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Assessing the Benefits of NextGen Performance Based Navigation (PBN)

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***Abstract*—The Next Generation Air Transportation System, or NextGen, is the ongoing transformation of air traffic control technologies and procedures in the United States. Two key components of NextGen are Performance Based Navigation (PBN) and the Optimization of Airspace and Procedures in the Metroplex (OAPM). PBN leverages state-of-the-art navigation technologies, such as satellite-based Area Navigation (RNAV) and Required Navigation Performance (RNP), to improve airport access, shorten flight paths, and increase en route efficiency. OAPM is a systematic and expedited approach to implementing PBN procedures and airspace changes.**

The Federal Aviation Administration (FAA) is seeking to quantify the benefits of PBN. The approach is to identify all PBN benefit mechanisms, develop explicit models capturing those mechanisms, and conduct simulations to quantify their impacts under representative operating conditions. In support of this effort, we investigated the throughput impact of implementing PBN to mitigate metroplex inefficiencies. Metroplex inefficiencies identified in this study involved individual or multiple airports, typically occurred in the terminal airspace domain, and impacted both departures and arrivals. PBN capabilities included RNAV Standard Instrument Departure (SID) and Standard Terminal Arrival (STAR) procedures, and RNP Approval Required (AR) final approach procedures.

The investigation included simulations to evaluate the throughput impacts of RNAV SIDs or STARs in addressing metroplex inefficiencies. We formulated simple, generic queuing system-based models of the baseline SIDs or STARs capturing the inefficiency, and the RNAV SIDs or STARs mitigating the inefficiency. We then extended the models to represent instances in the Northern California metroplex. Results show that RNAV SIDs and STARs demonstrated significant increases in throughput compared with baseline SIDs and STARs, particularly at saturated traffic demand levels. This paper describes the modeling assumptions, methods, and results including the quantitative throughput impacts and their sensitivity to traffic level, traffic distribution, and the in-trail separation minima.

Keywords-performance-based navigation; arrival, departure operations; metroplex; NextGen

I. INTRODUCTION

NextGen, is the ongoing transformation of air traffic control technologies and procedures in the United States. Two key components of NextGen are PBN and the OAPM. PBN leverages state-of-the-art navigation technologies, such as satellite-based RNAV and RNP, to improve airport access, shorten flight paths, and increase en route efficiency [1]. OAPM is a systematic and expedited approach to implementing PBN procedures and airspace changes. According to the Joint Planning and Development Office (JPDO), a metroplex is defined as a collection of two or more adjacent airports whose arrival and departure operations are highly interdependent [2].

This analysis investigated the potential throughput impact of implementing PBN to mitigate metroplex inefficiencies. The metroplex inefficiencies investigated involved multiple and individual airports and occurred in the departure, metering/descent and final approach phases of flight. To begin, we conducted a literature review in order to understand the breadth of metroplex-related inefficiencies; their potential mitigations via the design of RNAV SIDs, RNAV STARs and RNP AR procedures; PBN mitigation mechanisms; and the extent data quantifying the mitigation level. The RNAV mechanisms for mitigating metroplex inefficiencies identified by the literature review included decoupling STAR entry and SID exit fixes, SIDs and STARs with additional en route transitions, parallel offload STARs, and reduced in-trail spacing minima along SIDs and STARs. The literature contained only a patchwork of previous analyses quantitatively assessing the throughput impact of RNAV in mitigating each metroplex inefficiency. Therefore this work conducted a comprehensive modeling- and simulation-based evaluation of the throughput impacts of RNAV. First, explicit queuing system models of baseline and RNAV SIDs and STARs were developed to capture each metroplex inefficiency and its RNAV mitigation mechanism. Second, simple, generic models of the baseline and RNAV SIDs or STARs in each inefficiency case were evaluated to understand the influence of operational variables on the SID/STAR throughput impact of RNAV. Third, the models were extended to represent documented inefficiencies in the Northern California metroplex and candidate RNAV-enabled mitigations. Modeling was supported by analyzing current-day flight tracking and route data to characterize the inefficiencies and to derive modeling parameters for simulation. Fourth, simulations were conducted to quantify the throughputs of baseline and RNAV SIDs and STARs under ranges of traffic demand and, in some evaluations, levels of RNAV-capable traffic. In the simulations, the RNAV SIDs and STARs demonstrated significant increases in throughput, particularly at saturated traffic demand levels, across the range of inefficiencies. However, RNAV throughput impacts may only be realized to the extent that airport or airspace capacity is available upstream or downstream of the SID or STAR.

This paper is organized as follows. Section II summarizes the results of the literature search of metroplex operations and proposed applications of PBN to mitigate them. Section III presents an approach to modeling metroplex SID/STAR inefficiencies and RNAV SID/STAR mitigations. Section IV summarizes the findings from assessing simplified, generic models of each metroplex inefficiency and RNAV-enabled mitigation. Section V presents assessments of specific inefficiencies in the Northern California metroplex. Section VI provides concluding remarks.

II. LITERATURE REVIEW

We reviewed previous research on metroplex inefficiencies and PBN implementation. The literature review identified a broad range of metroplex inefficiencies and PBN mitigation mechanisms. However, the review also found a lack of data quantifying the throughput impacts of the proposed PBN mitigations across the breadth of metroplex inefficiencies, thus motivating our work.

