AIAA Guidance, Navigation, and Control Conference and Exhibit
16 - 19 August 2004, Providence, Rhode Island

AIAA 2004-5409

Surface-Operation Benefits of a Collaborative Automation Concept

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The predicted growth in air travel demands capacity enhancement in the National Airspace System, and congestion at key airports has been recognized as one of the most prominent future aviation problem areas. With flights operating at limits dictated by operational requirements associated with current airport configurations, airport expansion plans involving addition of new runways and taxiways are being realized to increase the airports' capacities. However, the expansion plans necessarily increase the complexity of the airport configurations, which tends to penalize the efficiency of the system, partially offsetting the capacity-related benefits of the investments. The Surface Operation Automation Research (SOAR) concept has been proposed as a collaborative concept to provide automation for surface-traffic management and the flight deck to enhance the operational efficiency in complex airport environments, thus reversing the penalties to fully realize the capacity benefits sought by the airport expansion plans. Development and evaluation of the SOAR concept is being pursued in a 5-year program. This paper describes the results from an initial evaluation of the concept based on computer simulations of surface traffic at a single airport. Future work will include system-wide evaluation of the concept and human-in-the-loop assessment of the automation technologies.

I. Introduction

THE problem of air traffic growth unmatched by commensurate growth in capacity has been witnessed with the peak summer flight delays prior to the September 11, 2001 terrorist attack. The flight-delay problem has been well documented and recognized by all concerned parties including the Federal Aviation Administration (FAA) and NASA, and the slow down in air travel since the 2001 attack is recognized by all to be a temporary effect. FAA recognizes the capacity problem, and the National Airspace System (NAS) Operational Evolution Plan (OEP) [1] specifically identifies congestion at key airports as one of the domains where the problem is most prominent.

Figure 1 illustrates how the air traffic characteristics change through the three commonly referenced domains: en route, terminal, and surface. The air traffic from the surface through the terminal airspace to the en route airspace resembles a tree structure branching off from the base upwards to its branches. Whereas taxi operations on the surface are confined to the planar surface along predefined runways and taxiways, air traffic in en route airspace enjoys additional degrees of freedom in terms of variable flight levels and the option to deviate from predefined air routes. As a result, the airspace provides more spatial flexibility as it transitions up the domains, permitting operational concepts such as free flight in the en route space to benefit the air transportation community. In the reverse direction, the airspace is increasingly more constrained spatially, and the traffic needs to be more orderly as it operates on the surface to address the funnel effect.

In particular, major airlines practicing hub-and-spoke operations for cost savings were determined to be suffering from major delays at the hub airports [1]. In view of landing and departure rate limits imposed by separation

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requirements, construction of new runways is ultimately inevitable to achieve capacity gain. In addition to the cost of construction, the increase in surface traffic complexity resulting from the airport expansion will incur other indirect costs or penalties that should be taken into consideration. The Surface Operation Automation Research (SOAR) concept [2], [3] has been proposed to provide automation tools for coordinating efficient surface traffic movement. Development and evaluation of the SOAR concept is currently being supported by the NASA Virtual Airspace Modeling and Simulation (VAMS) Project. An evaluation plan of the SOAR concept was provided in [4]. The evaluation was accomplished in 2003 using computer simulations developed for studying taxi operations and surface traffic management (STM) automation [5], and this paper discusses the results from the evaluation.

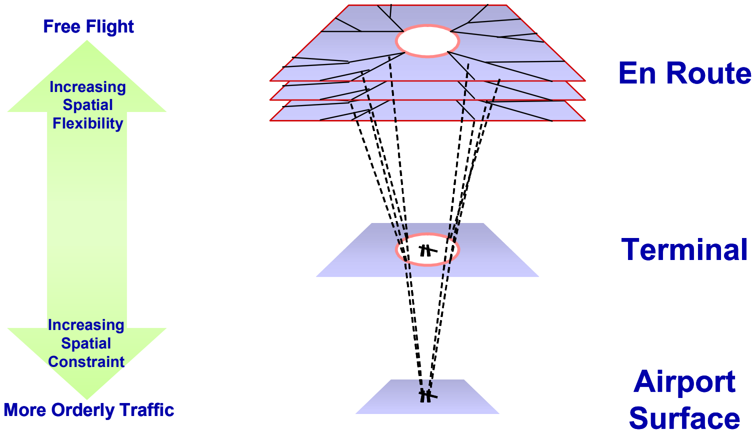

Figure 1. Various Domains of National Airspace

II. Overview of Soar Concept

The SOAR concept introduces advanced automation to the two main environments responsible for surface operation: the ground control environment and the flight deck. This collaborative automation concept will provide maximal performance when these two environments can be tightly integrated in a Centralized Decision-Making, Distributed Control (CDDC) paradigm, as illustrated by the block diagram in Figure 2 describing the roles of the automation components.

The ground-control automation system will provide the centralized decision-making functionality for surface traffic management (STM). It will base its decision on the surveillance data, flight plans and Airline Operational Control (AOC) requirements, to generate time-based taxi routes for optimum traffic efficiency. Advanced data-link will enable the issuance of complex taxi clearances for the flights to taxi according to the desired time-controlled taxi routes and monitoring the vehicles' compliance. The SOAR ATM automation component is based on the *Ground-Operation Situation Awareness and Flow Efficiency* (GO-SAFE) concept described in [5]. The existing experimental GO-SAFE system serves as the foundation for building the ground-control automation system envisioned by the SOAR concept.

The flight-deck automation systems in the aircraft participating in the surface operation will collectively provide the distributed control of the overall traffic system in a collaborative manner. Advanced automation and navigation technologies will enable the pilots with auto-taxi capabilities or automation aids for performing precision taxi to achieve the time-controlled taxi routes issued as clearances by the GO-SAFE system. New operational procedures will need to be defined for carrying out data-linked clearances, and for automatic loading of the clearances into the flight decks' flight management systems (FMS). A previous effort has demonstrated with computer simulations that advanced nonlinear control methods can enable the aircraft to track very precisely defined time-controlled taxi routes [6], even in the highly dynamic environment of

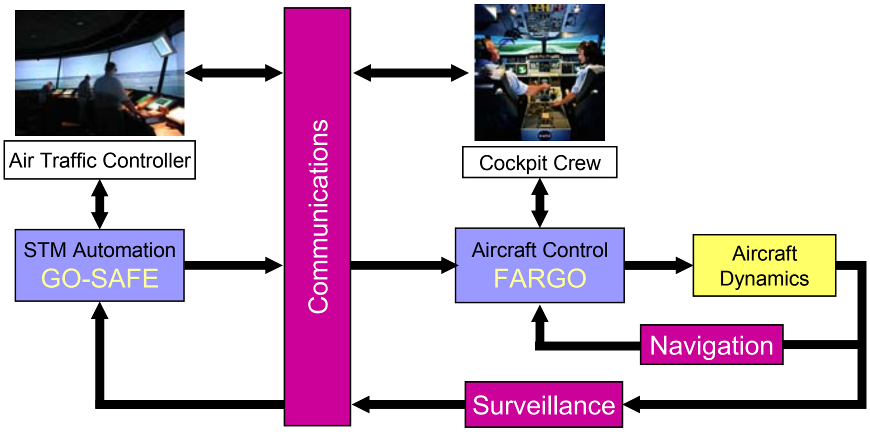

Figure 2. High-Level Block Diagram of SOAR Collaborative Automation Concept

performing active-runway crossing immediately after the aircraft has landed on an adjacent runway. The *Flight-deck Automation for Reliable Ground Operation* (FARGO) system represents further development of this idea to achieve the flight-deck automation component of the SOAR concept.

