

## **Terminal Routing Using Speed-control Techniques (TRUST): Initial Concept Evaluation Report**

**D. R. Barker, T. A. Becher, E. J. Blassic, S. P. Chase, J. L. Harding, and S. C. Mohleji**

**Center for Advanced Aviation System Development (CAASD)**

**The MITRE Corporation**

**1820 Dolley Madison Blvd.**

**McLean, Virginia 22101**

**(703)883-6000/Fax: (703)883-1911**

### **Abstract**

*This paper describes some of the intrinsic problems that lead to less than optimal TRACON operations. It also identifies available technology and proposed procedures that can be applied in a synergistic fashion to mitigate such problems via a terminal routing concept called TRUST. The prototype development plan including verification and validation activities is discussed along with progress to date. Preliminary results are reported as well as possible future applications of the TRUST functions.*

### **Introduction**

#### **Problem Description**

*Predictability*

*Variability*

*Aircraft Equipage Mix*

*TRACON Specificity*

*Demand and Throughput Mismatch*

#### **Available Technology**

#### **Concept Description**

*Predefined Routes*

*Arrival Planning*

*Speed Advisories*

*Arrival and Departure Coordination*

*En Route Metering Interface*

#### **Mapping of Problems to Solutions**

### **Benefits**

*Operational*

*Economic*

*Safety*

*Results of Paper Study*

### **Development Plan**

*Methodology*

*Evolving and Iterative Process*

*Core Capability*

*Verification and Validation Role*

### **Progress**

*Developed Core Capability*

*Verification Completed*

*Independent Verification and Validation*

### **Results**

*Operational Acceptability*

*Metrics and Their Determination*

*Route Design*

*Path Comparison*

### **Applications**

*Procedure Evaluation*

*Air Traffic Management*

*Speed Advisory*

### **Summary**

### **References**

*Note: The contents of this material reflect the views of the authors. Neither the Federal Aviation Administration nor the Department of Transportation makes any warranty or guarantee, or promise, expressed or implied, concerning the content or accuracy of the views expressed herein. © 1998 The MITRE Corporation.*

*This paper can be viewed at <http://ATM-seminar-98.eurocontrol.fr/>*

## Introduction

During high traffic demand periods, arriving aircraft may encounter significant delays at airports. The major contributors to the delays are large variances between flight paths/times considered for planning traffic flows and actual paths/times flown.

In this paper we report on the continuing evaluation of a concept which combines the use of predefined terminal routes with automation to reduce variation in terminal flying times. The predefined routes are defined from entry fixes to touchdown for use by Flight Management System (FMS) and Area Navigation (RNAV) equipped aircraft and unequipped aircraft. The automation system consists of arrival and departure coordination, sequencing, scheduling and accurate flight time estimation, with speed control effected via speed advisories to deal with residual flight time variances.

This concept envisions a different end state from previous automation efforts [1,2,3] for the efficient control of aircraft in the Terminal Radar Approach Control (TRACON). The concept can be introduced in near term with changed procedures and ultimately developed evolutionarily towards a fully automated system.

## Problem Description

### Predictability

The aircraft arriving at major airports in the U.S. typically follow Standard Terminal Arrival Routes (STAR)s from the en route transition airspace to the established fixes in the TRACON area. Aircraft navigate these STARs using VHF omnidirectional range (VOR)/distance measuring equipment (DME). From the end of STARs to the final approaches, the aircraft fly under approach control using *ad hoc* vectors (headings).<sup>1</sup>

The use of vectoring to achieve spacing creates a significant difficulty for any automation system in

---

<sup>1</sup> Similarly departing aircraft are vectored after take off to connect to departure procedural routes.

predicting landing times, or indeed, times at other meaningful nodes in the TRACON.

### Variability

Compounding the problem of flying time prediction are the variations in several system elements. Included in these variations are errors in assessment of the wind field; differences in navigational precision and execution of maneuvers [4,5] from aircraft to aircraft; variation in pilot response and actions; and variation in controller generated clearance times. Any or all of these variables can lead to less than optimal spacing and timing for aircraft arrivals or departures.

#### *Wind Estimation and Prediction Error*

Scheduling and planning algorithms rely upon predicting flight times for a given path and altitude profile. Integral to flight time estimation is knowledge of the wind. Wind error, defined as the difference between the forecast winds and the actual winds, is a major source of perturbation in estimating flight times.<sup>2</sup>

#### *Navigational Precision*

When each aircraft is vectored by the controller, there is inherently large variability in the paths.<sup>3</sup> This is due to large flight technical error when in a manual mode of flight. Even among FMS equipped aircraft with autopilot flying a given route, there can be some variation in maneuver timing and the ability of the aircraft to capture the new course.

RNAV/FMS/Global Positioning System (GPS) equipped aircraft can perform point-to-point navigation. Precision in lateral navigation is required to maintain route conformance. Improved route

---

<sup>2</sup> For example, consider an aircraft descending from 15,000 ft to 10,000 ft while maintaining a constant indicated airspeed of 250 kts and descending through a linearly varying wind field with an initial magnitude of 45 kts and a wind shear of 3kts/1000ft. Further assuming a tailwind, a 20% error in the estimated wind causes a 4.5% error in the flight time estimate.

<sup>3</sup> Indeed, in lieu of other techniques for adjusting spacing the controller can alter the spacing by judicious selection of turns and timings of turn initiation.

conformance reduces the differences between assumptions made during the maneuver planning versus actual execution of maneuvers. One significant source of nonconformance is the execution of turns. RNAV/FMS equipped aircraft can execute a smooth coordinated turn, whereas an unequipped aircraft may start a turn too soon or too late depending upon the time the ground clearance is issued. Systematic differences in navigation can lead to unexpected and undesirable effects on subsequent spacing.<sup>4</sup>

#### *Pilot Variation*

Pilots do not all respond identically when requested to initiate a maneuver, whether it be a turn or deceleration. Variation is seen also by aircraft types, and even by airlines.

At Seattle, it was found that for FMS procedures which were designed with speed management constraints in mind, varying pilot techniques in their execution of the necessary speed reductions introduced an "accordion" effect. In other words, the spacing between aircraft was not uniform and flight crew- induced "holes" or gaps were created in the traffic stream [4,5].

#### *Controller Variation*

In today's environment, final spacing of aircraft depends upon the timely generation of clearances and the hand off of aircraft from one controller to another. Sometimes there is a significant difference in efficiency between controllers [6].

A recent example of this was conveyed to some of the authors during a visit to the Seattle TRACON. At Seattle, there are two feeder controllers, east and west, who hand off the aircraft to the final controller. The final controller must interleave all traffic streams on the final. The rates at which the feeder controllers could provide a uniform stream of traffic to the final

controller vary with *ad hoc* demand and any abatement of this variation would improve operations.

### **Aircraft Equipage Mix**

Contemplating the use of RNAV/FMS equipped aircraft to help reduce variability in some aspects of the control system, begs the question of how unequipped aircraft can be planned with a common set of procedures. FMS operations at Seattle indicated some problems with merging equipped with unequipped aircraft (without additional automation aids).

Also, there were problems with sequencing successive FMS arrivals from different starting points and the sequencing of FMS with other aircraft. Since the performance of FMS aircraft was "predictable", controllers tended to work other traffic around them. This is not true integration of FMS technology into the terminal area traffic management process.

