, the table in Figure 6 shows the largest parameter contribution value on the chart, which is the number of DFW departures up to five minutes before an RNAV departure, is comparable to the number of DAL departures in the five minutes after the RNAV departure. The number of DFW departures are twice as significant as the parameter representing the cross effect of DAL departures 10 to 5 min prior and the DAL arrivals 0 to 5 min after in south flow configuration (–0.122 compared to –0.0679). Note, however, that each variable in these figures contributes less than 5% to the prediction of a short cut. The overall conclusion from the sensitivity analysis, then, is that none of these independent variables are main contributors to short cuts, based on a result of short cut or no short cut.

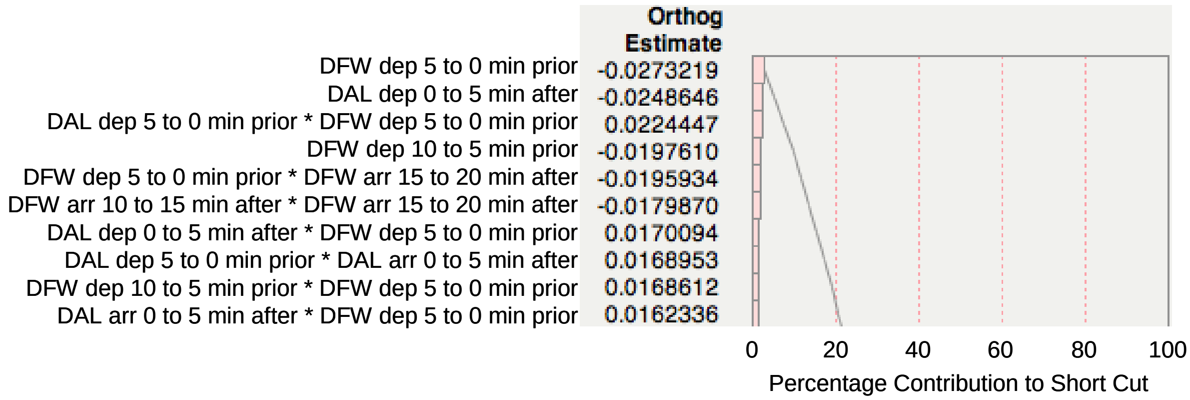

Figure 6. Effect of Air Traffic in Enabling Short Cuts for SOLDO Departures, North Flow

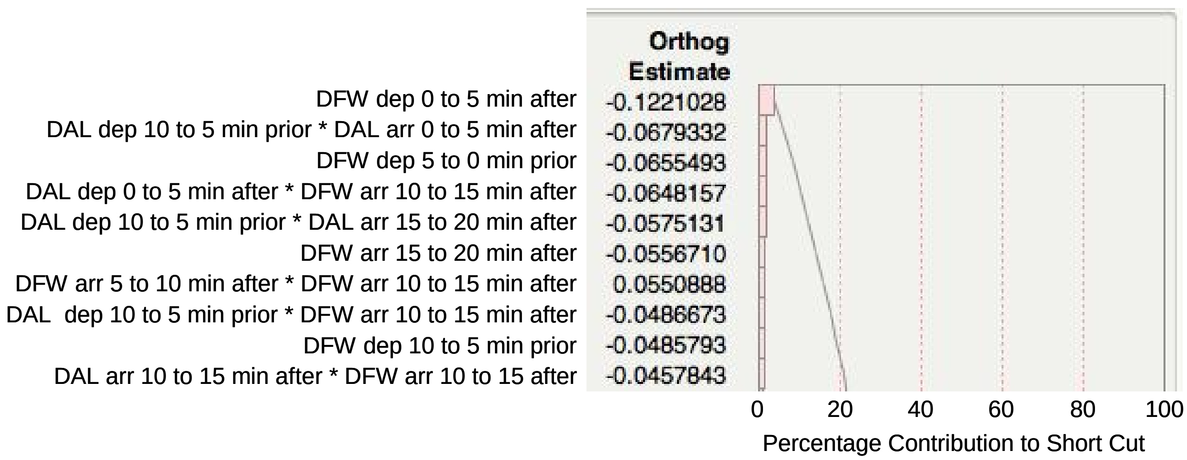

Figure 7. Effect of Air Traffic in Enabling Short Cuts for SOLDO Departures, South Flow

As the prediction of RNAV departure vectoring cannot be determined from the concurrent departure and arrival traffic alone, another approach must be evaluated.