Integrated operation of the GO-SAFE and FARGO automation systems allow ATC and the pilots to achieve the benefits envisioned by the SOAR concept. In summary, GO-SAFE performs traffic planning to simultaneously enhance arrival/departure efficiency and surface traffic efficiency. This is a key factor of the SOAR concept, related to its ability to deliver close to near-peak traffic rates without substantial taxi delay. Execution of the plan is enabled by accurate surveillance, data link for issuing clearances with detailed route information, and precision taxi performance delivered by the FARGO system enabled by accurate navigation. The traffic planning will also take advantage of high-quality traffic prediction data coming from other systems, such as the Center-TRACON Automation System (CTAS) [7] with its various tools [8]–[12] and the Surface Management System (SMS) [13], [14]. The GO-SAFE and FARGO user interfaces with the underlying automation enable human operators to deliver efficient operations otherwise unattainable with current systems; hence they allow the operators to achieve higher performance within acceptable workload. These user interfaces with accurate surveillance data also enhance safety by improving the situation awareness of the operators. They help to reduce confusion between different flights on the surface, and they also provide timely alert in the case of impending conflicts.

III. Performance Factors and Metrics

The main performance factor for any capacity-increasing concept is inevitably capacity. The notion of capacity may, however, require different interpretations in different domains of the NAS. The capacity of the whole NAS may be measured by the daily, monthly, or yearly tabulation of total flights flown, total passenger trips, or total passenger revenue miles, etc. For a domain-specific concept such as SOAR for the surface domain, the ability of a concept to increase total flight operations in a day may not amount to any realistic benefit. As there are usually periods of time in a day where the airport is not operating at capacity, simplistic concepts which merely add schedules to these low-load periods may not provide the kind of capacity gain from which the airlines can benefit. More specifically, in major hub airports, successful hub-and-spoke operations depend on quick passenger transfer and aircraft turnaround to minimize the incremental travel time imposed by such operations over point-to-point operations. This leads to the practice of airlines scheduling large banks of flights to arrive at the airports within a short period of time, efficiently transferring passengers and baggage and executing aircraft turnaround, and scheduling the flights to depart with minimum delay. With a large number of flights arriving and departing in narrow time windows, it is reasonable to view the capacity of the airport as the maximum achievable throughput of the arrival and departure traffic.

It is indisputable that airport periphery throughput in terms of arrival and departure rates is important. However, if in the process of maximizing arrival and departure throughput additional taxi delays are incurred, such delays will contribute to system travel delays. An example is the increase in taxi delay caused by the operational practice to maximize arrival and departure throughput by queuing up planes for active running crossing as a group to minimize the runway-crossing interruption of arrival and departure traffic. As hub-and-spoke operations usually consist of a large bank of arrival flights arriving at the gates to enable passenger transfer before the departure bank can begin, even the delay of a small number of flights getting to their gates will delay many departing flights. Inefficient taxi operations will stretch out the time windows for both the arrival and departure banks. This observation suggests that the notion of airport capacity may be more meaningfully studied as a combination of two sub-domains: capacity at the airport "periphery," and capacity within the airport "surface." Specifically, the airport surface capacity addresses how well the network of runways and taxiways can absorb the air traffic in and out of the airport, without creating a bottleneck or serving as a parking lot between the runways and the terminal gates. These two notions of capacity are discussed in the following subsections.

A. Airport Periphery Capacity in Terms of Arrival and Departure Throughput

The SOAR concept enables airport capacity enhancement, especially that associated with airport expansion plans which produce complex airport configurations. For a given airport layout, the airport periphery capacity is constrained by an upper bound that depends on two primary factors: the number of runways, and the maximum traffic rate per runway. The maximum traffic rate per runway in turn depends on many factors, such as operational requirements on arrival/departure traffic mix, and aircraft separation due to wake vortex concerns. The integral product of the number of runways with the maximum traffic rate per runway under ideal situations constitutes an upper bound on the total traffic throughput of the airport. This upper bound can be considered the "ideal" capacity, which can be defined in terms of Pareto frontiers [15]–[17] as illustrated by the generic plot of Figure 3. The Pareto frontier describes the capacity as a tradeoff between arrival and departure rates. It does not account for any capacity loss due to surface operation or other factors.

In practice, the achievable capacity at the airport may be substantially lower than the ideal capacity due to inefficiency, much of which is caused by interference among the traffic. The increase in airport configuration complexity resulting from the airport expansion exacerbates the inefficiency. A notable example is the increased number of active-runway crossings resulting from increased traffic and airport expansion. The lower achievable capacity is marked by its operating point well within the Pareto frontier. To bring the achievable capacity close to the ideal capacity, ATC operation can minimize the impact of active-runway crossings on takeoff and landing operations by minimizing the total time taken up by runway-crossing activities. This can be achieved by queuing up the flights that require crossing and clearing them to cross as a batch. The side effect is inevitably the increase in taxi delay when the flights have to line up and wait for a large enough group to form before crossing. This represents a tradeoff between the two efficiency factors:

- Reduction in achievable periphery throughput, a penalty on arrival/departure efficiency
- Increase in taxi delay, a penalty on surface traffic efficiency

This tradeoff suggests that airport runway throughput constitutes a good metric to assess airport periphery capacity, and taxi delay is a good metric to assess airport surface capacity.

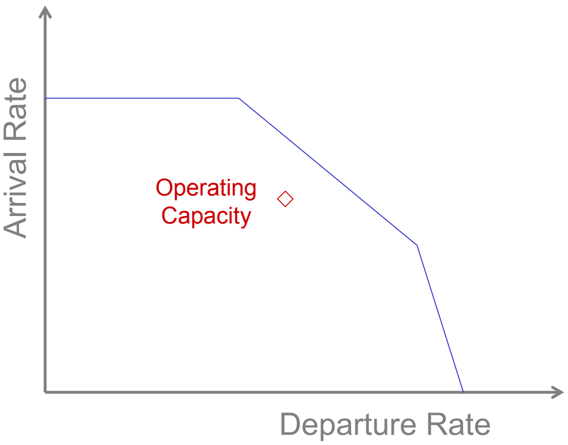

Figure 3. Airport Periphery Capacity in Terms of Pareto Frontiers Describing Relationship between Ideal Arrival and Departure Rates

The evaluation reported here is based on a surface traffic simulation modeled around the Dallas/Fort Worth (DFW) International Airport. Figure 4 shows the DFW layout with the current seven runways. The majority of the operations at DFW take place in a south-flow configuration, in which four runways (17L, 17C, 18R, and 13 R) are for the arrival traffic and the remaining three (13L, 17R, and 18L) are for departure. This south-flow configuration is typically used during the rush periods. With the runways providing peak capacity to accommodate the combination of arrival and departure traffic, the airport periphery capacity should be assessed as the sum of the

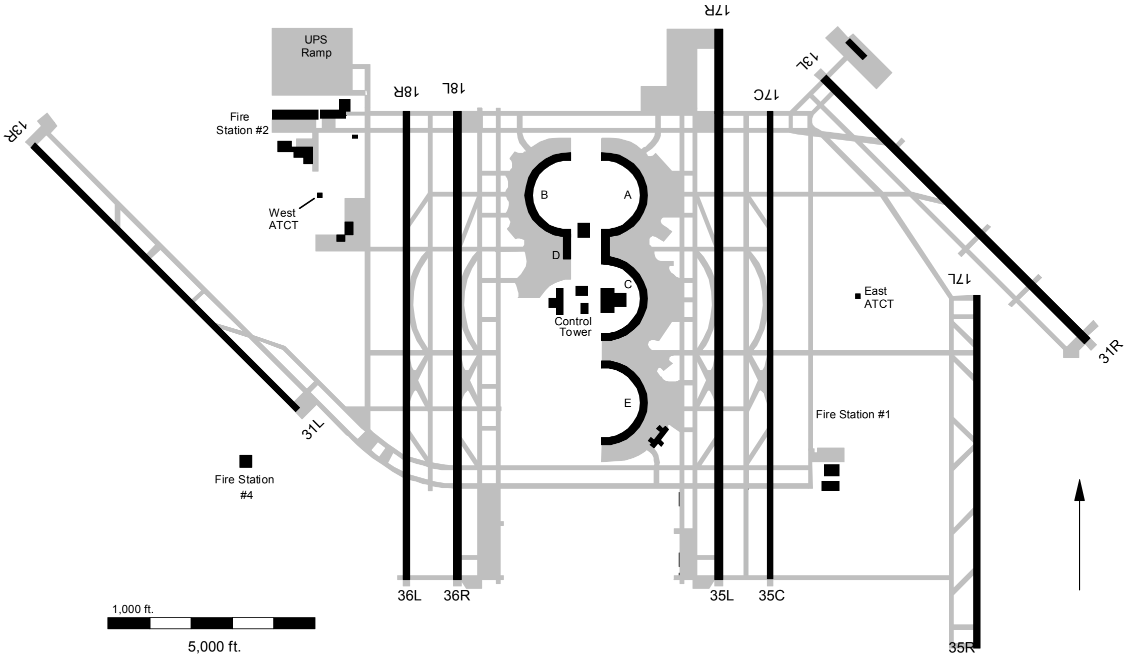

Figure 4. Current DFW Layout with 7 Runways

arrival and departure throughput.