The FAA's current vision for PBN applicability in U.S. domestic airspace calls for different aircraft navigation capabilities by flight phase: RNAV 1 SIDs for departure, RNAV 2 Q- and T-Routes in cruise, RNAV 1 STARs for metering/descent, and RNP AR for final approach [3]. RNAV 1 employs aircraft area navigation capability to track a lateral path independent of ground-based navigational aid locations with 1 nmi lateral precision 95 percent of the time along the path [4][5][9]. RNAV 2 Q- and T-routes employ aircraft area navigation capability with 2 nmi lateral precision. Q Routes are high-altitude airways [6]. T routes are low-altitude airways, typically around/through busy terminal areas [7]. RNP ARs employ aircraft precision navigation capability to navigate to a specified lateral or vertical navigation precision, real-time flight deck conformance monitoring and control, and aircraft radius-to-fix curved path navigation capability [5][8][9].

The FAA's OAPM is a multi-year effort assessing RNAV and RNP implementation at key metroplexes across the National Airspace System (NAS) [10]. We reviewed OAPM reports for the Washington, D.C. [11], Charlotte [12], Houston [13], North Texas [14], and Northern California [15] metroplexes. From the OAPM reports and from other published literature concerning metroplex inefficiencies and the implementation of PBN procedures, we identified key inefficiencies and RNAV SID and STAR designs proposed to mitigate them.

Our review of prior studies of RNAV mitigations for metroplexes revealed the following possibilities:

1. RNAV STARs to decouple fixes, routes or airspace shared with other SIDs or STARs; RNAV STARs with additional en route transitions; RNAV STARs permitting reduced in-trail separation minima between successive arrivals; and parallel RNAV STARs to relieve existing overloaded STARs.
2. RNAV SIDs to decouple fixes, routes or airspace shared with other SIDs or STARs; RNAV SIDs with additional en route transitions; and RNAV SIDs permitting reduced in-trail separation minima between successive departures.

Our review of the RNAV STAR mitigations for metroplexes found the following. Regarding decoupling STARs sharing arrival fixes, routes or airspace with other SIDs or STARs, simulations of generic and New York metroplex models in [16] evaluated the impact of coordinated scheduling versus RNAV route-based decoupling of multi-airport arrival flows. They showed that the decoupled inner arrival route structures for eight New York metroplex airports described in [17] reduced the average flight delay by varying amounts for seven of the airports under a representative traffic demand. Simulations in [18] showed that decoupling fixes shared by two airports in a metroplex reduces arrival delay at low, medium and high traffic demand levels. However, the flight delay reduction is greater for the lightly trafficked metroplex airport, which no longer has to bear the flight delays of the other heavily trafficked metroplex airport. Simulations in [19] evaluate dynamically scheduling or decoupling multi-airport traffic flows to minimize flight delay. They show that decoupling may reduce flight delay, however generally requires longer flight routes, and the flight delay impact of either strategy is sensitive to in-trail separation minima at runways and route points. Regarding additional STAR en route transitions, cursory simulations in [20] show arrival flight delays are sensitive to the capacities of the arrival fixes serving the airport, suggesting increased capacity via additional transitions could be beneficial. Regarding reduced in-trail arrival separation minima, analysis in [21] of Las Vegas airport (KLAS) arrivals via RNAV STARs showed reduced inter-arrival spacing variance at the meter fixes and runway threshold. Simulations in [22] showed similar results. Simulations in [23] and [24] showed airport arrival throughput increases with smaller spacing buffers permitted by reduced inter-arrival time spacing variance. Regarding parallel offload STARs, they may permit balancing traffic to parallel runways. Analysis of Dallas/Fort Worth airport (KDFW) arrivals in [25] showed Traffic Management Advisor-enabled runway balancing increased the AAR from 108 to 118 under Instrument Flight Rules (IFR) and from 116 to 132 under Visual Flight Rules (VFR).

Our review of the RNAV SID mitigations for metroplexes found the following. Regarding SIDs sharing arrival fixes with other STARs or SIDs, simulations in [26] show that metroplex-wide departure scheduling of shared fixes use increases throughput. This suggests significant flight delay reductions can be achieved by decoupling the traffic flows. Regarding additional SID en route transitions, simulations in [20] show that, as with arrivals, departure flight delays are sensitive to the capacities of the departure fixes, and suggest additional en route transitions could be beneficial. Regarding reduced in-trail departure spacing minima, analyses in [27] of departures at KDFW and Hartsfield-Jackson Atlanta airport (KATL) show RNAV SIDs permit lesser in-trail versus radar inter-departure spacing, thereby increasing departure throughput. The sensitivity of throughput to departure traffic RNAV equipage level depends on the airport operating procedures, and ranges from invariant to somewhat sensitive. Simulations in [12] of Charlotte/Douglas airport (KCLT) departures show closer SID divergence points permit reduced inter-departure times for certain flight pairs.

The work reported here sought to quantify the throughput impacts of RNAV SIDs and STARs on metroplex operations, but we desired a more methodical examination. Therefore we conducted a comprehensive modeling- and simulation-based evaluation of baseline metroplex inefficiencies and the proposed RNAV SID- and STAR-based mitigations to assess their throughput impacts. The throughput impacts were assessed on a SID/STAR basis; that is, how much more traffic the RNAV SID or STAR could accommodate over the baseline SID or STAR by mitigating the particular inefficiency. However, we note that the RNAV throughput increases may only be realized to the extent that airport or airspace capacity is available upstream or downstream of the SID or STAR.