### **TRACON Specificity**

Wide differences in TRACON and airport specific characteristics pose challenges to traffic flow planning when attempting to use a generalized solution. Examples of site dependent operational differences are:

- the number of runways and runway geometry
- airspace restrictions due to noise and adjacent or satellite airports
- the coordination procedures between surrounding en route centers and TRACONs
- the percentage of operations under Instrument Meteorological Conditions (IMC) versus Visual Meteorological Conditions (VMC) weather

Often traffic problems and flow management solutions grow up around a specific TRACON or airport and are not easily applied to or ported to other sites. There is always a trade off between solving a particular operation's problems and being general, flexible, and adaptable. When evaluating candidate solutions, it is important to be able to balance general versus specific requirements.

---

<sup>4</sup> One example gleaned from discussion with operational personnel is that departing aircraft on vectors are often overtaken (separation reduced) when followed by FMS aircraft, since the FMS turns are typically smooth. For arrivals, when an aircraft on vectors is followed by an FMS aircraft, an analogous situation can occur.

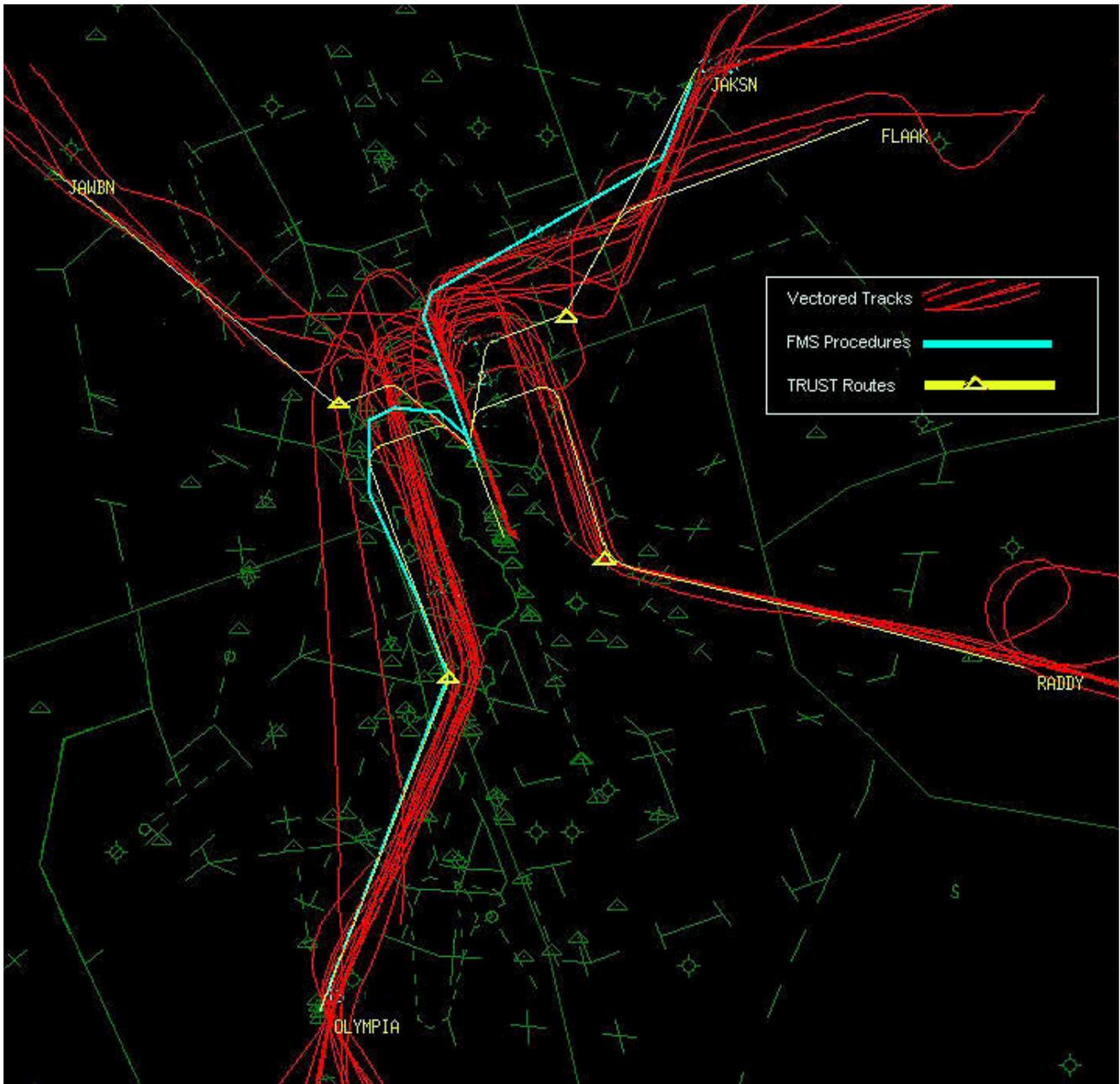
## **Demand and Throughput Mismatch**

Arrival capacity for an airport is a function of the sum of required time separations between successive aircraft in a continuous stream of traffic. The time separations depend upon the approach and landing speeds of the aircraft and the distance separations established based on wake vortex considerations for the weight classes of lead/following aircraft. Depending upon the aircraft type pairs, the separation standards vary among 2.5, 3, 4, 5, and 6 nmi. Without well defined paths all the way to touchdown, it is difficult to establish landing times and effective sequences. Unless landing sequences are known, it is difficult to determine time separations and therefore determine airport capacity. As such, the ATC system uses hourly airport acceptance rates (AAR) or miles-in-trail restrictions based on individual operator experience to meter traffic to the airports. The estimation of capacity becomes even more difficult if the runways are shared for both arrivals and departures. During time periods when traffic demand exceeds AARs, the aircraft are vectored not only for navigation, but also for separation resulting in extended flight paths, increased flight times (costing fuel) and increased air/ground communications.

Figure 1 shows some actual track data from Seattle. The tracks reflect the fact that Seattle is a four-post operation (FLAAK is for turbo-props only). Wide path variations in the turn from the downwind onto baselegs to final are a superposition of the problems just described. The laboratory predefined paths are also shown in Figure 1 along with two FMS arrival routes designed and used at Seattle from the JAKSN and OLYMPIA fixes. The northeast JAKSN arrival has been in use whereas the OLYMPIA Bay FMS route from the southwest was discontinued.

## **Available Technology**

FMS/RNAV equipped aircraft have the ability to precisely navigate from point to point. A majority of aircraft operating at major airports today have RNAV. In order to better serve these aircraft in the terminal environment, the TRUST concept has been developed. The concept is intended to improve overall efficiency of operations at those airports where a significant number of aircraft are equipped with FMS/RNAV.



**Figure 1 Illustration Of Variation In Paths Actually Flown.**  
**Also shown are the laboratory-defined routes and two FMS procedure routes developed by SEA-TAC.**

Navigational precision will improve even more with the advent of satellite based navigation offered by GPS as more aircraft acquire GPS receivers. Any improvement in navigational capability, and subsequently, route conformance, will increase the accuracy of terminal operations planning and aircraft adherence to the plan, thereby maximizing airport capacity.

### Concept Description

Each of the problems discussed in the previous section can be mitigated through the application of improved procedures and appropriate technology, with a paradigm which at once exploits that technology and facilitates a more structured, more

efficient means of operation. This paradigm is embodied in the TRUST concept which has its foundation in the Route Oriented Planning and Control (ROPAC) concept [7,8,9]. ROPAC and now TRUST is designed to monitor aircraft progress against an established schedule and generate speed reduction advisories to be used by the controllers at appropriate times. Proper timing of the advisories enable aircraft to maintain schedule conformance by mitigating the flight time variances.