FAA Office of Aviation Policy and Plans has created the Aviation System Performance Metrics (ASPM) [18] to provide metrics of individual flights according to the phases of their flight. ASPM integrates data from two primary sources: the Enhanced Traffic Management System (ETMS) and "Gate-Out, Wheels-Off, Wheels-On and Gate-In" (OOOI) data from Aeronautical Radio, Inc. (ARINC). For the surface domain, in particular, ASPM includes metrics for both airport throughput and taxi efficiency determination. These data are collected for over 50 airports in the US. With regard to throughput data for measuring airport periphery capacity, Table 1 provides the optimum and reduced rates for the target airport, DFW. Since DFW almost always operates in the south-flow configuration, the arrival and departure data in Table 1 are consistent with this specific runway configuration. The same conclusion cannot be drawn about other airports where no single airport configuration is used the majority of the time. In the DFW south-flow configuration, four runways are used for arrival and three for departure. Referencing the optimum arrival and departure rates in Table 1, it can be concluded that each runway allows up to about 40 operations per hour, irrespective of whether the runway is for arrival or departure. This optimum rate is consistent with average aircraft separation of approximately 1.5 min between landing or takeoff operations.

Table 1. Optimum and Reduced Rates for DFW Provided by ASPM

	Hourly Rates			**15-min Rates**		
	Departure	**Arrival**	**Total**	**Departure**	**Arrival**	**Total**
Optimum	**120**	**150**	**270**	**30**	**38**	**68**
Reduced	**90**	**95**	**185**	**23**	**24**	**46**

For the evaluation reported here, it is therefore assumed that the peak periphery capacity is fundamentally limited by this level of separation requirements, and the traffic schedule demand should not deviate significantly from it. Any runway throughput increase beyond this level of performance will need to be justified with other capacity-increasing concepts that can deliver operations with reduced separations for the landing and takeoff operations. An example of such capacity-increasing concepts is the use of advanced wake-vortex detection technology to allow flight operations with minimum separation.

B. Airport Surface Capacity in Terms of Taxi Delay and Efficiency

The notion of airport surface capacity should address how well the network of runways and taxiways can absorb the air traffic in and out of the airport, so that it does not constitute a bottleneck to the traffic or appear as a parking lot between the runways and the terminal gates. Metrics such as arrival and departure throughput, or traffic rate through the ramp area boundary, simply are not applicable in gauging the taxi performance. From an operational point of view, surface traffic performance is strongly reflected in taxi delay, which thus constitutes the most meaningful metric for assessing the performance [19].

This is consistent with the metrics defined in ASPM for taxi operations. The "taxi-out" and "taxi-in" metrics in ASPM are defined as the difference in actual taxi time and unimpeded taxi time for taxi-out and taxi-in operations, respectively. The data are collected according to the airport, carrier, and season. The unimpeded taxi time is the estimated taxi time for an aircraft "under optimal operating conditions when neither congestion, weather, nor other factors delay its movement," from gate to takeoff for taxi-out, and from landing to gate for taxi-in.

The taxi-in and taxi-out times for ASPM are determined according to the median of the pertinent data collected by ARINC. Unimpeded taxi times in ASPM are also estimated from available data, but they require additional processing from real traffic data because totally unimpeded operation is not available in actual operations for all possible taxi routes. For instance, the unimpeded taxi-out time is defined as the taxi-out time under two simultaneous conditions — when the departure queue is equal to 1 and the arrival queue is equal to 0. The departure queue is the number of aircraft at each minute of the day that have pushed back from the gate (gate-out) but have not yet taken off (wheels-off). The arrival queue is the number of aircraft that have landed (wheels-on) but have not yet reached the gate (gate-in). The departure and arrival queues are derived through a minute-by-minute analysis of actual flights in the ARINC database. The taxi-out time is determined for each flight. The queue length assigned to a flight pushing back is the length of the departure queue, including this particular flight, within the one-minute window of analysis. ASPM then applies a form of multiple regression to express the taxi-out time as an affine function of the departure queue and arrival queue: i.e.,

$$\text{Taxi - Out Time} = b_1 \cdot \text{Departure Queue} + b_2 \cdot \text{Arrival Queue} + c$$

where the coefficients b_1, b_2 and c are estimated from the regression. Once the expression is available, the unimpeded taxi-out time is obtained by setting the Departure Queue to 1 and the Arrival Queue to 0; hence,

$$\text{Unimpeded Taxi - Out Time} = b_1 + c$$

The unimpeded taxi times are determined by airport, carrier, and season. Estimation of unimpeded taxi times by this method has two fundamental limitations. Firstly, since there is no data on the runway configurations used for each flight, the impact of different runway configurations on the results cannot be measured, not to mention the lack of ability to estimate actual unimpeded taxi time for the individual flight's taxi route. Secondly, not all aircraft operating on the airport surface contribute to the OOOI data used to compute the queues, and so the actual queues may be longer. Consequently, the ASPM estimates would tend to be greater than the actual unimpeded taxi times. In other words, the taxi delays estimated by ASPM would tend to be smaller than the actual quantities.

Since the SOAR evaluation is based on computer simulations, the taxi time and unimpeded taxi time for each flight can be determined by simply running the simulation under the appropriate conditions. The unimpeded taxi time can be pre-determined for each taxi operation (e.g., from landing to the gate terminal, or from the gate terminal to departure), and can even be adapted for each aircraft type. These unimpeded quantities should be established with nominal vehicle performance and without interference from other factors (e.g., this should not include any waiting for active-runway crossing). With these unimpeded taxi times, taxi delays can be calculated as the time difference required for taxi operation under the scenario traffic. Under the assumption that one would not taxi faster than under nominal situations, the taxi delay is always non-negative:

$$\text{Taxi Delay} = \text{Actual Taxi Time} - \text{Unimpeded Taxi Time} > 0$$

The taxi delay metric is also related to surface traffic efficiency. One can use the taxi time and unimpeded taxi time to define an individual-vehicle taxi efficiency:

$$\begin{aligned}\text{Taxi Efficiency} &= \frac{\text{Unimpeded Taxi Time}}{\text{Actual Taxi Time}} \\ &= \frac{\text{Actual Effective Speed}}{\text{Unimpeded Effective Speed}} \leq 1\end{aligned}$$

This taxi efficiency metric can be generalized to a composite surface traffic efficiency metric to cover all of the surface operations:

$$\text{Surface Traffic Efficiency} = \frac{\sum \text{Unimpeded Taxi Time}}{\sum \text{Actual Taxi Time}}$$

IV. Evaluation Experiment Design

The main objective of the self-evaluation is to assess the potential benefits of the SOAR concept relative to current surface operations without the automation systems. It is obvious that the main difference is the presence of the automation systems in the SOAR concept, with corresponding differences in operational procedures and rules and the human performance associated with the automation. In order to make sure that these causal differences are adequately addressed in the evaluation, the roles and responsibilities of the human operators and the automation systems were examined. The findings led to the adaptation of the ground-operation simulation (GO-Sim) software to two separate simulations: one for evaluating the SOAR concept, and one for simulating current operations, as illustrated in Figure 5. For the SOAR concept, GO-Sim was modified so that the taxi control for the individual flights would simulate FARGO operations that could precisely track the GO-SAFE time-based clearances.