III. ASSESSMENT APPROACH

We employed a queuing system-based approach to model the baseline SID or STAR capturing each metroplex inefficiency, and the RNAV SID or STAR capturing the proposed mitigation mechanism. A queuing system comprises a user source, a queue, and a service facility [28]. For each metroplex inefficiency, models of the baseline and RNAV-enabled SIDs or STARs were constructed and evaluated in custom simulations to quantify the potential for throughput increase.

A SID or STAR was represented as a queuing network with queuing systems at its entry point(s), diverge or merge point, and exit point(s). Each queuing system was represented as a service rate. Queue length constraints were not represented. The queuing systems were connected by the en route transitions and common route of the SID or STAR. Each model captured the structure and parameters particular to the SID or STAR. We applied the technique to model a baseline SID or STAR exhibiting a specific inefficiency, and the RNAV SID or STAR mitigating the inefficiency.

Figure 1 depicts the abstracted physical model and queuing model for a STAR. The physical model includes entry fixes F_1 and F_2, merge fix F_3, exit fix F_4, en route transition legs L_1 and L_2, common route leg L_3, and traffic demand D_1 and D_2 to each entry point. The queuing system model captures the demand rate D at each entry point, the service rate S at each point, and transit time T along each leg.

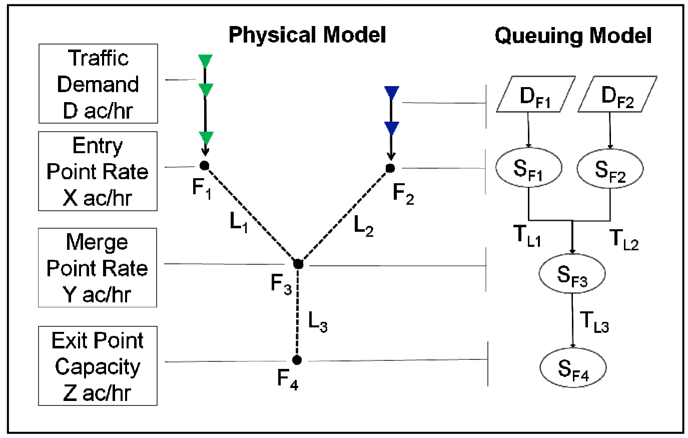

Figure 1. Simplified Generic STAR Physical and Queuing Models.

As one example, we applied this modeling approach to the metroplex inefficiency of two STARs sharing a common entry fix. Figure 2 presents the baseline and RNAV STARs. The entry points to the baseline STARs share a common fix F_2. The RNAV STARs have additional, separate fixes F_8 and F_9 for RNAV capable aircraft, however retain common fix F_2 for aircraft that are not RNAV capable.

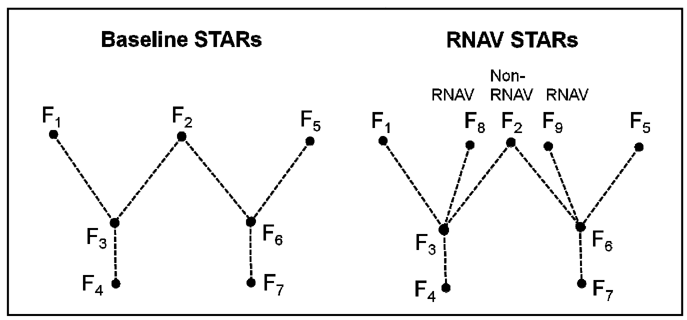

Figure 2. Physical Models of Baseline STARs with Shared Fix and RNAV STARs With Decoupled Entry Fixes.

Figure 3 presents the queuing system network models of the baseline and RNAV STARs. The baseline model has servers at the entry points F_1, F_2 and F_5, merge points F_3 and F_6, and end points F_4 and F_7. The RNAV model has servers for additional fixes F_8 and F_9.

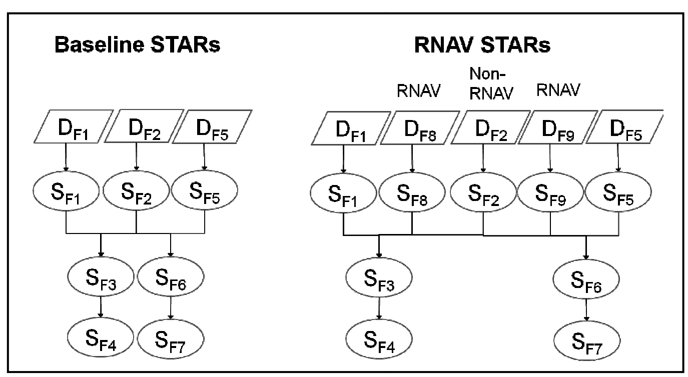

Figure 3. Queuing Models of Baseline STARs with Shared Fix and RNAV STARs With Decoupled Entry Fixes.

In this manner, equivalent physical and queuing system models were constructed for the baseline SIDs or STARs capturing each metroplex inefficiency and the RNAV SIDs or STARs capturing the inefficiency mitigation mechanism. The baseline and RNAV SIDs or STARs models were evaluated in custom simulations to assess the throughput impact of RNAV in mitigating each metroplex inefficiency. Generic, simplified models were evaluated to understand the RNAV mechanisms for inefficiency mitigation and the influence of environmental variables on the level of mitigation. Models of specific instances in the Northern California metroplex were evaluated to estimate the throughput impact of RNAV in a real metroplex.