### **Predefined Routes**

The concept assumes that aircraft fly from meter fixes to runway threshold via predefined but flexible routes. Efficient paths from the meter fix all the way to touchdown are defined. Presumably FMS equipped, or RNAV equipped aircraft could navigate without guidance from the ground (*ad hoc* vectors or heading commands). Unequipped aircraft are expected to be vectored by the controllers essentially along the same route(s) as the FMS equipped aircraft. The routes are designed to be conflict free (laterally). Maintaining overall aircraft separation is still the responsibility of the controllers.

Figure 1 shows the conventional flight paths for about one hour of actual traffic at a busy airport. The aircraft enter the terminal area using STARs, and at some intermediate points as shown in the figure, the aircraft are vectored over downwind and/or baseleg paths to their final approaches. Because the pilots can not turn after the end of STARs until receiving clearances from the ATC system, the aircraft paths vary over a large segment of airspace due to overshoots and undershoots.

Since FMS/RNAV equipped aircraft can navigate over any predefined path regardless of the location of navigation aids, if a route structure were defined from the terminal area entry (meter) fixes to the final approach, not only could the aircraft flight times be predicted accurately over different segments of flight, but also the aircraft could navigate precisely to meet these times. This could enhance the en route metering function's ability to efficiently schedule

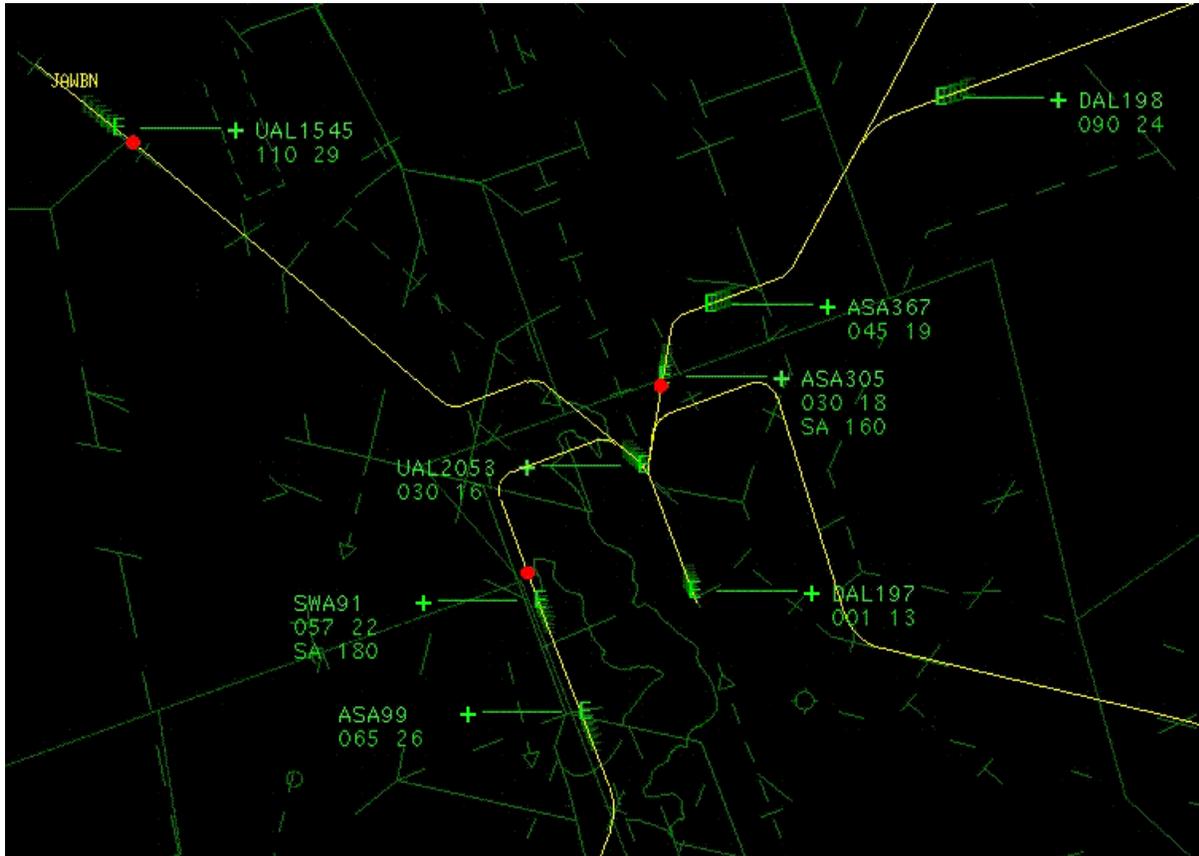
aircraft and minimize delays resulting from large planning uncertainties.

### **Arrival Planning**

The TRUST logic acquires each aircraft as it enters the terminal area, and then determines an estimate of its flight time to threshold assuming the predefined route, and considering winds and aircraft specific performance parameters. This is done for all aircraft in turn. From the estimated flight times a tentative sequence is determined. The sequence is used to establish a schedule, (i.e., scheduled landing times for each aircraft are determined) by applying appropriate separation criteria based on wake vortex separation considerations between lead and following aircraft at the threshold, or when the aircraft are established on the final approach.

### **Speed Advisories**

Having determined a scheduled landing time for each aircraft, the TRUST logic continually monitors (on some regular time basis) the progress of the respective aircraft towards the threshold. Built into the routes are segments where pre-established speed changes will be made. The speed reduction process is based on routine speed clearances issued by the controllers in the current environment. The nominal location of the speed advisory points are chosen to expedite each aircraft so that it flies as fast as possible over the shortest paths to the final approach, in lieu of other constraints. Each time the TRUST logic monitors an aircraft, it calculates a new estimated landing time using a Flight Time Estimator (FTE). As deviations (greater than some threshold value) are noted against the planned schedule, the TRUST logic moves the speed advisory point in an attempt to keep the aircraft on schedule. In this manner, various perturbations (uncertain wind, aircraft non-conformance, reaction time delays, etc.) can be mitigated to keep aircraft on schedule. Speed advisory points are illustrated in Figure 2.



**Figure 2 TRUST Laboratory Routes With Speed Advisory Locations.**

### Arrival and Departure Coordination

After allowing for speed controllability in the TRACON (discussed later), the desired terminal area entry times are established and communicated to the Traffic Management Unit (TMU) in the center. In situations where the departure times are known *a priori*, the departure time slots can be automatically inserted in the gaps in the arrival stream. For some aircraft, where landing times may need to be pushed back, their terminal entry times are adjusted accordingly while the aircraft are still at higher altitudes in the en route airspace. The slots for departures, popups, and reentry of missed approaches can be manually inserted into the schedule, and TRUST will recalculate the TRACON entry times for the subsequent aircraft. If needed, TRUST allows limited path extension for aircraft already on STARs in the TRACON. Once the departure times are established, TRUST can also compute the terminal exit times for coordination with en route using defined

paths and aircraft performance data. Time prediction at a departure “fix” are subject to large variation because of the variation in taxi times and in climb performance for departing aircraft. However, early information on departures transmitted to the en route Center can improve management of traffic with crossing traffic and overflights.

### En Route Metering Interface

Desired “TRACON entry times” for arriving aircraft are communicated to the en route metering function based on the planned scheduled arrivals and the known flight paths that the aircraft would follow. This would alleviate the need for vectoring aircraft. If needed, TRUST could also generate TRACON exit times for the en route Center using the analogous algorithms and updated aircraft performance data base to include climb and acceleration parameters.