For simulated current operations, no GO-SAFE automation is available to the controllers. As shown in Figure 5, the GO-SAFE software is kept in the simulation to simulate the route planning capability of the controllers. However, the time information of the taxi routes is stripped from the ATC clearances issued to the flights. Additional software logic is introduced to simulate the ATC function of issuing clearances for controlling runway usage based on actual arrival at runway for access. The flight control function has also been modified to simulate taxi without any time-based taxi control objective. It instead used only speed reference so that if a flight is slightly delayed along the route, it would not try to speed up to make up for it.

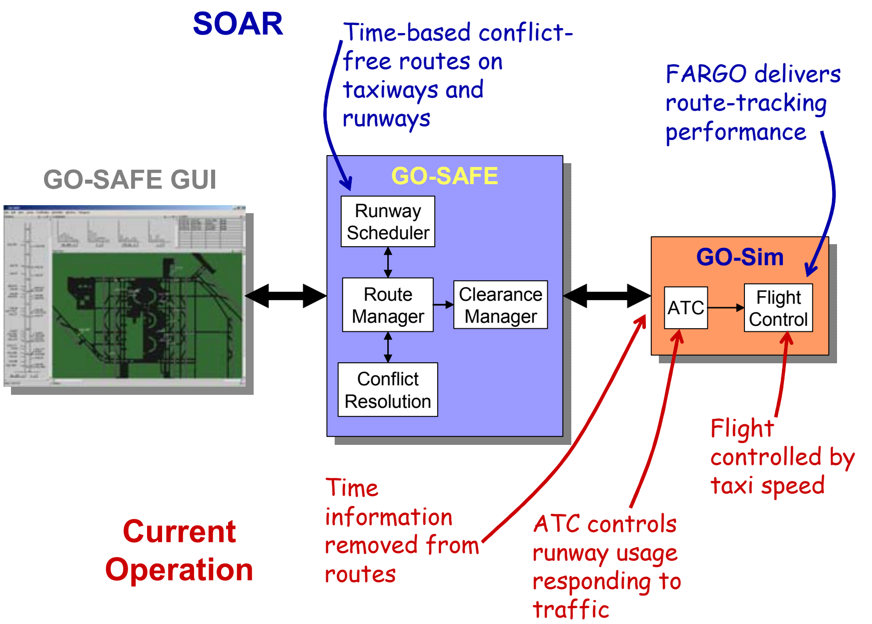

Figure 5. Adaptation of Computer Simulations for Evaluating SOAR Concept Compared to Current Operations

The demand sets used for the evaluation were provided by the VAMS project. The data includes the demand schedules extracted from ETMS for the day of May 17, 2002, a day representing a "high traffic" operational day. It also included a future demand data set developed from a transportation demand and economic analysis forecast for the year 2022 [20]. Three sets of traffic demand schedules were available:

- A data set representing operations at 250 domestic airports with 30,237operations extracted from ETMS data for May 17, 2002
- A filtered data set corresponding to domestic commercial passenger flights at 98 major US airports with 16,468 operations
- A future demand data set developed from a transportation demand and economic analysis forecast for the year 2022, for the 98 major US airports contain 33,167 flights

These three data sets form the basis of the SOAR evaluation. Each data record in these data sets contains the information of a single flight, including the origin and destination airports. These data sets are filtered to extract the flight records for all flights having DFW as either the origin or destination airport. Departure times from the data sets are used as scheduled departure time for the departure flights from DFW. However, since the data sets do not include arrival times, scheduled arrival times for flights arriving at DFW are estimated based on the origin airport. The estimation process involves adding estimated flight time to the scheduled departure time from the origin airport to obtain an initial estimate of the arrival time at DFW. DFW represents a major hub airport in the US for hub-and-spoke operations, and the two main airlines operating at this airport are American Airlines and Delta Air Lines. The flight times are estimated based on city-pair information obtained from these two airlines' schedules.

The SOAR concept assumes that runway assignment and scheduled arrival and departure times are either provided separately by other systems such as the Final Approach Spacing Tool (FAST) [9]–[11] or the Expedite Departure Path (EDP) tool [12], or new functions in the GO-SAFE system. For the purpose of the evaluation, the runway assignment is done manually as part of the traffic data preprocessing. Since the computer simulations have no capability in holding arrival flights, they require the arrival traffic schedule to observe realistic separation requirements. The scheduled arrival times are obtained by adjusting the estimated arrival times to make sure that the separation between arrival flights for each arrival runway is no less than 1.5 min. This was accomplished with a simple schedule processing program. On the other hand, the scheduled departure times have not been subjected to such schedule processing, because the flexibility to hold the departure flights on the ground exists with the ground controllers or the GO-SAFE system. Overly tight departure schedules will naturally translate into taxi delays.

Figure 6 through Figure 8 show the estimated and scheduled traffic counts for the arrival and departure flights from the three respective data sets. A few observations can be made.

- The traffic shows a few major rush periods through the day.
- The effect of the arrival scheduling is not significant except for the future-demand data set, in which case the limit of 40 arrival flights per 15-min interval is evident.

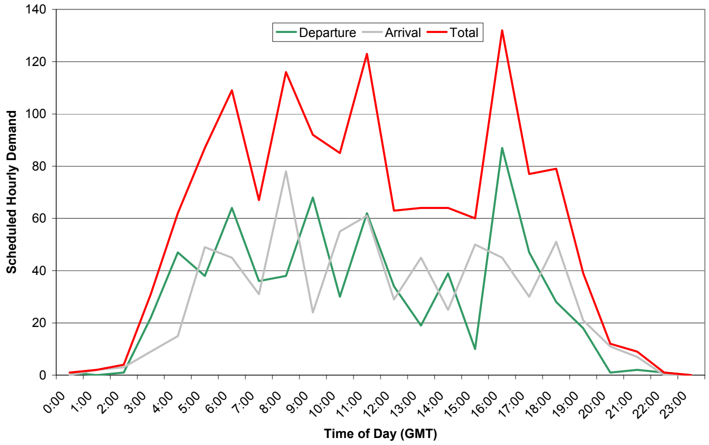

Figure 6. Scheduled Hourly Demands at DFW from 98-Airport Demand Set

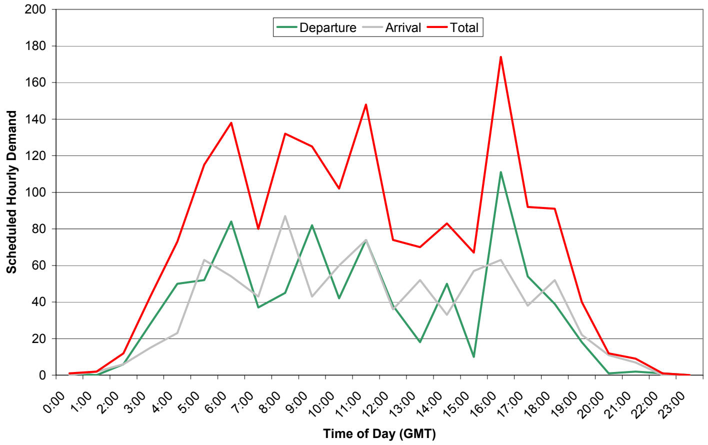

Figure 7. Scheduled Hourly Demands at DFW from 250-Airport Demand Set

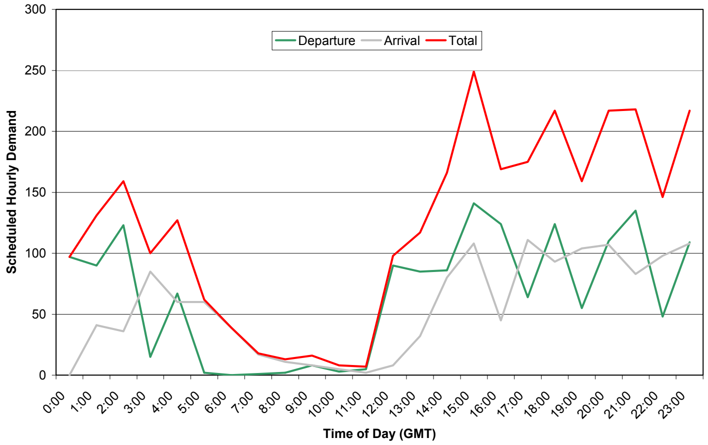

Figure 8. Scheduled Hourly Demands at DFW from Future Demand Set

- The demand distribution for the future-demand set does not resemble those of the other two sets. This may reflect effects of the forecast assumptions used in generating the data set.