The metric for assessing each inefficiency and its RNAV-enabled mitigation was SID or STAR throughput. Throughput was computed as the number of aircraft exiting the SID or STAR, divided by the difference between the exit times (in minutes) of the first and last aircraft. In turn, throughput was expressed as a percentage of the capacity of the SID or STAR impact point. The impact point was designated as the point underused due to the upstream or downstream constraint eliminated or reduced in the RNAV SID or STAR. For instance, an additional RNAV en route transition permits greater use of the STAR merge point capacity or SID diverge point capacity.

The following sections present the methods for, and results of, evaluating generic and Northern California metroplexes models.

IV. GENERIC MODEL ASSESSMENTS

The generic SID and STAR models had two en route transitions and one common route. The assessments used 50 aircraft per hour as the capacity of each generic SID/STAR en route transition exit/entry fix, corresponding to 5 nautical mile in-trail distance separation between aircraft transiting at 250 knots, for an inter-flight time spacing of 72 seconds. The assessments used 100 aircraft per hour as the capacity of the generic SID/STAR merge/diverge point and entry/exit points. While this value was high, it was equivalent to the collective capacity of the en route transitions, which served to highlight other variables impacting throughput. Traffic was assumed 100 percent RNAV capable, and demand level was varied from fractionally loaded to saturated relative to SID/STAR merge/diverge point capacity. The distribution of SID/STAR traffic demand across its en route transitions was also varied between evenly and unevenly distributed conditions.

An example is the baseline condition of two metroplex airports' STARs sharing a common entry fix and the RNAV routes decoupling them. Figure 4 shows the throughput of each STAR in the baseline and RNAV conditions for two different traffic loads to the shared entry point: 50 percent of each STAR's traffic and 75 percent of each STAR's traffic to the shared entry point. In the results, the throughput profiles of STAR 1 and STAR 2 overlay one another because they use equivalent models and parameters.

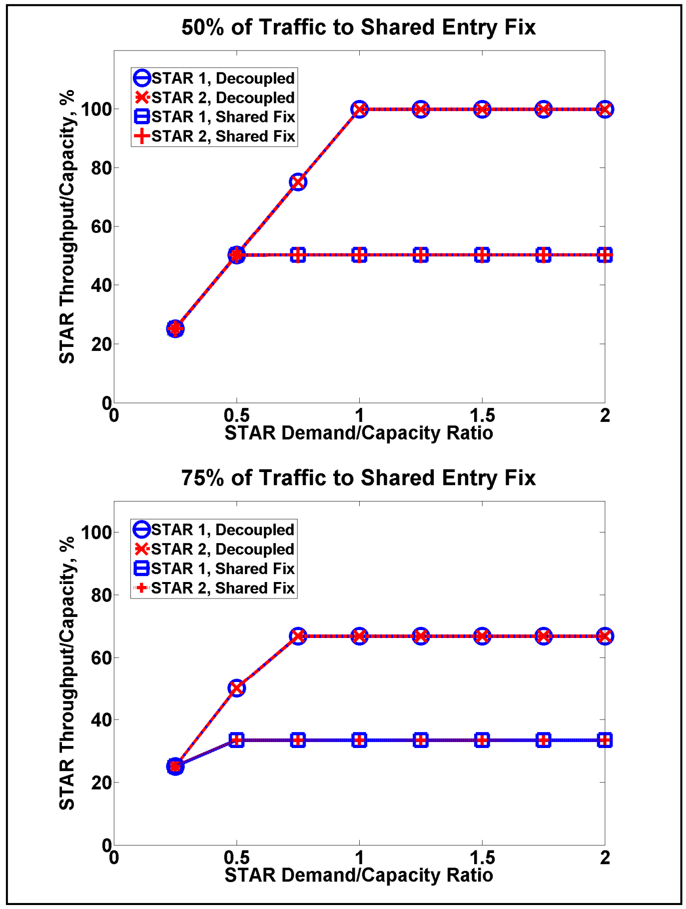

Figure 4. Throughputs of STARs for Baseline Shared and RNAV Decoupled Entry Fix.

The results show that separating the traffic flows increased the throughput of each STAR, as expected. The throughput is sensitive to the traffic demand to the shared entry fix. With 50 percent of each airport's traffic to the shared fix, the results show the maximum throughput of each airport's STAR increases from 50 percent to 100 percent of the STAR's merge point capacity at traffic demand levels equal to or greater than that capacity. With 75 percent of each airport's traffic to the shared fix, the results show the maximum throughput of each airport's STAR increases from 33 percent to 67 percent of the STAR's merge point capacity at traffic demand levels equal to or greater than that capacity. In the latter case, the entry point capacity limited the throughput of the baseline and RNAV STARs.

In this manner, simple, generic models of each baseline inefficiency and RNAV-enabled mitigation were evaluated. For each inefficiency, we found the RNAV routes exhibited increased throughput, however the amount of increase was sensitive to traffic level, the distribution of SID/STAR traffic among its en route transitions, and the in-trail separation minima values and their ratios between the SID/STAR entry, diverge/merge, and exit points.

In turn, the simple, generic SID/STAR models were extended to capture specific baseline and hypothetical RNAV SIDs and STARs in the Northern California metroplex for each type of metroplex inefficiency and associated RNAV mitigation mechanism. The Northern California metroplex was selected for analysis based on our review of the OAPM reports for the five metroplexes [11][12][13][14][15], which found the Northern California metroplex had the greatest breadth of inefficiencies in the metering/descent and final approach flight phases, and had key inefficiencies in the descent flight phase.