## Mapping of Problems to Solutions

Table 1 indicates the conceptual mapping of the relevant perceived problem(s) to components or aspects of the TRUST concept that provide some degree of solution. Associated with each problem and solution are intermediary activities linking the abstraction to a solution of real world problems.

## Benefits

### Operational Benefits

The design of terminal and en route routes were previously tied to the physical location of ground based navigation aids. With the advent of RNAV and FMS equipped aircraft, procedures can be developed which no longer have this dependency [5,10]. More flexibility in designing the routes is now available making it easier for procedure designers to efficiently meet noise and airspace constraints. The integration of multiple routes with aircraft separation managed via speed control would create a more uniform arrival stream. Finally, due to the increased predictability and route conformance, design of procedures which integrate arrivals and departures, become viable providing increased runway utilization, especially for shared arrival and departure runway operations.

### Economic Benefits

#### *Minimized Flying Times*

The predefined terminal routes are designed to be minimum flying time paths subject to environmental and ATC constraints. Aircraft following these routes will have reduced TRACON flying times. The reduced flying times result in fuel savings and also reduce aircraft direct operating costs.

Problem	Activity	Solutions
Predictability	<ul style="list-style-type: none"> <li>• Route definition</li> <li>• Algorithmic development</li> </ul>	<ul style="list-style-type: none"> <li>• Route "design"</li> <li>• Route integration</li> <li>• Wake vortex based separations</li> </ul>
Variability	<ul style="list-style-type: none"> <li>• Training</li> <li>• Advisories</li> </ul>	<ul style="list-style-type: none"> <li>• Modified Procedures</li> <li>• Speed Control</li> <li>• Route Conformance</li> <li>• Estimation of Winds</li> </ul>
Equipage Mix	<ul style="list-style-type: none"> <li>• Identify sites with high FMS equipage</li> <li>• Integrate RNAV, FMS, and GPS technology</li> </ul>	<ul style="list-style-type: none"> <li>• Develop procedure to accommodate mixed equipage</li> <li>• Does not require data-link</li> </ul>
TRACON Specificity	<ul style="list-style-type: none"> <li>• Design modular route and site independent data structures</li> <li>• Understand site constraints for routes</li> <li>• Route (re-)design</li> </ul>	<ul style="list-style-type: none"> <li>• Flexible site adaptation needs</li> <li>• Algorithms are site-independent</li> <li>• Route design tool</li> </ul>
Demand Mismatch	<ul style="list-style-type: none"> <li>• Identify mechanisms for TRACON and en route center interaction</li> <li>• Involve TMC in simulations and concept</li> <li>• Investigate transition airspace tools</li> </ul>	<ul style="list-style-type: none"> <li>• Arrival management</li> <li>• TMC aid</li> <li>• Feedback optimal entry times to en route</li> <li>• Arrival and departure sequencing and scheduling</li> </ul>

**Table 1 Correspondence of TRUST to TRACON Problems**

#### *Improved Throughput*

As mentioned earlier, gaps can occur in the arrival stream for a variety of reasons, the primary being the mismatch of demand to airport capacity. Application of the TRUST concept would close these gaps so more aircraft could land per unit time, thereby increasing runway utilization. Given *a priori* departure times, coordination between arrivals and departures would result in an optimal use for naturally occurring gaps in the arrival stream. Gaps

could be maintained or widened for purposes of allowing for departures. A shared runway operation would realize a larger gain in airport throughput.

*Adaptability*

The TRUST concept described herein could have different operational instantiations. Some of these possible solutions would require new or enhanced software. Deployment of software systems which are not easily adapted to additional sites can be costly. It has already been demonstrated that this system is easy to adapt to most airport configurations. Additionally, economic benefit would be obtained if the procedure development and deployment cycle could be shortened. At airports where a majority of aircraft are equipped with RNAV/FMS, TRUST may expedite the design, testing, and implementation of routes and FMS arrival and departure procedures.

**Safety Benefits**

*Reduced Air and Ground Communications*

Self-navigation will reduce the need for communication between the pilot and controller currently used to vector aircraft. This will allow the controller to focus on maintaining separations and allow the pilot more time to efficiently fly the aircraft. Reduced air and ground communication will reduce operational errors due to miscommunication and alleviate some of the voice congestion. Also, route conformance will naturally lead to a more orderly, safely separated arrival stream.

*Reduced Workload*

Clearing aircraft to fly a predefined route provides the controllers with additional time to focus on other air traffic concerns such as vectoring the unequipped aircraft. Because of reduced communication between pilots and controllers, the pilots will have more time to focus on their situational awareness versus focusing on management of the aircraft.

**Results of Paper Study**

Operational data from a major airport traffic sample were analyzed as a baseline to determine

preliminary benefits of using the concept. The following Table 2 provides a summary of these preliminary benefits [8].

Item	Results
Average Delay Reduction per Aircraft	3 min
Average Fuel Savings per Aircraft	54 gal
Maximum Fuel Savings for One Aircraft	338 gal
Increase in Runway Throughput	14%
Reduction in Number of Vectoring Commands	30%

**Table 2 Paper Study Estimates of Benefits**

Precision navigation capabilities in conjunction with predefined terminal routes managed using speed control provide a range of operational, economic, and safety benefits. Development of procedures based upon the TRUST concept would complement existing and planned decision support systems and, in turn, help these systems realize additional benefits [11]. Table 3 summarizes the potential benefits from applying the TRUST concept.

Benefits		
Operational	Economic	Safety
Procedure independent of navaid location	Reduced flying times	Reduced air-ground communications
Route design flexibility	Improved Throughput	Reduced workload
Arrival and departure integration	Reduced implementation and maintenance costs	Reduced TRACON/Center coordination

**Table 3 Qualitative Benefits of TRUST**

## Development Plan

### Methodology

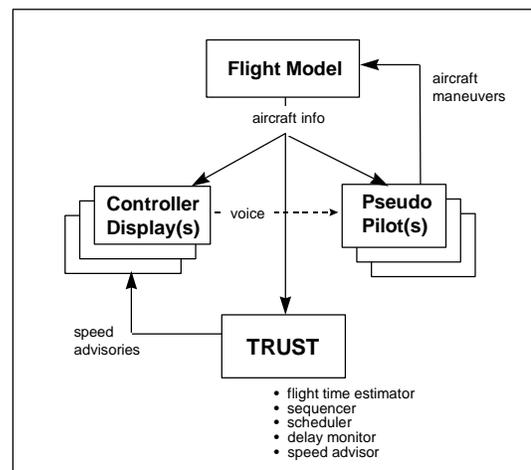
Part of the process of concept exploration and concept development is the use of prototypes and simulations to further define and refine technical issues. A simulation has been developed for exploring the concept of defining new procedures rooted in pre-defined terminal routes and speed control. A connection is made between the concept/possible solutions and the end state/perceived problems via a computerized model. The computerized model provides a means for evaluating potential concepts as viable solutions. Verification and Validation (V&V) plays a central role to this evaluation process [12]. As a result, a V&V plan was developed as means of creating a solid foundation for work progression and future success [13].

### Evolving and Iterative Process

The V&V process is iterative and may expand or contract according to the needs of the project and the path taken. A V&V plan provides a valuable tool for responding to project scrutiny since it is a standard technique embraced by the simulation and modeling community. The path taken by a project as it evolves from a concept to a laboratory prototype to a field prototype changes in response to environmental stimuli.