To see how these data sets relate to current traffic, Figure 9 plots the hourly traffic counts reported by ASPM. It is observed that the traffic demand from the 250-airport demand data set show some resemblance in shape and similar traffic levels. There appears to be a shift in the time axis that is not entirely consistent. The ASPM data in Figure 9 purportedly is based on local hours, whereas the 250-airport demand data in Figure 7 is purportedly given in GMT. The shift in the time axis between these two figures appears to be too small to account for the difference. For the purpose of the current evaluation, however, this factor is unimportant because we are not really concerned with the actual hour of the day.

V. EVALUATION RESULTS

Although the evaluation involved the three demand data sets discussed above, only the results from two demand sets are included here for the sake of brevity. In particular, the 250-airport data set is considered a good representation of the current demand, as illustrated by its similarity with the ASPM data, and the future demand data set represents the increased demand anticipated for the future.

The simulations are all based on the seven-runway south-flow configuration at DFW, with no runways or taxiways added to simulate possible future expansion projects. Furthermore, the arrival schedules and departure planning all observe a 1.5-min minimum separation between operations, without reducing the requirement to simulate operational concepts that could bring about the reduction.

A. Airport Periphery Throughput

The airport periphery throughput, as a measure of the airport periphery capacity, are shown in Figure 10 and Figure 11 for the simulations of current operations and the SOAR concept, respectively, using the

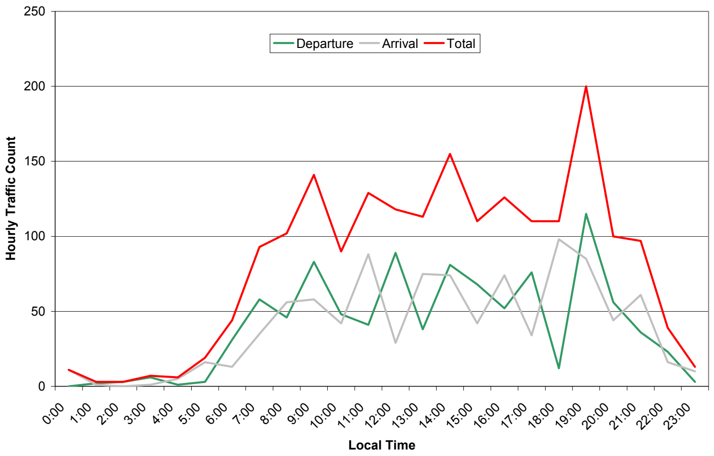

Figure 9. Hourly Traffic Count at DFW from ASPM

Figure 10. Hourly Throughput with Current Operations at DFW from 250-Airport Demand Set

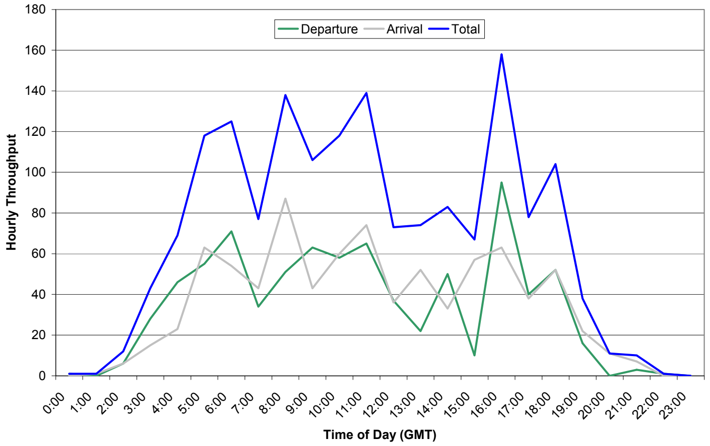

Figure 11. Hourly Throughput with SOAR Concept at DFW from 250-Airport Demand Set

250-airport demand data set. The throughput is shown for departure, arrival, and the sum of the two. Figure 12 compares the total throughput between the current operations and the SOAR concept by combining the data from these two cases. It can be seen that the SOAR concept shows that it is delivering higher peak throughput, and it is able to deliver the throughput earlier to allow it more time to absorb more traffic later on.

Figure 13 compares the total throughput between the current operations and the SOAR concept for the future demand data set. It can be seen here that the throughput improvement due to the SOAR concept is more pronounced.

B. Taxi Delay Results

As discussed above, the airport periphery capacity in terms of throughput does not adequately describe the operational efficiency on the surface, and taxi delay is a more appropriate measure for characterizing airport surface capacity. Taxi delay metrics are generated for each of the operational concepts and demand data sets. For each of these cases, three taxi delay quantities are generated:

- average taxi-out delay,
- average taxi-in delay, and
- average taxi delay for the combined departure and arrival traffic.

Figure 14 shows the taxi delays for current operation with the 250-airport demand set, while Figure 15 shows the same data for the SOAR concept. It is obvious by referring to the magnitude of the plots that the SOAR concept is very effective in reducing taxi delays, even when the demand is not very high. Figure 16 compares the average taxi delays between the two operational approaches and the SOAR concept is demonstrating an obvious advantage. The benefit of the SOAR concept is, however, more valuable than what is shown by the relative shape of the plots because it is the absolute difference in the time delays that characterizes the amount of time and resources saved.

Since the 250-airport demand set is expected to be close to the real traffic, the results in Figure 14 should be compared again to the delay metrics generated by

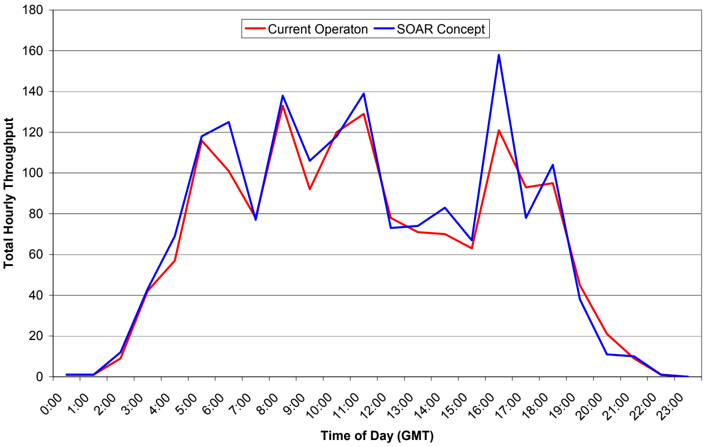

Figure 12. Comparison of Hourly Throughput between Current Operation and SOAR Concept at DFW from 250-Airport Demand Set

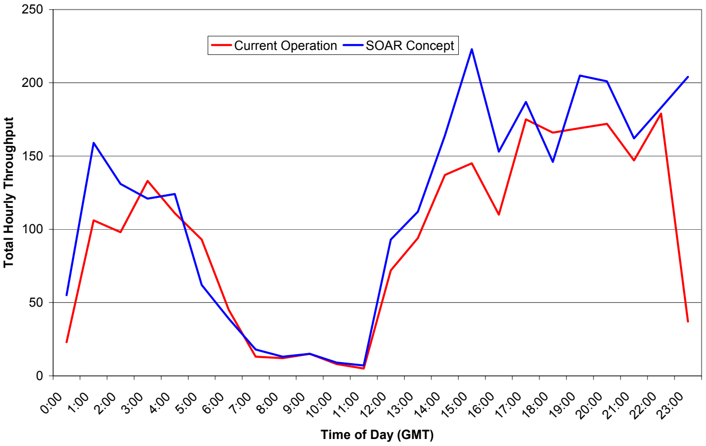

Figure 13. Comparison of Hourly Throughput between Current Operation and SOAR Concept at DFW from Future Demand Set