V. Interviews/Discussions with Retired Controllers

Following the results of the studies discussed above, it became evident that the main drivers for short cuts lay mostly within the air traffic controllers' judgment. A series of interviews with retired D10 departure controllers was conducted to gain insights into when and why aircraft received short cuts from RNAV departure routes. Any results from these discussions that could be assessed quantitatively were used in another attempt to statistically model short cuts for one of the RNAV departure procedures.

A. Experimental Method

The experiment was based on the interview of six recently retired controllers from D10. The controllers were divided into two groups. Then three sets of interviews were conducted, with each set consisting of one controller from each group.

Controller interviews were divided into two parts. First, the controllers provided verbal answers to a questionnaire that was developed with the assistance of other subject matter experts. The questionnaire consisted of general knowledge questions about the departure procedures. This was meant to provide understanding about the controllers' views on the use of short cut and determine quantifiable factors for the prediction model. Also, there were questions geared toward identifying other factors that they would consider when electing to vector an aircraft off an RNAV departure procedure on the one hand and factors that would preclude them from doing so on the other. The ultimate goal of the questionnaire was to identify quantifiable factors to improve the prediction model.

The second part of the interviews consisted of the controllers reviewing static screen capture images from archived radar track data. Each screen capture image was a scenario involving a SOLDO departure, along with other departure and arrival aircraft that the D10 DR1 controller would have to take into consideration in south flow. SOLDO was chosen because a high percentage of these filed departures receive a short cut, and SOLDO departures are usually the most frequently filed each day. Aircraft type, heading, and speed were displayed in aircraft data blocks. The SOLDO departure in each case was on the track defined by the departure procedure, and the controllers were asked whether or not they would grant this departure a short cut based on that aircraft's current position and the neighboring traffic. They were to explain the basis of their decision. It is important to note that had these controllers actually been working with live traffic, it would have been a dynamic environment, with all the workload and stress associated with working air traffic; this of course could not be replicated barring an actual simulation, but the trade off was a full explanation of the factors each would use in the decision-making process. In many of the cases shown to the controllers, the SOLDO departure that they evaluated was actually sent on a short cut, within six seconds after the situation shown in the figure; others were not short cut and flew the complete route to SOLDO.

Table 2. Shorthand Responses for Short Cut Scenarios

Controller Response	Numerical Equivalent
Absolutely or Definitely	1
Likely	0.75
Maybe	0.5
Unlikely	0.25
Absolutely Not or Definitely Not	0

The authors decided to allow more flexibility in controllers' response by providing them with a choice of five possible answers to the question, "Would you short cut a designated aircraft off the RNAV procedure?" The controllers' responses were converted to numerical values between 0 and 1 as shown in Table 2.

B. Questionnaire Results

Through the answers to the questionnaire, the authors learned that:

- The controllers recalled that at least 90% of the short cuts result from controllers acting on their own initiative. Less than 10% of the short cuts result from pilot request under normal operational procedures.
- Pilot-requested short cuts increase substantially when weather potentially interferes with aircraft routing For example, one controller said, "When weather comes, all bets are off."
- The controllers stated their priorities for providing short cuts are: (1) sequencing assistance, (2) reduced track miles, (3) pilot request.
- Among the many factors that these controllers consider when initiating a short cut, aircraft type and performance play significant roles in the techniques they would use to provide proper departure sequencing.
- Heavy traffic usually prevented them from initiating short cuts, although other factors also prevent them.
- Generally, these controllers believe short cuts increase their workload and increase their chance of an operational error, especially for less experienced controllers. While controllers always retain ultimate responsibility for aircraft separation, controllers must depend more upon their judgment and experience for predicting aircraft trajectories when they direct aircraft off the RNAV procedure, versus leaving the departures on the defined routes.
- Controllers are not required to initiate or grant any short cuts.

C. Results from Interviews Regarding Potential Short Cut Scenarios

As an example of the responses to the SOLDO short cut scenarios, Table 3 shows the diversity of the responses to the question of granting a short cut to a particular aircraft. The responses of two of the controllers are shown, using the terms and number ratings defined in the previous section. In some cases, the points of disagreement between the controllers weren't entirely clear.