V. Northern California Metroplex Assessments

This section describes the assessment of baseline and RNAV SIDs or STARs for each metroplex inefficiency type documented in [15] to occur in the Northern California metroplex. Each model was evaluated for a range of traffic levels, and, in certain cases, for a range of RNAV equipage, to capture the range of potential impact. Detailed results of shared fixes and insufficient en route transitions, and summary results for all metroplex inefficiencies and RNAV SID/STAR mitigations, are presented.

Data were analyzed to specify model parameters and to characterize baseline operations. Source data included: FAA Aviation System Display to Industry (ASDI) flight tracking and flight plan data from January 1 2009 to January 25 2009, and FAA National Flight Data Center (NFDC) database STAR/SID data from February 9 2012 to April 5 2012. Each track was estimated to transit the SID/STAR route with waypoints of closest lateral proximity to the track. Service time intervals at the SID/STAR entry, merge/diverge and exit fixes were estimated as the 5th percentile of the inter-flight time spacing distribution at the fix, as was done in [24]. To ensure reasonable values, the service intervals were bounded by minimum and maximum values. The minimum value of 1 minute corresponded to 3 nautical miles in-trail separation at 180 knots, a rule-of-thumb value used in [16]. The maximum value of 10 minutes was the standard longitudinal spacing for en route and terminal environments where lateral and vertical separation methods are not available [29]. Inter-fix transit times for a SID/STAR route segment were estimated as the mean of the transit times among the tracks. The distribution of SID/STAR traffic among its en route transitions was estimated as the number of flights crossing each exit/entry fix divided by the SID/STAR route traffic counts.

A. *Shared Fixes*

For the Northern California metroplex, [15] recommends segregating the San Francisco airport (KSFO) MOD, Oakland airport (KOAK) MADN and San Jose airport (KSJC) HYP STARs at shared entry fix Coaldale (OAL). Figure 5 depicts the three STARs and their shared entry fixes FMG, MVA and OAL. MVA is shared only by KSFO MOD and KOAK MADN. Visualization of the baseline STARs, shown in Fig. 5, is provided by the Terminal Area Route Generation, Evaluation, and Trajectory Simulation (TARGETS) software [30].

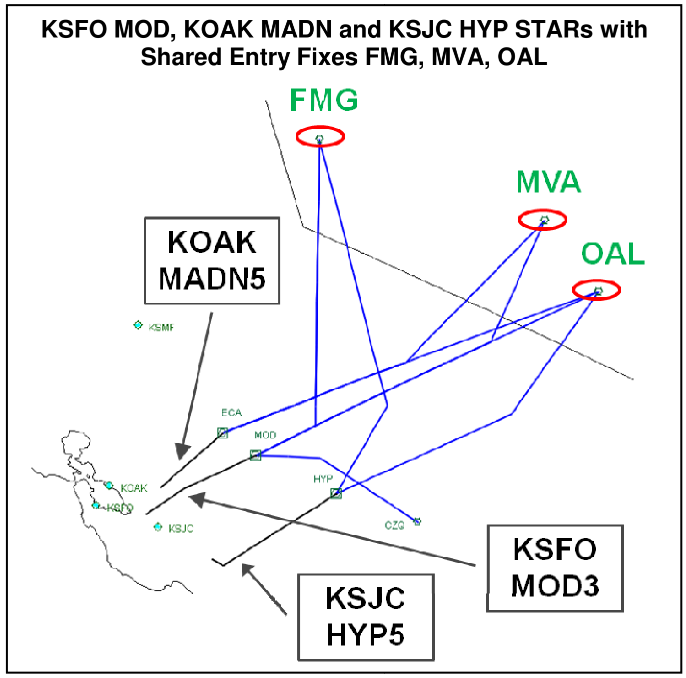

Figure 5. Northern California Metroplex STARs with Shared Entry Fixes.

Prior to conducting simulation assessments, we analyzed data to verify the traffic flows interacting at the entry fixes. First, the quantity of traffic to each airport which crossed the shared fixes was analyzed. The results in Figure 6 show for fix OAL the traffic comprised 54 percent KSFO MOD, 27 percent KOAK MADN and 19 percent KSJC HYP arrivals. Fix OAL traffic was found to comprise 19 percent of KSFO arrivals, 18 percent of KOAK arrivals, and 14 percent of KSJC arrivals.

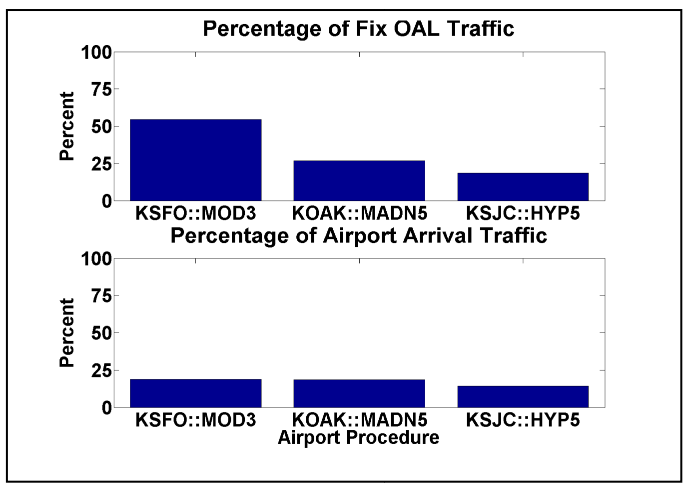

Figure 6. Composition of Shared Entry Fix OAL Traffic.