## Core Capability

In order to evaluate the feasibility of the TRUST concept, a core capability was developed to serve as a laboratory prototype of TRACON operations using TRUST. The core capability was based on an existing Air Traffic Control (ATC) simulation running on a UNIX workstation, which consisted of a real-time flight model, along with simulated controller display, and Pseudo-pilot capabilities. The TRUST concept was integrated into the existing legacy simulation [14,15] by adding a TRUST algorithm component as illustrated in Figure 3. The following subsections describe the core elements of the TRUST design. Basic algorithms for each function have been developed with the intent of making site adaptation easier.



**Figure 3 Schematic for Core Capability Functionality Used for Concept Evaluation**

### Information Infrastructure

The information infrastructure used for building the TRUST laboratory prototype is site independent. Capabilities already existed to simulate the terminal area. These capabilities include the presentation of site-specific video map, aircraft with data blocks, system clocks, controller interactions via keyboard and trackball, controller communication to pseudo-pilots, and several modes of moving aircraft: routes, scripts, and flight trajectory models based on aircraft performance data which are specific to aircraft type.

### *Site Configurable Routes*

The TRUST route structure was designed so that it is not specific to any airport. The routes are broken down into straight level and descent segments and turns, with speeds and altitudes defined for each segment. Adapting the routes for another site is as simple as defining a set of segments with latitudes and longitudes, with speeds and altitudes defined at the beginning and at each endpoint. This flexibility was demonstrated when the TRUST prototype was adapted to Brussels National Airport within a few weeks.

### *Sequencing and Scheduling*

Aircraft landing sequences and corresponding scheduled arrival times at the runway threshold are established by taking into consideration the desired separations among different weight classes of aircraft. Departure slots are allowed to be built into the arrival sequences/schedules by permitting controllers to interactively reserve departure slots at specific times between the arrivals.

### *Speed Advisory Generation*

Aircraft typically enter the TRACON at speeds above 250 knots Indicated Airspeed (IAS), and reduce to 250 knots when they reach an altitude of 10,000 ft. The ATC system typically uses two speed reductions to 210 knots and 180 knots in the downwind/baseleg region. The aircraft reduce to the final approach speeds of about 150 knots before the outer marker. The same speed reduction process is used by the TRUST speed control logic<sup>5</sup>. A continuous descent from the terminal entry altitude to the desired outer marker altitude is assumed to determine flight levels at intermediate points along the defined path segments, after properly accounting for smooth turns and level decelerations.

The aircraft scheduled landing times are planned on the assumption that the reduction to the next permissible speed along each path segment would be initiated near the end of each path segment. Managing the speed control point to achieve an

earlier speed reduction could correct deviations from the scheduled landing times. The speed control algorithm adjusts the current segment's speed reduction location to correct for delay. If delay cannot be alleviated by taking an early speed reduction in the current segment alone, the algorithm looks ahead to future segments and shifts future speed reduction points as necessary. When an early speed reduction is needed in the current segment, an advisory will be displayed to the controller. The computer human interface (CHI) for this advisory is preliminary and yet to be determined. One way to communicate the information to the controller is via a dot which could appear on the screen. This indicates an advisory to the controller to issue a clearance based on the desired speed reduction over the flight segment. The speed advisory information could also be shown in the third line of the data block on the radar display.

### *Estimation of Terminal Entry and Exit Times*

TRUST computes the earliest landing time for each aircraft using the defined route structure, winds and aircraft-specific parameters (speed profile, descent, deceleration, and turn rates) from an appropriate data base. A tentative landing sequence for aircraft is established based on first-come-first served approach to the runway. The scheduled landing time for the first aircraft is set equal to its earliest landing time. The scheduled landing times for the subsequent aircraft are derived by adding the desired time separation between each pair of aircraft to the scheduled landing time of the lead aircraft. A delay is defined as the time difference between the aircraft's scheduled landing time and its earliest landing time. In the case where the earliest landing time of any following aircraft is later than its computed scheduled landing time, the scheduled landing time is set equal to the aircraft's earliest landing time. A negative delay in such cases indicates a gap in the arrival stream. Analogous logic would define TRACON exit times.

### *Flight Time Estimator (FTE)*

The FTE is used to obtain flight time estimates for aircraft following the predefined routes. Each route is a union of straight line segments and turns.

---

<sup>5</sup> The actual speeds are parameterized in the data structure.

The FTE assumes the aircraft maintains constant indicated airspeed in descents and that the aircraft decelerates at a constant altitude. Turns are also assumed to be performed at a constant altitude. A linear wind shear model is considered to estimate the impact of the along-track wind component [16]. The input parameters for the flight time estimation algorithms are aircraft performance data (based upon aircraft type) and the route definition (planned flight profile). Eventually the FTE algorithms will estimate flight time biases arising from composite sources and correct for these biases.

### *Flight Model*

The flight model is used to update the aircraft state in the simulation. Based upon default settings or user input, the flight simulation will update each aircraft's state based upon various operational modes. In addition, the flight model was enhanced to include a trajectory-following capability, which could model an aircraft flying in FMS or RNAV mode. A gridded wind model was implemented to be used by both the flight model and TRUST components. Furthermore, several error models were implemented in the simulation, including from navigational errors, variation in pilot response time, controllers' speed instructions response time, and errors between forecast winds (used by flight time estimation algorithms) and real winds (used by the flight model).

### *Scenario Generator*

The Scenario Generator has the capability to create traffic scenarios either from prerecorded aircraft track data or by specifying scenario parameters. To create a scenario from prerecorded data, the Scenario Generator determines the times at which each aircraft is closest to a meter fix entry point. That time will be used for creating the aircraft in the scenario entering the system at that meter fix. If two aircraft are violating separation at the start time, then they are separated according to separation rules. This capability allows the user to create realistic scenarios based on what actually occurred in the prerecorded data.

The Scenario Generator also allows the user to create a scenario based on the following parameters:

duration of traffic demand, arrival rate, percentage of small, large, or heavy aircraft, of FMS/RNAV or unequipped aircraft, of arrivals over each meter fix, and a maximum meter fix delivery time perturbation. Once the input parameters have been selected, the traffic scenario is generated by creating a successive sequence of aircraft and assigning them times on the runway. The runway times are based on wake vortex separations, landing speeds and a specified intrail buffer to allow for final approach deviations. The aircraft are then assigned to the desired route and their time to fly the route is calculated. Then the aircraft time is projected back to the meter fix and the simulation start time is calculated.

Once a scenario is created, any of the aircraft's fields may be changed. The Scenario Generator will reestablish the rest of the scenario accordingly.

### **Verification and Validation Role**

As an integral part of the development process of TRUST, a formal Verification and Validation (V&V) Plan has been developed [13,17,18]. The V&V Plan defines numerous tests to be applied to the TRUST laboratory prototype. The verification tests ensure that the algorithms and prototype are performing as designed. The validation tests indicate the suitability of the concept for meaningful ATC applications, viability of operations under what set of conditions. Validation includes controller-in-the-loop evaluations, which determine controller effective use of the TRUST generated information and display needs.

Results are reported on the robustness of the system within designed bounds assessed through closed-loop testing of simultaneous parameter variation. Sensitivity analysis parameters were assigned to three different categories: concept parameters, prototype parameters, and environmental parameters. The prototype parameters are specific to the computer model, the environmental parameters refer to items which do not change radically and are not the focus of the study; and the concept parameters are the key parameters of interest by determining whether the concept makes sense for a particular site.