Figure 8 and the discussion that follows do not elaborate all of the reasons for granting or denying short cuts to RNAV departures in these situations, but they do illustrate a variety of the concerns that came out in these discussions. Many of these considerations would apply to short cuts for RNAV procedures other than SOLDO, although flow direction and the structure of D10 would change the applicability of these points. The upper portion of Fig. 8 shows actual radar tracks of aircraft flying the SOLDO departure procedure in south flow, whereas the bottom portion shows the path defined by the SOLDO procedure. The fixes along the SOLDO RNAV route appear in black, as do the DFW and DAL runways, and the routes for the adjacent RNAV procedures with dashed lines (TRISS to the north, and CLARE to the south with three fixes common to the SOLDO route). Arrows along the track denote the direction of flight for DFW departures, depicted here for the most numerous departures from the east-side runway threshold, and through the fixes labeled TREXX, JOLEN, and PAXTN before heading to the border of D10 at SOLDO. Areas in Fig. 8 marked Zone A and Zone B in blue along the route show where controllers typically initiate short cuts to the SOLDO fix, and the paths of DFW arrivals and DAL departures appear in green and red, respectively. Note that DFW arrivals from the southeast descend to and hold 11000 feet while passing over the departure routes, while the departures are held beneath the arrivals, at a maximum altitude of 10000 feet.

Table 3. A Sample of the Responses to the Short Cut Scenarios

Aircraft	Category Size	"Would you grant a short cut?" (equivalent numerical value) Controller A	Controller B	Comments
A	Large	Maybe (0.5)	Definitely (1)	Disagreement. Close enough to NAVYE that short cut not a problem.
B	Large	Likely (0.75)	Likely (0.75)	No arrival traffic, can turn and climb. Not yet far enough south to say "Definitely".
C	B757	Likely (0.75)	Unlikely (0.25)	Disagreement. Weight class a factor for Controller B.
D	Large	Unlikely (0.25)	Likely (1)	Disagreement.
E	B757	Likely (0.75)	Definitely (1)	Only one in airspace. Has gained enough altitude so that aircraft can be stopped if another departure follows closely.
F	B757	Unlikely (0.25)	Unlikely (0.25)	Nothing gained with short cut.
G	Large	Definitely Not (0)	Definitely Not (0)	Spacing between aircraft ideal, no reason to change.
H	Large	Likely (0.75)	Likely (0.75)	--
I	Large	Definitely (1)	Definitely (1)	No other traffic, but not gaining much.
J	Large	Definitely (1)	Definitely (1)	Aircraft ahead of this one is fast. Turn on short cut now, or never given other traffic.
K	Large	Definitely (1)	Definitely (1)	Short cut feels right.
L	Large	Definitely Not (0)	Definitely Not (0)	Leave aircraft on RNAV route because of arrival aircraft.

Some of the considerations for short cuts initiated in Zone A relate to other DFW departures. First, an aircraft given a short cut in the northern portion of Zone A will generally fly directly toward SOLDO, taking it near the fixes used by NOBLY and TRISS departures (that is, JGIRL and CORTS), or "inside the turn" relative to the SOLDO departure procedure. Therefore, controllers must account for a subsequent east side departure that would be using these fixes, in other words, an alternate heading departure. If such a departure is on the way, the controllers might not grant the short cut, because it could lead to a loss of separation between the aircraft. Similarly, if a slow aircraft is already using the inside track and the short cut candidate has better performance, a short cut might also cause a separation problem. In the same way, an on-track SOLDO departure ahead of an aircraft that could be short cut might prevent that short cut, should the candidate close the distance to SOLDO too quickly by following the shortened route. When several aircraft that have filed the SOLDO procedure take off without other aircraft between them, this latter consideration can mean that the controller will shorten the route for all of these aircraft, or none of them. Controllers generally find it easier to keep such a succession of departures on the same general route and maintain their spacing with speed control if necessary, rather than compensate for one aircraft in the set that is flying a route different from the rest.