Second, the traffic altitude and temporal distributions at fix OAL were analyzed. The results depicted in Figure 7 show that the aircraft from each airport which crossed fix OAL significantly overlapped in altitude between FL320 and FL400 and crossed in coincident hour time periods. Thus the traffic flows exhibited some coupling, likely requiring that the aircraft from each airport be sequenced with one another prior to crossing entry fix OAL.

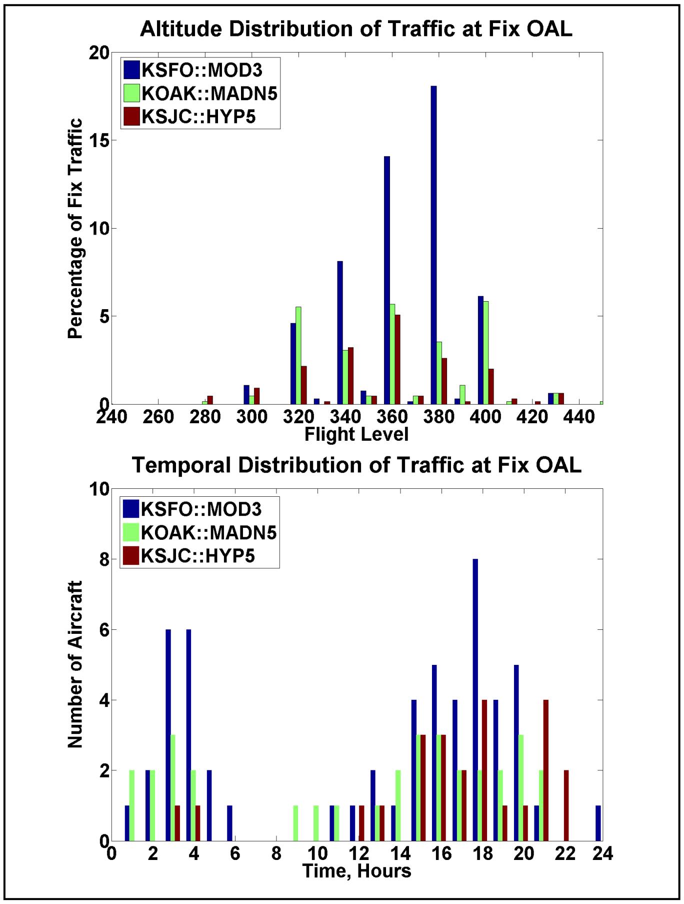

Figure 7. Distributions of Traffic at Shared Fix OAL.

For the simulation assessments, we modeled the baseline KSFO MOD, KOAK MADN and KSJC HYP STARs with shared entry fixes FMG, MVA and OAL, and modeled hypothetical RNAV STARs with decoupled entry fixes FMG-1, -2, -3; MVA-1, -2; and OAL-1, -2, -3.

Simulations evaluated the throughput of the three STARs at increasing traffic levels in the baseline shared fixes configuration, and in the RNAV-enabled configuration of completely decoupled fixes, with 100 percent of traffic RNAV capable. Figure 8 shows the throughput of each STAR as percent of its merge point capacity.

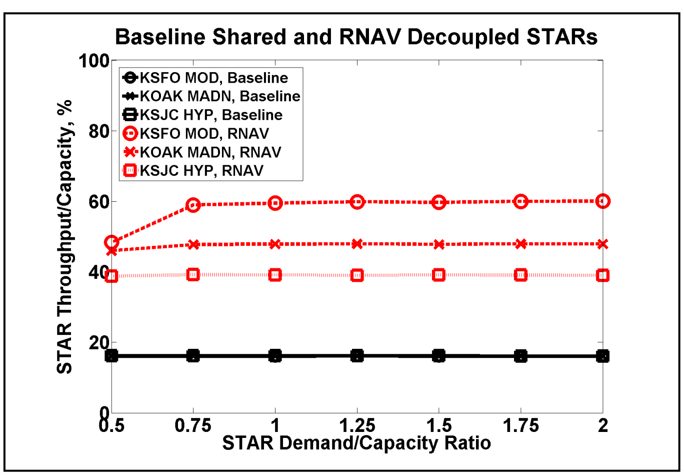

Figure 8. Throughputs of STARs with Baseline Shared and RNAV Decoupled Entry Fixes.

The results show in the baseline condition the throughput of each STAR is 16 percent of its merge point capacity. With the decoupling of the STARs at entry fixes FMG, MVA and OAL, the throughput of the STARs increases markedly at saturated traffic demand levels. The respective throughputs of KSFO MOD, KOAK MADN and KSJC HYP increase to 60, 48, and 39 percent of their respective merge point capacities. Additional simulations conducted with each STAR's traffic evenly distributed among its en route transitions, and with reduced inter-flight time spacing at some entry points, demonstrated even greater throughput impacts. Thus, separating STAR entry points may significantly impact STAR throughput.

B. Insufficient En Route Transitions

For the Northern California metroplex, [15] proposed to redesign the KOAK MADN STAR as an RNAV STAR with one additional en route transition.