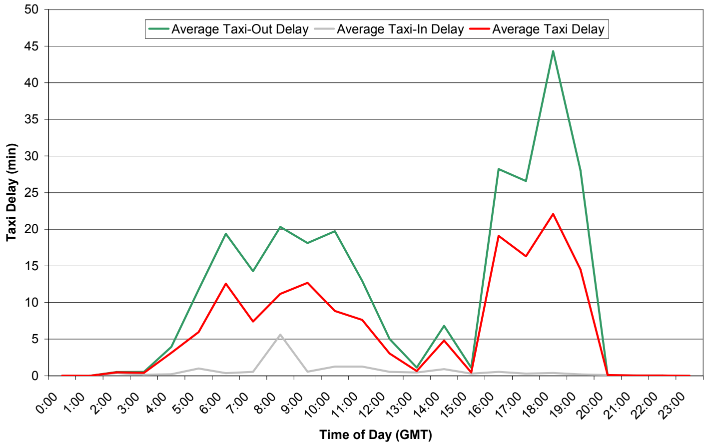

Figure 14. Average Taxi Delays with Current Operations at DFW from 250-Airport Demand Set

ASPM in Figure 17. Although the traffic demand from the 250-airport case resembles the ASPM traffic data, the taxi delay times are not as consistent. For the initial heavy traffic through most of the early and middle parts of the day, the ASPM data has shown taxi delays about twice as large as those experienced with the 250-airport data under current operations. The difference can be attributed to the difference in the manner in which the delays are computed: ASPM data are based on OOOI data, e.g., taxi-out is computed from the gate to wheels off, whereas the computer simulation only counts the taxi-out time from the ramp area to the point where the aircraft is cleared for takeoff. Hence the computer simulation is based on a shorter taxi segment, thus explaining the shorter delay.

What is curious about the ASPM data is that it does not show any significant taxi delays during the rush later in the day, when the traffic reached the highest peak of the day. There are two likely explanations: One is that some taxi data may be missing from the OOOI database used by ASPM or the processing had to so some filtering of the data. The second possibility is that the controllers totally expected the rush and performed so well that their performance was near optimal. This is possible since this rush did not last very long, and there was a slow period immediately preceding it where the controllers might have the opportunity to organize the surface traffic in anticipation of the rush.

Figure 18 compares the average taxi delays between the current operations and the SOAR concept for the really demanding traffic from the future demand data set. Here the benefit of the SOAR concept in saving taxi time is even more pronounced.

C. Taxi Efficiencies

The metric of surface traffic efficiency is related to taxi delay and can be evaluated using the data generated from the computer simulations. Figure 19 and Figure 20 show comparisons of this metric between current operations and the SOAR concept for the 250-airport and future demand data sets, respectively. In both cases the SOAR

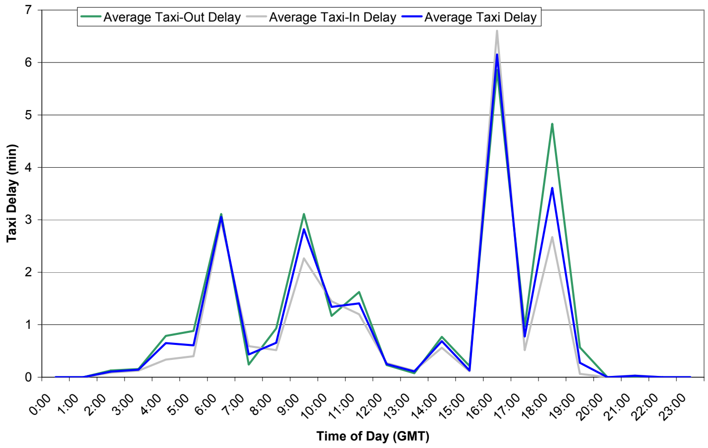

Figure 15. Average Taxi Delays with SOAR Concept at DFW from 250-Airport Demand Set

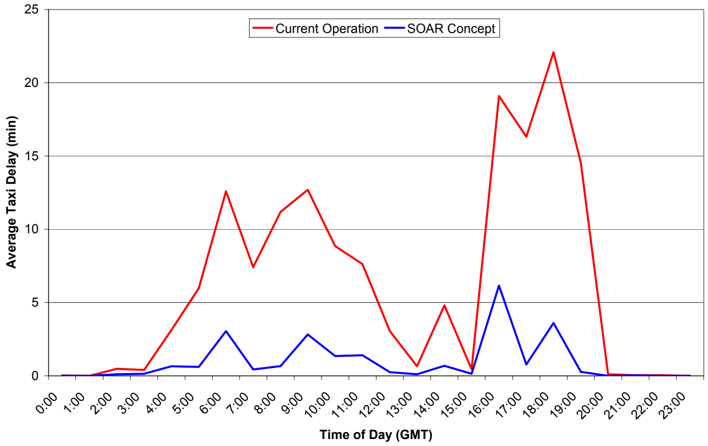

Figure 16. Comparison of Average Taxi Delays between Current Operation and SOAR Concept at DFW from 250-Airport Demand Set

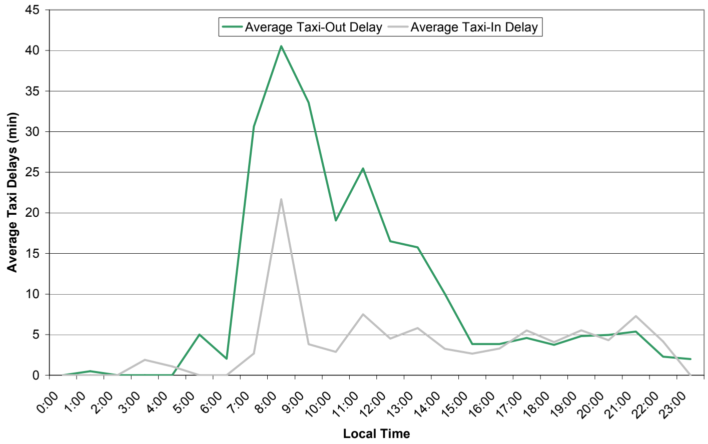

Figure 17. Average Taxi Delays for DFW on May 17, 2002 per ASPM

concept shows obvious advantage over current operations.

The improvement of taxi efficiencies of individual aircraft can also be examined by viewing the number of flights with through the day taxi efficiencies above specified values. Figure 21 compares the cumulative percentage of the number of flights plotted against taxi efficiency values between current operations and the SOAR concept for the 250-airport demand set. Statistically, each of these plots represents the cumulative distribution of taxi efficiencies associated with the ensemble of flights in the demand data set under the specified operational concept. Figure 22 provides similar plots for the future demand set. In both cases the results from current operations consistently show a larger percentage of flights with low taxi efficiencies than those from the SOAR concept. In other words, the SOAR concept produces a higher distribution of traffic with higher efficiencies.

D. Relationship between Taxi Delays and Airport Periphery Throughput

With the evaluation data collected from the previous sections, the relationship between taxi delays and airport periphery throughput can be examined. Figure 23 shows an anticipated relationship between these two metrics. The taxi delay increases as the amount of throughput increases. There is a peak capacity corresponding to the runway configuration that serves as the absolute maximum achieved by any operational concept. Inferior operational approaches would tend to create larger taxi delays and may not be able to approach this ideal capacity value. The SOAR automation is expected to bring the curve down, thus reducing delay for the same required throughput. Here we also expect the increase in taxi delay to be flatter with the automation systems.