The concept parameters are meter fix time accuracy, FMS/RNAV equipage ratio, accuracy of wind information, and arrival rate/traffic density.

Prototype parameters are intrail buffer, speed advisory clearance time, speed advisory delivery buffer, and the aircraft movement conformance update cycle. Environmental parameters include tolerance of wind error, tolerance of navigation errors, aircraft performance parameters, controller/pilot response delay, and surveillance error.

In controller-in-the-loop simulations, FMS equipped aircraft will fly their nominal routes without the requirement for controller vectoring. Unequipped simulated aircraft will be conventionally vectored. The ratio of FMS to RNAV equipped and unequipped aircraft will be varied to determine the level of equipage that is necessary to make the concept work. Feedback from controllers on the issuance and display of the speed advisories and specifically, to record and study their reaction to a paradigm that allows them to control aircraft via speed control with limited vectoring contributes to an assessment of the concept viability. After successful V&V, it is expected to test the concept in an operational environment using a field prototype.

## Progress

### Developed Core Capability

The initial prototype development will support controller-in-the-loop evaluations which will not incorporate pop-ups or missed approaches. It is intended to support preliminary controller feedback and highlight controller CHI issues versus pilot CHI issues [19].

The current core capability will support sensitivity studies on:

- minimum percentage of FMS/RNAV equipped versus unequipped aircraft
- timing thresholds and buffers
- navigational error
- knowledge of winds
- meter fix delivery time precision

The core capability will be extended to allow:

- changing sequences or changing schedules
- creation of slots for pop-ups or missed approaches

- conformance monitoring
- enhanced speed advisory logic

All of the components required to simulate traffic and test the TRUST system response have been developed.

### Verification Completed

Before using the core capability to assess the operational validity of the TRUST concept, it was necessary to verify that the algorithms for sequencing, scheduling, flight time estimation, speed advisory generation, trajectory-following and other functions had been implemented properly in the simulation software. To this end, a series of 16 verification tests were designed as part of a V&V Plan. For each test, the purpose of the test, basic methodology for conducting the test, and verification criteria were defined. The tests covered all aspects of the core capability, including: FMS/RNAV trajectory-following capability, error models, wind model, aircraft performance parameters, conversions between indicated air speed and ground speed, flight time estimation algorithms, and speed advisory algorithms.

In order to conduct the verification tests, a set of output data was defined to be collected during each verification run. The output data was parsed and analyzed using a combination of Perl scripts and the MATLAB® software package.

The verification effort spanned a period of several months, and was extremely useful in preparing for laboratory validation activities. Preparation of the core capability for the verification effort uncovered some missing features that subsequently were implemented in the core capability.

For certain verification tests, initial results did not match the Verification Criteria for passing the test, which enabled developers to detect and correct bugs in the software. This led to an iterative process of de-bugging and re-executing the verification tests until the results achieved matched expectations. Of the 16 tests defined in the V&V Plan, 15 have been completed successfully [20]. The remaining test, which consists of a series of Monte Carlo studies, is currently in progress.

## **Independent Verification and Validation**

A personal computer (PC) based simulation has been developed for exploring the concept of defining new procedures for using pre-established routes in conjunction with speed control in the terminal area [21]. As a part of the Independent Verification and Validation effort of the TRUST concept and automation, the PC-based simulation allows real and fast time simulation of route-bound aircraft receiving speed control advisories to effect threshold spacing. The PC simulation includes many self-verifying features via animation linked to the movement of aircraft and the response of the TRUST system. The simulation implements all algorithms independent of the laboratory prototype, usually in a simplified but consistent form. The degree of simplification and resulting fidelity compared to results obtained from the laboratory prototype is itself interesting and a useful validation technique. The PC-based simulation can be used for iterative, quick time studies and for the rapid prototyping of new algorithms, methods or other ideas pertaining to validating the TRUST concept or its variants.

The simulations share some common data structures (e.g., Automated Radar Terminal System (ARTS) data input, aircraft track recording, etc.) to facilitate direct comparison of scenarios and tests.

## **Results**

### **Operational Acceptability**

#### *Industry Feedback*

The core capability has been used to demonstrate the TRUST concept to various stakeholders in the aviation community, including representatives from Federal Aviation Administration (FAA) Headquarters, FAA Regional Offices, National Air Traffic Controllers Association (NATCA) representatives, National Airspace System (NAS) Users including (American Airlines, USAirways and ComAir), industry representatives (including Airbus), and representatives from the international community. In addition, demonstrations of the TRUST concept received wide exposure as part of an exhibit at the

Fall 1998 Radio Technical Commission for Aeronautics (RTCA) Conference.

Reaction to the concept demonstrations has been generally positive. Some demonstrations have prompted suggestions for new applications of the TRUST algorithms, or for ways of combining the TRUST concept with other tools such as the Converging Runway Display Aid (CRDA), which is baselined in the ARTS, or Data Link. Demonstrations have also elicited comments on issues that may affect the operational implementation of the TRUST concept, including integration of pop-ups and missed approaches into the sequence, accommodation of dynamic re-routing due to weather, methods of handling aircraft that are out of conformance with their assigned FMS/RNAV route, and issues surrounding the ability of en route controllers to meet assigned meter fix times with the required accuracy.

#### *Site Feedback*

Concurrent with our simulation development and testing efforts, we have continued our interactions with staff and controllers at Seattle-Tacoma International Airport (SEA-TAC), to better understand their operations and to properly adapt our simulation [22]. During the most recent site visit we were able to use the PC-based simulation on a laptop commuter to facilitate interactions with the staff and controllers. The reaction to the TRUST concept was very encouraging. The site interactions were unanimous in indicating that the concept made sense and had merit. They recognized the opportunity to *integrate* FMS/RNAV routes, rather than having to work unequipped aircraft around the route constrained for FMS equipped aircraft. They were amenable to partial solutions; thought SEA-TAC was an appropriate site; and wanted to be involved in the development of new procedures and automation.

SEA-TAC provided suggestions on route design. Furthermore, SEA-TAC has experience dealing with FMS aircraft and also has some experience with the use of speed control on FMS routes. SEA-TAC personnel explicitly indicated that they would be interested in partial solutions (for example, improving

the coordination of the feeder controllers' hand-off to final).

*Controller Feedback*

A preliminary assessment of the feasibility of the TRUST concept was conducted in September 1998 during a visit to the Center for Advanced Aviation System Development (CAASD) by a controller from SEA-TAC. The controller was shown a demonstration of the TRUST concept using the developed core capability. The demonstration included the initial assessment of TRUST route design for Seattle, and a sample traffic scenario created with the Scenario Generator.

The Seattle controller provided suggestions for modifying the TRUST routes to avoid noise-sensitive areas, and to conform to current airspace restrictions with respect to the altitudes at which aircraft should be at specific points along the TRUST routes. The controller also provided input on making the traffic scenarios more realistic in terms of typical levels of traffic arriving at each meter fix, and more realistic mix of jets and props. In addition, other necessary simulation features were discussed, including requirements for handoffs between controllers, specific pseudo-pilot functions, and specific display functions. The Seattle controller did not have any immediate suggestions for changes or improvements to the proposed CHI for displaying speed information to controllers. He expressed an interest to gain more experience working with the simulation before commenting further.

**Metrics and Their Determination**

*Controllability*

An important metric for the TRUST automation is the amount of control (time adjustment to meet landing time via speed control) in the system for a given aircraft. All other things being equal, and relying on no other control mechanism including route extensions, the controllability would help define the minimum requirements for metering fix delivery accuracy to be dealt with by a control system such as TRUST.