Prior to conducting simulation assessments, we analyzed data to determine the distribution of KOAK MADN traffic among its three en route transitions' entry fixes FMG, MVA and OAL. The results in Figure 9 show OAL carries 72 percent of KOAK MADN traffic, while FMG and MVA carry 21 and 7 percent, respectively. Thus, OAL is a candidate for traffic redistribution to the additional en route transition.

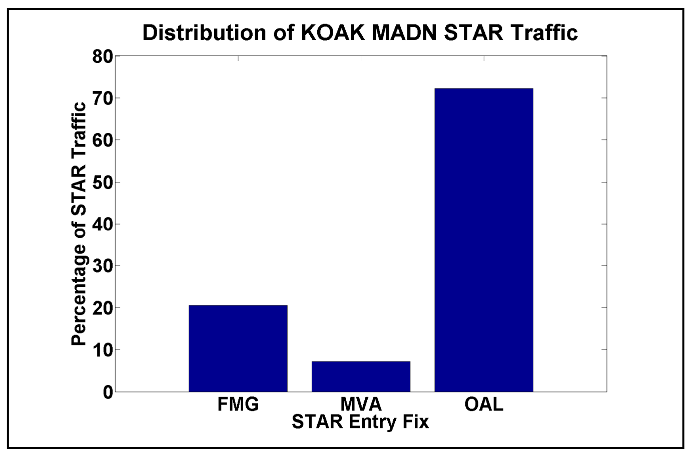

Figure 9. Distribution of STAR Traffic.

For the simulation assessments, we modeled the baseline KOAK MADN STAR capturing its three en route transitions and their shares of KOAK MADN traffic, and modeled a hypothetical RNAV STAR, depicted in Figure 10, having additional en route transition OAL-2 for RNAV capable aircraft.

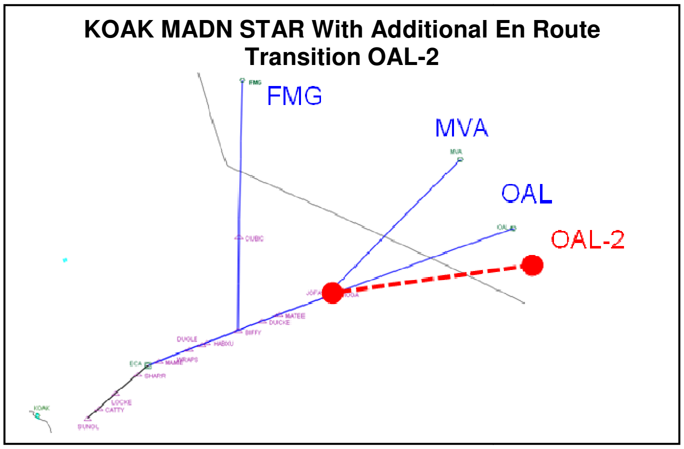

Figure 10. Hypothetical KOAK MADN RNAV STAR.

Simulations evaluated the KOAK MADN STAR throughput at increasing traffic levels. At each traffic level, increasing RNAV equipage levels were represented by increasing the fractions of OAL traffic apportioned to OAL-2. Figure 11 shows, for each demand and RNAV equipage level, the STAR throughput as a percentage of its merge point capacity.

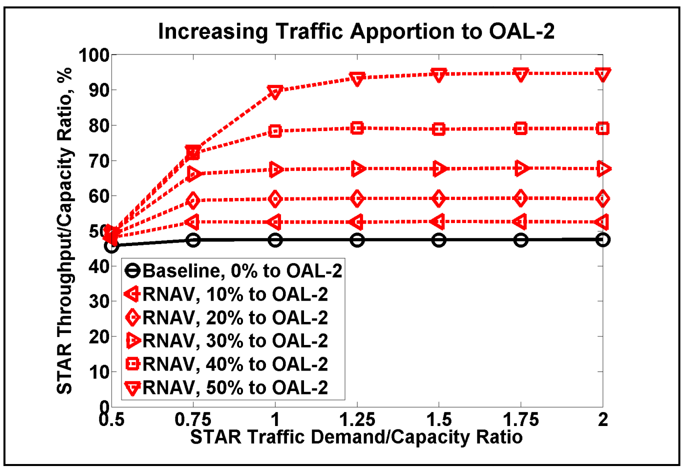

Figure 11. Throughput of STAR with Additional En Route Transition OAL-2.

The results indicate that, in the baseline condition, KOAK MADN throughput is limited to less than 50 percent of its merge point capacity. With the introduction of en route transition OAL-2, KOAK MADN throughput increases to almost 100 percent of the merge point capacity at saturated demand levels as the traffic apportioned from OAL to OAL-2 increases from 10 to 50 percent. Thus, introduction of additional en route transitions may have a significant impact on STAR throughput at even fractional levels of traffic RNAV capability.

C. Results Summary

In this section we summarize the results of assessing the throughput impact of RNAV SIDs and STARs in the Northern California metroplex. Results are presented for saturated traffic levels to capture the maximum possible benefit. Results assume 100 percent of traffic RNAV-capable unless otherwise stated.

Table I summarizes the results for RNAV STARs.

TABLE I. THROUGHPUT RESULTS FOR RNAV STARS.