To see if the generated data would fit into this anticipated relationship, the hourly data of average taxi delays and the total hourly throughput are shown as cluster plots in Figure 24 and Figure 25 for the two demand data sets. The points in the plots do not form smooth curves as suggested in Figure 21, because these metrics experience dynamics in the system and therefore depend on the situations

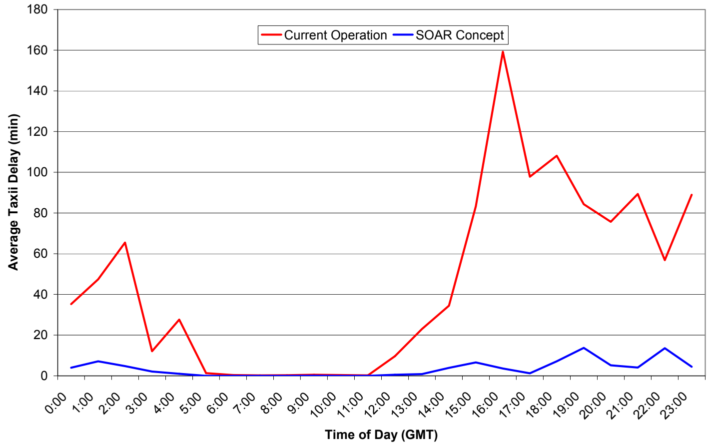

Figure 18. Comparison of Average Taxi Delays between Current Operation and SOAR Concept at DFW from Future Demand Set

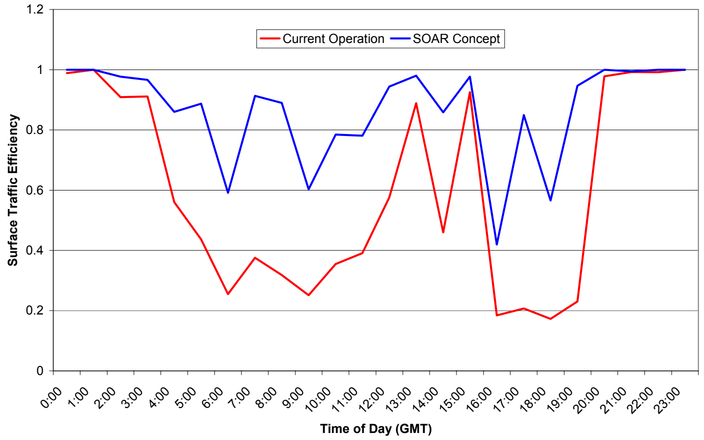

Figure 19. Comparison of Surface Traffic Efficiencies between Current Operation and SOAR Concept at DFW from 250-Airport Demand Set

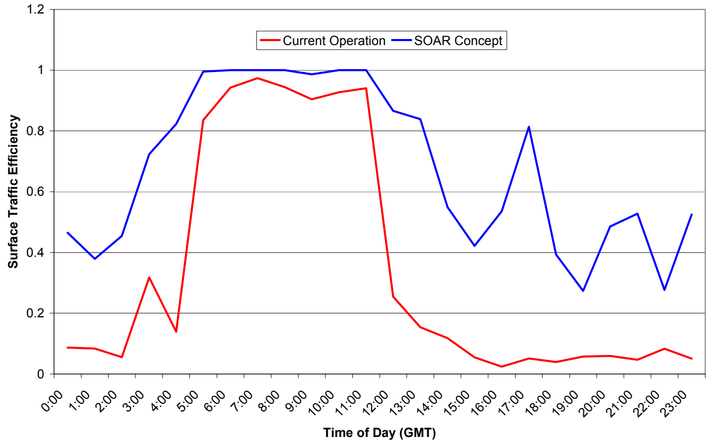

Figure 20. Comparison of Surface Traffic Efficiencies between Current Operation and SOAR Concept at DFW from Future Demand Set

during and before the hours when the data are recorded. If more filtering such as averaging is applied to the hourly data, the data points may show less dispersion. In any case, two observations are obvious:

- The SOAR concept produces smaller taxi delays.
- The SOAR concept has traffic data that contain points with the highest periphery throughput.

E. Relationship between Taxi Efficiencies and Airport Periphery Throughputs

Similar to the discussions in the previous section, different operational approaches can also be evaluated through the relationship between their surface traffic efficiencies and their airport periphery throughput. Figure 26 shows an idealized plot of this relationship. It is anticipated that, when compared to current operations, the SOAR concept would move the curve upwards, thus producing higher surface traffic efficiency for any given throughput. It is also anticipated that the curve would be flatter compared to current operations.

Figure 27 and Figure 28 contain the cluster plots of the hourly surface traffic efficiencies against the achieved airport periphery throughput for the two demand data sets. The resulting plots show that the efficiencies from the SOAR concept generally stay higher than current operations with increased throughput, and that the SOAR concept produces the points with the highest throughput values.

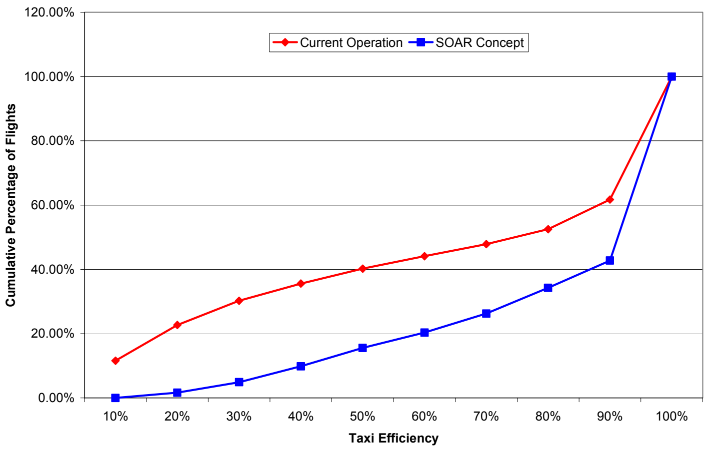

Figure 21. Cumulative Distributions of Taxi Efficiencies for 250-Airport Demand Set

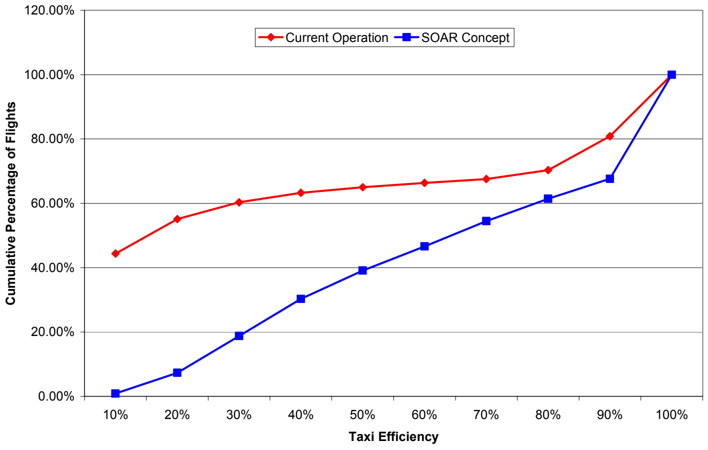

Figure 22. Cumulative Distributions of Taxi Efficiencies for Future Demand Set

VI. Concluding Remarks

The evaluation has successfully verified the potential of the SOAR concept to deliver airport surface operational benefits using appropriately configured computer simulations. Based on computer models of the SOAR concept and current operational characteristics, the evaluation has established the efficacy of the SOAR concept in enhancing surface operation efficiency by significantly reducing taxi delays at major hub airports during busy hub-and-spoke operations. This benefit is achieved with simultaneous increase in airport periphery throughput. Although modeling of the scenarios and the SOAR functions may not be completely accurate with regard to future reality, the evaluation nevertheless reveals the benefits of the SOAR concept over conventional operational practices on a comparative basis. Since this evaluation is based on a concept being developed, the SOAR concept is evaluated without the