While saving less distance, short cuts are sometimes granted to aircraft in Zone B, allowing aircraft to bypass JOLEN and/or PAXTN. While the separation considerations pertinent to Zone A short cuts are equally relevant here, arrivals from the southeast corner of D10 can impact the decision for a short cut. Shortening the route for a SOLDO departure in this case can decrease the time that the aircraft spends beneath the arrival stream, and therefore allows the departure to commence its climb from 10000 feet sooner than if it had been left on the route.

Lastly, the proper sequencing of departure aircraft from other D10 airports can impact if and when SOLDO departures receive short cuts. In this case, it's a matter of providing the proper miles in trail between aircraft as they enter ARTCC (ZFW) airspace. This must take into account not just the RNAV departures crossing SOLDO, but also the RNAV departures that might be on parallel routes over TRISS and CLARE, and non-RNAV departures using the same boundary fixes, in particular DAL departures.

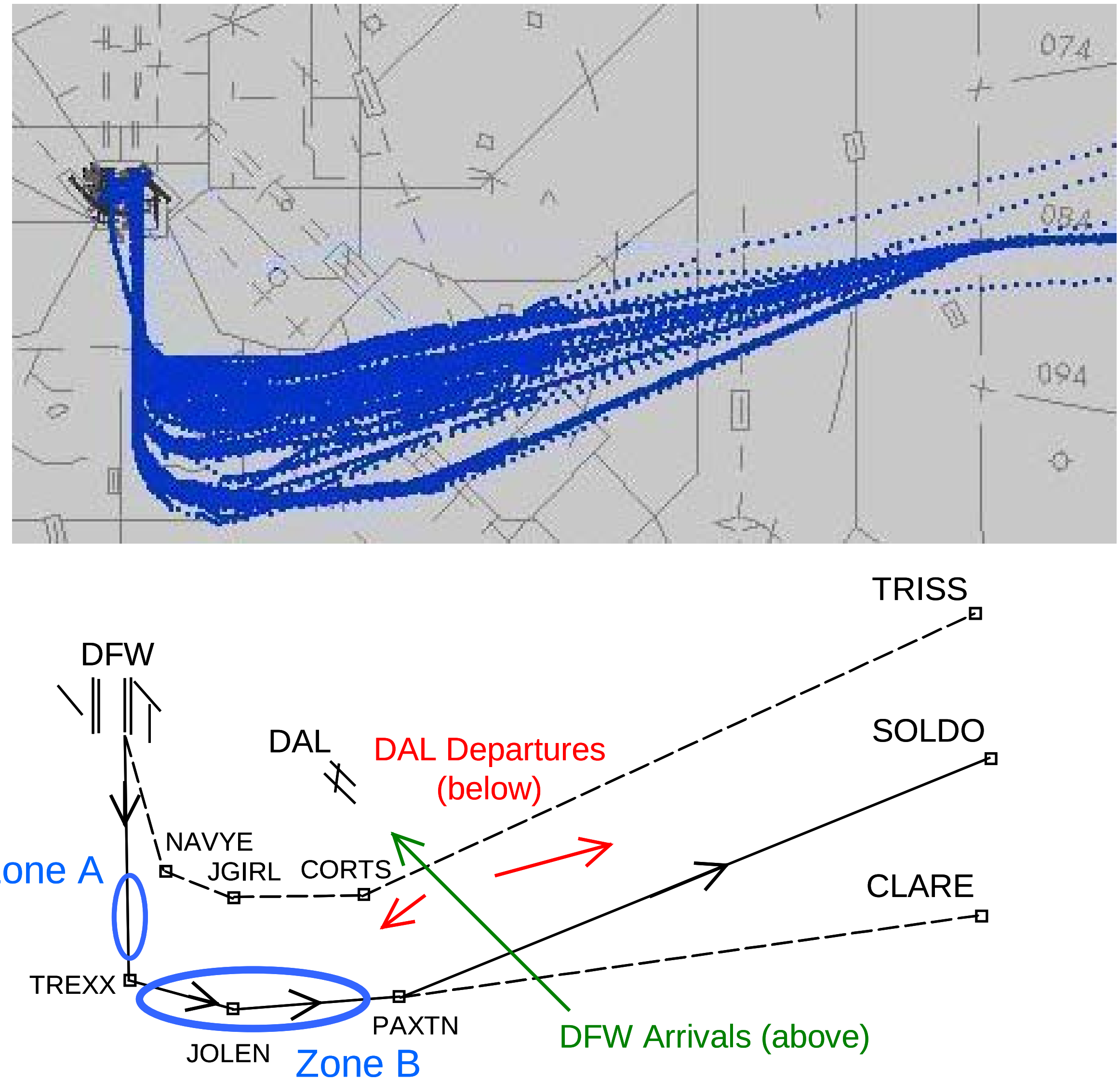

Figure 8. Possible Considerations for SOLDO Short Cuts, South Flow

D. Discussion and Final Attempt at Modeling Occurrences of Short Cuts

The initial study showed that a short cut prediction model that relies solely on the number of DFW and DAL departures and arrivals was poor. Unfortunately, several of the factors that controllers identified as the major drivers for their decision to grant short cuts are subjective characteristics and therefore are not easily quantifiable for the purpose of statistical analysis. Thus the authors decided to include one more quantifiable parameter, aircraft weight class, to the last model evaluated. As weight class drives allowable aircraft separation, the controllers frequently mentioned this as a