RNAV-Enabled Inefficiency Mitigation	**Modeled STAR**	**Evaluation Condition**	**STAR Capacity Utilization**	
			Baseline	***RNAV***
Arrival Fixes Decoupling	KSFO MOD, KOAK MADN, KSJC HYP	Entry points FMG, MVA, OAL decoupled.	16% (MOD), 16% (MADN), 16% (HYP)	60% (MOD), 48% (MADN), 39% (HYP)
Additional ERTs	KOAK MADN	50% of en route transition OAL traffic allocated to en route transition OAL-2.	47%	95%
Parallel Offload STAR	KSFO MOD, KSFO YOSEM	Traffic demand evenly distributed to both STARs. Baseline traffic distributions among en route transitions.	55%	64%
Reduced In-Trail Spacing	KSFO GOLDN	20% reduction in minimum IFT at entry points FOT, RBG, RBL, FMG and merge point PYE.	60%	74%

The results indicate the RNAV STARs may yield a significant throughput increase over the baseline STARs. For RNAV STARs with decoupled fixes, the throughputs of KSFO MOD, KOAK MADN, and KSJC HYP increased to 60, 48, and 39 percent of their respective merge point capacities, from 19 percent in the baseline condition. For an RNAV STAR with additional en route transition OAL-2, with half of en route transition OAL traffic apportioned to OAL-2 (36 percent of STAR traffic RNAV capable), the throughput of KOAK MADN increased to 95 percent of its merge point capacity. With 43 percent KSFO MOD traffic apportioned to KSFO YOSEM, their total throughput increased to 64 percent of their collective merge point capacities. Evenly distributing traffic across their en route transitions further increased their collective throughput. For an RNAV STAR exhibiting reduced inter-flight spacing variability, analysis of inter-arrival time standard deviation data in [21] and spacing buffer versus inter-arrival time data in [24] indicated the in-trail separation minima at the KSFO GOLDN entry and merge points may be reduced by approximately 20 percent. We determined the resulting KSFO GOLDN throughput increased from 60 to 74 percent of its baseline merge point capacity.

Table II summarizes the results for RNAV SIDs.

TABLE II. THROUGHPUT RESULTS FOR RNAV SIDS.

RNAV-Enabled Inefficiency Mitigation	Modeled SID	Evaluation Condition	SID Capacity Utilization	
			Baseline	*RNAV*
Departure Routes Decoupling	KOAK SLNT, KSFO CUIT	Decoupled entry point REBAS and exit points ENI, RBL, CIC, SAC, LIN.	55% (CUIT), 61% (SLNT)	77% (CUIT), 98% (SLNT)
Additional ERTs	KSFO PORTE	50% of en route transition AVE traffic allocated to en route transition AVE-2.	53%	95%
Reduced In-Trail Spacing	KSJC SJC	Evaluated 12.5% and 30% reductions in IFT at entry point MOONY	39%	45% (12.5% IFT reduction), 58% (30% IFT reduction)

The results indicate the RNAV SIDs may yield a significant throughput increase over the baseline SIDs. For RNAV SIDs decoupled from one another, the throughputs of KOAK SLNT and KSFO CUIT increased to 77 and 98 percent of their respective diverge point capacities, from 55 and 61 percent in the baseline condition in which they share common entry and exit fixes. As an RNAV SID with additional en route transition AVE-2, with half of AVE traffic apportioned to AVE-2 (25 percent of SID traffic RNAV capable), the throughput of KSFO PORTE increased from 53 to 95 percent of its baseline diverge point capacity. With KSJC SJC as an RNAV SID permitting reduced in-trail separation minima between successive departures, a 12.5 percent inter-flight spacing reduction [12] increased SID throughput to 45 percent of the collective capacity of its en route transitions; and a 30 percent reduction [27] increased throughput to 58 percent of total en route transitions' capacity.

VI. CONCLUSIONS

This study included an extensive literature review to summarize the inefficiencies in current-day metroplexes that could potentially be mitigated with PBN, to identify the mitigation mechanisms, and to quantify inefficiency mitigation levels. We identified a broad range of inefficiencies potentially mitigated with RNAV SIDs and RNAV STARs. However, the potential throughput impacts of the RNAV SIDs and STARs had not been comprehensively evaluated for the breadth of metroplex inefficiencies identified.

This study evaluated the throughput impacts of implementing RNAV SIDs and STARs to mitigate metroplex inefficiencies. We employed a queuing system-based approach to model the baseline and RNAV SIDs and STARs for each metroplex inefficiency. In each case, the models explicitly captured the SID/STAR structures and parameters characteristic of the inefficiency and mitigation mechanism. The models were amenable to quantitative assessment in custom simulations.

Our quantitative assessments of individual inefficiencies in the Northern California metroplex found that RNAV SIDs and STARs exhibited increased throughput over the baseline SIDs and STARs in each metroplex inefficiency case. RNAV SIDs and STARs with additional en route transitions showed the greatest throughput increase, from approximately 50 percent to almost 100 percent of the SID/STAR diverge/merge point capacity, and with less than 50 percent of traffic RNAV capable. RNAV-enabled decoupling of SIDs and STARs also exhibited significant throughput increase. Evaluation of simple, generic models helped to demonstrate that SID/STAR traffic distribution across the en route transitions and the ratios of entry, merge/diverge, and exit point service rates influence the level of throughput increase for RNAV SIDs and STARs.

RNAV throughput increases may only be realized to the extent that airport or airspace capacity is available upstream or downstream of the SID or STAR. Future work could include conducting integrated airport-terminal airspace simulations similar to [16] to assess the airport- and metroplex-wide impacts of other RNAV-enabled inefficiency mitigation mechanisms, extending analysis approaches to RNP AR final approach procedures, and continuing to identify and evaluate additional PBN impact mechanisms.

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