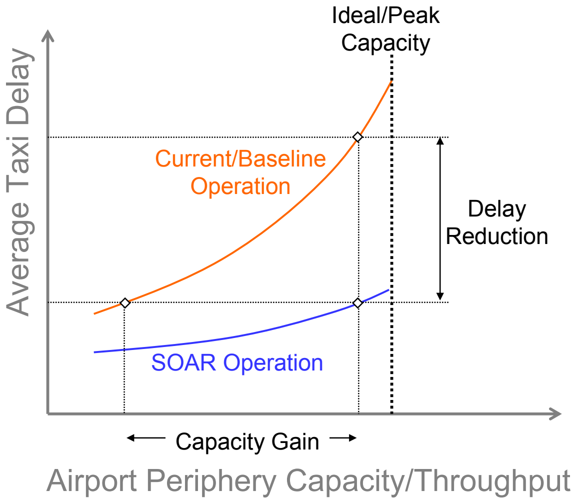

Figure 23. Anticipated SOAR Benefits of Capacity Gain and Delay Reduction

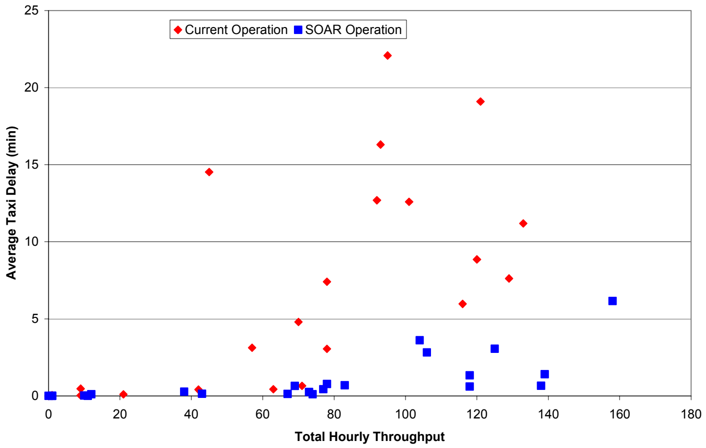

Figure 24. Relationship between Average Taxi Delay and Hourly Throughput for Current Operation and SOAR Concept at DFW from 250-Airport Demand Set

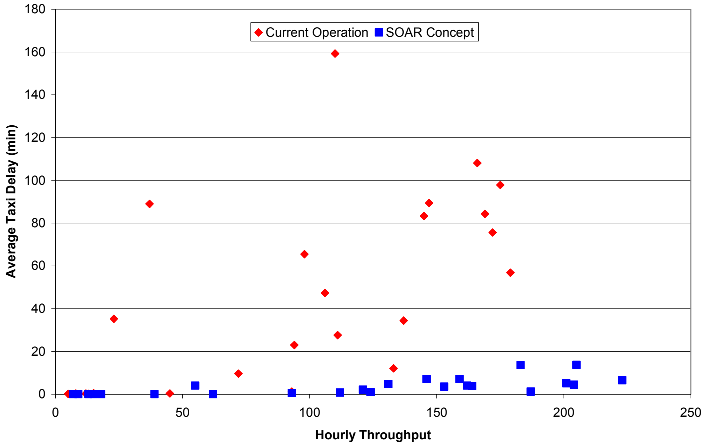

Figure 25. Relationship between Average Taxi Delay and Hourly Throughput for Current Operation and SOAR Concept at DFW from Future Demand Set

benefit of fully-developed SOAR technologies, despite the availability of some preliminary technologies available on the GO-SAFE and FARGO systems from previous research efforts.

The currently available experimental GO-SAFE system is far from being complete and ready for operational testing. For instance, the algorithms are not necessarily optimal in a more general context. In addition, the demanding schedules used in the evaluation have shown that the system is not very robust. Substantial work will be needed for development of the GO-SAFE technologies before it will be ready for operational testing. Development efforts will include algorithm development, system development, user interface, and human factors considerations. On the cockpit side, the FARGO automation is currently only a concept. Previous experience included the design and computer evaluation of a nonlinear controller that established the feasibility of precision taxi control. Full

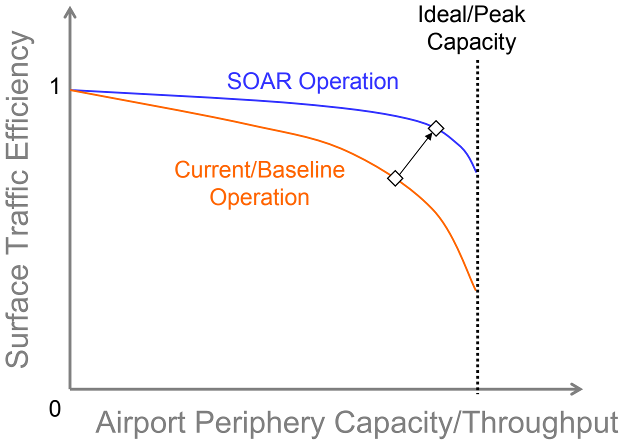

Figure 26. Enhanced Tradeoff Between Surface Traffic Efficiency and Airport Periphery Capacity

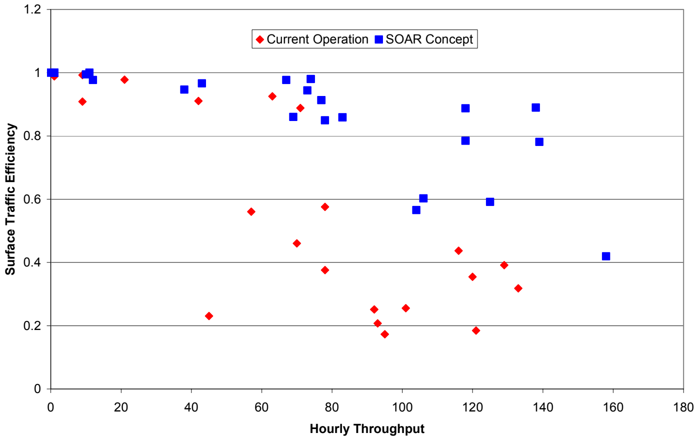

Figure 27. Relationship between Surface Traffic Efficiency and Hourly Throughput for Current Operation and SOAR Concept at DFW from 250-Airport Demand Set

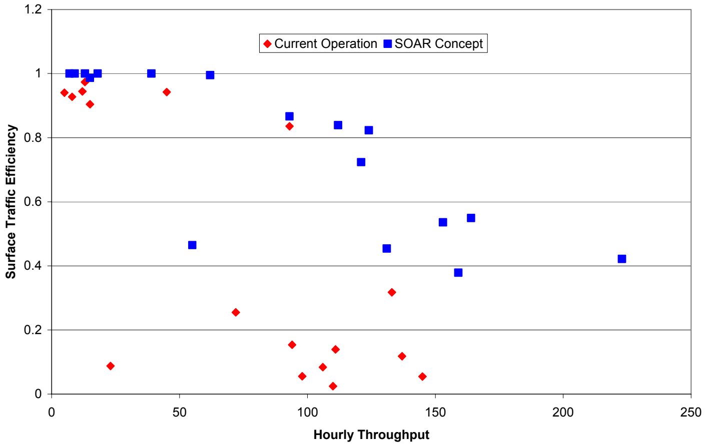

Figure 28. Relationship between Surface Traffic Efficiency and Hourly Throughput for Current Operation and SOAR Concept at DFW from Future Demand Set

development of the FARGO system will require substantial work in control-algorithm development and system-level development, user interface, and human factors considerations.

With both GO-SAFE and FARGO automation, detailed specification of operational procedure will be needed for the success of the concept. This will require extensive evaluations, including human-in-the-loop simulations and field tests. A system-wide evaluation of the concept is being planned for the coming year using a NAS-wide simulation being developed by the VAMS program.

Acknowledgments

Development and evaluation of the Surface Operation Automation Research (SOAR) concept has been supported since 2002 by the NASA Virtual Airspace Modeling and Simulation (VAMS) Project, while development of the automation technologies has been supported as various Small Business Innovative Research projects awarded by NASA Ames Research Center.

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