factor that they considered in granting short cuts that was not directly reflected in the past analyses. Aircraft weight class was converted to its equivalent separation requirement of nautical miles in trail, that is, a weight class of Large (L) corresponded to a 3, B757 corresponded to 4, and a Heavy (H) weight class corresponded to 5.

A sensitivity analysis was performed with this revised model. As shown on the factors contribution chart on Fig. 9, the separation requirement (Sep-req) is a negligible factor as its contribution is less than 18 times the contribution of the main contributing factor of DFW_dep_5-0_pr (DFW departure 5 to 0 min prior to the departure of interest). Therefore the inclusion of the separation requirement parameter did not yield any noticeable improvement to the prediction model.

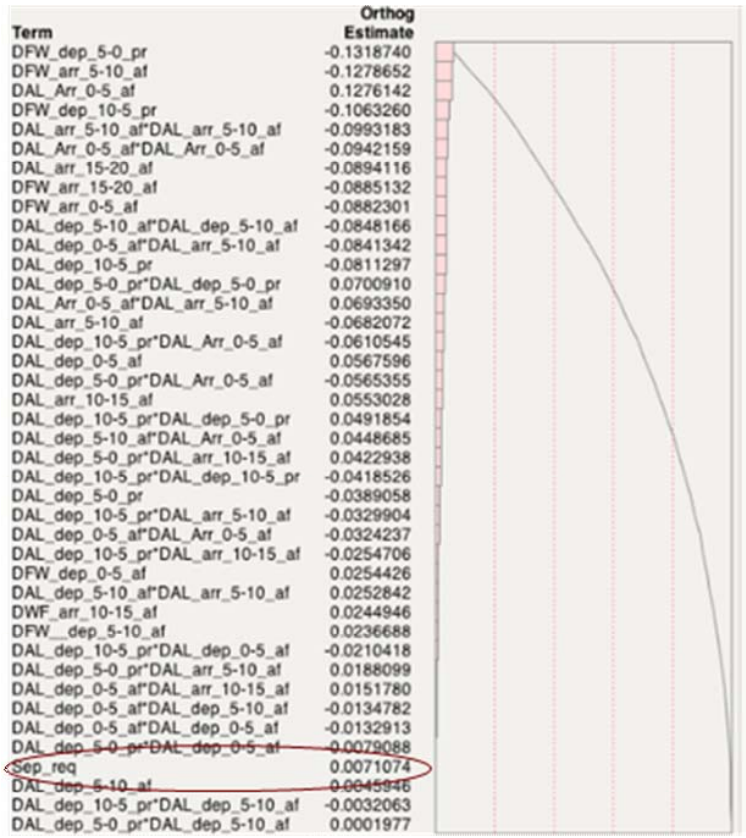

Figure 9. Contributions to SOLDO Short Cuts, Including Separation Requirement

The interviews and the analysis of the controllers' responses confirmed the belief that the factors that drive a controller's decision to grant a short cut are mainly subjective. In fact, one of the few questions where the interviewees unanimously agreed on the answer was that taking an aircraft off its filed RNAV departure procedure to shorten its route increases the controller's workload, both because of the need to more closely monitor aircraft separation away from the defined route and because of additional verbal communication. Regarding the latter, the controllers' additional transmissions would have to include when and how the pilot is to alter the route of the departure, the reason for the change, and when and how the aircraft is to rejoin the original route. The number of short cuts nonetheless granted indicates that this perceived increase in workload must be tolerable in many cases.