For measuring the controllability<sup>6</sup>, a monitor looks at the current status of the aircraft. It compares the estimated landing time (ELT) (obtained via the flight time estimator + clock ) to the scheduled landing time (SLT) of the aircraft. Ordinarily, when the ELT and SLT are sufficiently different, the monitor will set the aircraft status accordingly, and then the speed advisor (SA) will move the point (in each of three SA segments per route) at which the speed advisory is issued so as to minimize or eliminate the difference between ELT and SLT. The extremes to which the SA point(s) can be moved, determine the amount that the flight time can be adjusted. The total amount that the flight time can be adjusted from TRACON entry to the final approach segment is termed as the controllability.

The technique that was used to measure controllability is as follows. By design, the simulation includes various extreme-test switches. One such switch is a monitor-status-override. This allows a scenario to be executed with the aircraft status set to one of the following values: nominal, on time, late, or early. By comparing flight times between the scenarios executed with status equal "late" and status equal "early" the amount of controllability is easily deduced since the SA will be issued at the extreme limits for the respective cases. Using this technique, the estimates of controllability of the current lab-defined routes (refer to Figure 1) found are indicated in Table 4.

Entry Fix/Route	Sector	Measured Controllability (seconds)
OLYMPIA	SE	84
RADDY	SW	92
JAWBN	NE	53
JAKSN	NW	61

**Table 4 Estimates Of Controllability**

The range of controllability measured and reported here is consistent with previous studies [23].

<sup>6</sup> The results and methodology reported here are from [21] and are consistent with the laboratory prototype.

All times were measured with a “level deceleration” model with nominal deceleration values of 50 kts/min and descent values of 350 ft/nmi [24].

The routes entering from the north (JAWBN and JAKSN) have less controllability, since the STARS turn directly over the baselegs to the threshold in the south operation we are prototyping (refer to Figure 1).

### *Flight Time Variation*

Another evaluation conducted as a part of the IV&V of the TRUST laboratory prototype concerns the determination of how much flight time variation can be introduced for a given route due only to variation of the descent and deceleration parameters. The data represent over 100 hours of *simulated* time.

The TRUST flight time estimator makes assumptions about how the aircraft will fly (route conformance, and values for deceleration and descent gradients, etc.). This begs the question “what if the aircraft does not perform as expected?” Can TRUST provide enough speed control to handle the flight time variation? The conclusion from these simulations show that, all other things being equal, the range of flight time variations introduced by aircraft nominal deceleration and descent performance is well within the measured controllability over the routes tested (OLYMPIA, RADDY, JAWBN and JAKSN).

These results were consistent across three different variants of the flight model(s) that were implemented—(1) simultaneous<sup>7</sup> deceleration & descent allowed, (2) "level decel"— aircraft levels off during any deceleration phase with 100 feet/nmi maximum downward drift during the deceleration phase, and (3) truly level descent (i.e., zero downward drift during any deceleration phase). Route conformance and final approach performance was held constant for all tests.

Note that these tests were performed with the speed advisor "locked" at the nominal positions for all

---

<sup>7</sup> Some combinations of deceleration and descent values for a given route will not necessarily result in concurrent execution of the deceleration and descent, but should they "overlap," simultaneous/independent decelerations and descents are allowed.

aircraft, i.e., all aircraft received the decelerations at exactly the same points on the routes. In effect the speed advisor is "turned off." Otherwise, TRUST would have been affecting the flying times by trying to keep the aircraft on schedule, which would have obscured the measurement in question. The findings are summarized below:

- All flight models show, that for a reasonable assumption for the performance envelope, the flight times changed by no more than 20-30 seconds.
- Whether one models "level deceleration" or "truly level deceleration" as defined here, makes very little difference in flight times. However there are significant differences in the level deceleration model flight times vs. the simultaneous deceleration/descent model.
- The variation is exceeded by the measured controllability.

While conducting these tests we noticed that not all nominal aircraft performance values allowed the aircraft to "fly the lab-defined routes". The aircraft could not complete the planned flight profile by adhering to the assumptions of the profile. The assumptions are that an aircraft must complete a descent or deceleration before initiating a turn, or before another deceleration and descent maneuver begins.

## **Route Design**

### *Approach to Route Design*

An important result of the effort to date is the design and implementation of an adaptable route definition data structure [9]. Routes are specified by segments characterized by the expected maneuvers and are delimited by lat/lons. In effect, the route and maneuver segments could be adapted to meet the requirements at a particular TRACON. Indeed, all TRUST algorithms built on this data structure (such as the flight time estimator) are, at the computer implementation level, oblivious to site specific routes and procedures. This approach has proved very valuable in the rapid prototyping, modularization, and verification of the system.

### *Site Participation in Route Design*

To begin development of the simulation of TRUST for SEA-TAC, some reasonable approximations were made to construct routes consistent with observed aircraft flight paths for the operation in question. Routes were constructed which originated at the respective meter fixes and were oriented (“vectored”) according to ground based navigation aids (VORs). As appropriate, downwind and baseleg segments were laid out, and all routes joined the extended final at a thirty degree angle of intercept (please refer again to Figure 1).

Concurrently we began a study of the appropriateness of the lab-defined routes, both in terms of their “flyability”—an aircraft performance issue; and in terms of the particular constraints of the site—an operational issue. Interactions with the site concerning the previous efforts to understand their established FMS procedures were useful in helping to identify design criteria for the routes.

The routes were also redrafted<sup>8</sup> to more accurately account for site-specific noise abatement constraints (see Figure 4).

### *Flyability of the Lab-Designed Routes*

While conducting verification tests for the laboratory prototype, it was noticed not all aircraft could fly the lab-defined routes<sup>9</sup> using nominal performance values while adhering to the constraints of the flight profile. The constraint were that maneuvers (turns, descents and decelerations) be independent.<sup>10</sup> The redesigned routes were then slightly modified for flyability. In this regard the simulation is clearly a valuable tool for evaluating proposed routes.