The subjectivity of controllers' approach to initiating short cuts is well illustrated in some of the comments gathered during the interviews. One of the test subjects stated, "I would only initiate a short cut if it feels right." Another stated: "I like giving a short cut, because helping pilots makes them feel like I've given them a favor." Throughout the interviews, some of the major factors driving the controllers' decisions in these cases are likely subjective ones, such as the controller's: personality and general mood, overall feeling about the situation, experience level, et cetera. Unfortunately, all these important factors are not quantifiable, and therefore cannot be used in the building of a prediction model.

The subjectivity of controllers' decision to short cut can be demonstrated through their responses to possibly granting a short cut based on the radar track screen shot scenarios. A simple correlation value was calculated based on the numerical value of the answers (as explained in Section V.A) between controller A and controller B for the three interview sessions; this is summarized in Table 4.

Table 4. Correlation Between Controller A and B Short Cut Decisions

Session	Correlation
Set 1	0.91
Set 2	0.70
Set 3	0.83

The correlation value in Table 4 shows no overwhelming consensus in controllers' answers. As an example, in the case of set 2, the correlation is a mere 0.70, which is a weak correlation. When all the responses are merged into their corresponding groups, the correlation value between Group 1 and Group 2 is 0.83. In contrast, a strong correlation would have ranged from 0.85 to 1.0, the latter meaning 100% agreement between the groups A and B.

Finally, the average of the numerical short cut decisions from the two groups of controllers were calculated. Based on what actually happened in the real-life radar track data, that is whether or not the tracks indicated a controller-initiated short cut or not, an equivalent average was determined for the scenarios. The correlation between the interviewees' short cut decisions and the actual execution of short cuts was 0.67. As disclaimers, the low correlation value of 0.67 also emphasizes the limitations of using a static screen shots to represent the highly dynamic and complex airspace environment. It is also impossible to know whether or not the controller in the actual cases recorded regretted his or her choice of granting a short cut. A more meaningful correlation could be determined with human-in-the-loop simulation, which is beyond the scope of this investigation.

Coupling this analysis with the previous questionnaire and scenario discussions, the key element missing from the model is the actual decision-making process of the controllers when they are directing departure traffic. This challenge would be a key feature of any future modeling effort, and would require a larger data collection effort involving a larger number of controllers as well as a wider sampling of traffic. Other modeling techniques would have to be evaluated, possibly to include forms of artificial intelligence, to determine likely conditions for short cuts. Justification for such an expanded effort, though, would also mean that other airports that use RNAV departures would need to be included, and would involve studies of the other factors that influence efficient departure procedures. The impact that vectoring departures away from RNAV routes has on airspace operations would need to be quantified, in addition to determining its beneficial or detrimental effect.

VI. Conclusions

This paper shows the difficulty in constructing a statistical model that consistently predicts the issuance of RNAV departure short cuts using air traffic data alone. While this investigation has outlined some of the reasons a controller might choose to short cut the path that an aircraft using an RNAV departure procedure flies, it also indicates that this is a highly subjective controller decision. In short, the short cut decision is a matter of controller technique in solving the complex problem of departure sequencing while providing safe service. Although the prediction model constructed in this investigation captured some of the factors that drive a controller's decision to shorten a route, such as the inverse impact of heavy traffic on the likelihood of a short cut, a more accurate prediction model would call for a more complex development using models of controllers, or even human-in-the-loop simulation to understand the variety of ways controllers would respond to a myriad of departure traffic scenarios. The controllers' decision-making process in vectoring departure traffic while maintaining safe and efficient operations would have to be understood and quantified.

Extrapolating this work to the broader context of super density operations, advanced air traffic control concepts must allow for operational flexibility and account for a variety of off-nominal situations. Controllers need to have options available, through turns, speed, and altitude changes, to modify procedures when necessary to account for off-nominal conditions.

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