---

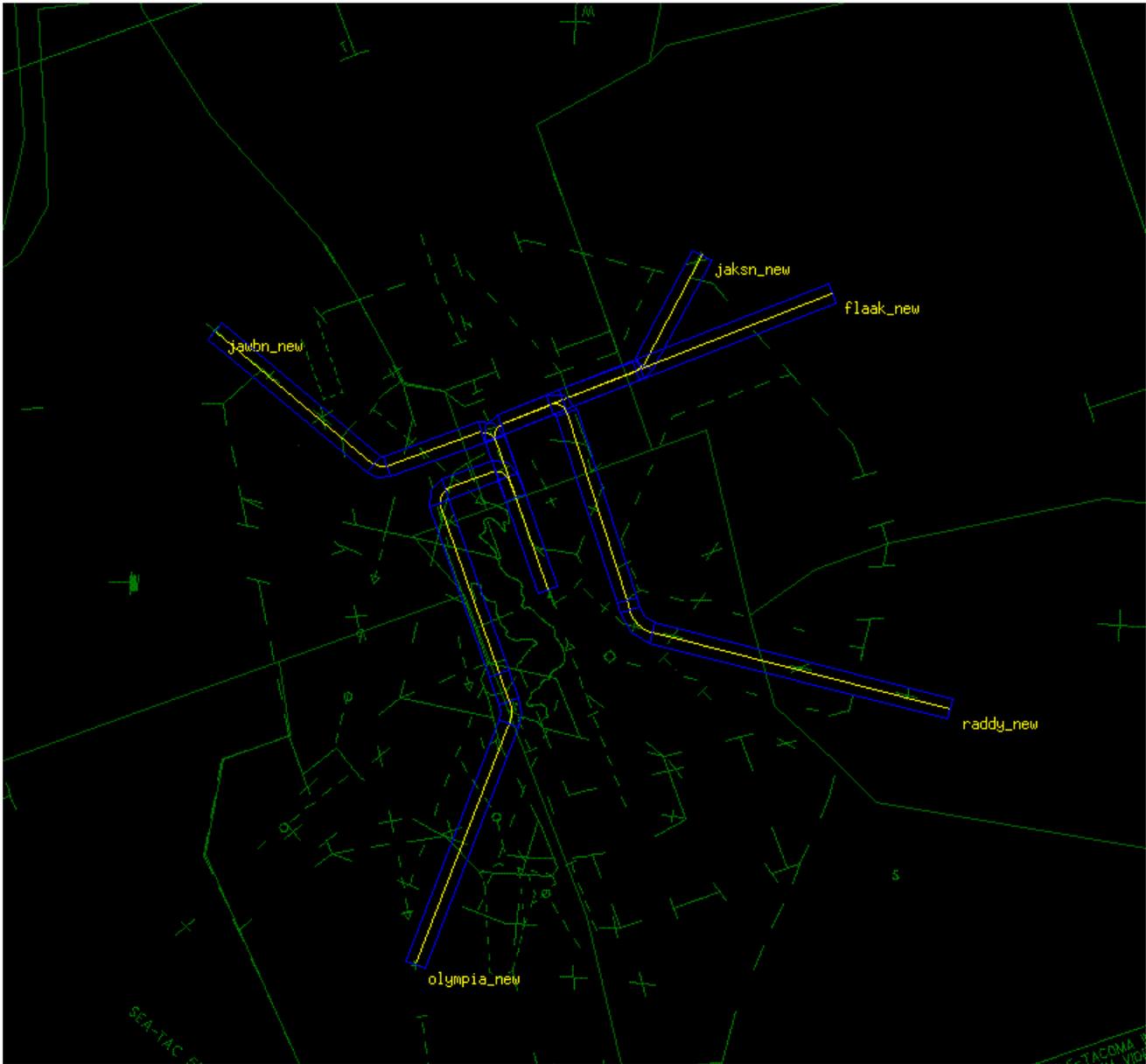
<sup>8</sup> There is no indication that the redesign as currently understood will change the conclusions reached here regarding flight time variation and controllability. The “final” lab-designed routes will be compatible with site-specific constraints and with most aircraft performance.

<sup>9</sup> This fact was observed not only in the laboratory prototype but in the independently developed PC-simulation and other analyses [25]. This is a good example of the benefits of the V&V process.

<sup>10</sup> Concurrent executions of descents, decelerations and turns are not modeled in the flight model software.

### *Route Adaptation*

The general structure of the routes is not changed, however to accommodate the site constraints and aircraft performance constraints, the segment definitions (lat/lon, expected maneuvers, etc.) were changed. For example, some downwind segments extended. The site-independent nature of the data definition allows the straightforward adaptation of the relevant TRUST algorithms from one site to another. Adapted simulations have been implemented already for Seattle, Brussels and Philadelphia.



**Figure 4 Redesigned Laboratory Routes Consistent With Noise Abatement Procedures At Seattle.**

#### *Route Design Tool*

Since it may be necessary to define new routes or modify candidate draft designs for routes at a particular site, CAASD has begun development of a route design tool. In its simplest form it allows layout and definition of a route structure with links to the FTE and flight model so that fly-ability can be concurrently evaluated. An interface will be developed that would allow online modification of the route data structure being used by TRUST. This may

not only facilitate route design and exploration of related airspace redesign issues, but also will provide an opportunity to explore the notion of the dynamic modification of the site route structure for applications such as weather avoidance, path extension, etc.

## Path Variation Comparison

A sample of track data from Seattle was used for comparing actual flight times and distances based upon current operations with the laboratory terminal routes. Flight times and distances were computed for each route along with flight times and distances for actual tracks associated with each particular route. Not surprisingly, the use of pre-defined routes which overlay the de-facto average path of arriving aircraft along with RMS/RNAV self-navigation reduces the average path distance and time of aircraft flying from meter fix to threshold; also—and this is the point: reduces the overall variability.<sup>11</sup>

The baseline data used for comparison was obtained from SEA-TAC ARTS tapes and was carefully filtered and reduced so that only representative arrivals to runway 16L were analyzed. Tracks which had holding patterns or which did not significantly overlap the TRUST routes were not used. The actual track was assigned to the appropriate TRUST route based upon the closest meter fix when the aircraft entered the TRACON. In order to obtain means for the variability analyses, the average routes lengths and variation were then computed and compared to simulated traffic flying the lab-defined routes as shown in Figure 1.

With a preponderance of FMS-equipped aircraft for each route the variability (of both time and distance) was reduced for aircraft flying the TRUST routes.

The following Table 5 indicates the statistical comparison (n=14) for the OLYMPIA route (from the southwest). Data from the other routes are not reported statistically due to small sample size.

OLYMPIA	TRUST Route	ARTS Baseline
	$s$	$\sigma$
TIME (sec)	17	103
DISTANCE (nmi)	0.6	4.4

**Table 5 Standard Deviation of Flight Times and Distances**

In the future we will repeat the comparisons with controller-in-the-loop simulations.

## Applications

The components of the TRUST concept and associated automation can be selected according to the needs and requirements of ATC applications. There are three basic modes in which TRUST can operate: Procedure Evaluation, Air Traffic Management, and Speed Advisory.

### Procedure Evaluation

There are four subactivities that define the procedure evaluation mode.

#### *Controller-in-the-Loop Simulations*

TRUST can be used to facilitate the evaluation of the impact of new routes and procedures using scenarios based on the prerecorded flight operations data. After it is determined in a lab environment (using a controller-in-the-loop mode of the simulation) that the procedures are effective and usable by the ATC operators, the core capability could be used to familiarize the air traffic managers and planners. The procedures could then be implemented for actual operations.

#### *Training*

Used in an offline setting, TRUST is valuable for assisting controllers to become proficient with use of speed control. With all routes integrated by the automation and correlated by the adopted procedure, controllers can learn techniques and skills to use speed control on route-bound aircraft, including unequipped aircraft, and become comfortable with a new paradigm of control.

<sup>11</sup>It is a premise of the TRUST concept that similar reductions in variation would be seen regardless of the actual positioning of the routes.

<i>ACID</i>	<i>Type</i>	<i>Route</i>	<i>Class</i>	<i>#</i>	<i>Delay</i>	<i>SLT</i>	<i>SDT</i>	<i>ARRIVAL Spacing</i>
DLH4306	EA32	KLENE	H	1	-11	00:23:44	--	--
SAB756	ARJ	TOLEN	H	2	-2	00:26:31	--	167
DLH5198	CRJ	KLENE	H	3	0	00:28:27	--	117
FIN817	MD80	KLENE	L	4	10	00:30:47	--	140
SAB415	B737	DEPARTURE	L	--	--	--	00:32:37	--
DLH516	CHJ	DEPARTURE	H	--	--	--	00:34:07	--
SAB465	BA46	KOKSY	L	5	34	00:36:32	--	345

**Table 6 Facsimile of Arrival and Departure Interface**

*Route Definition and Evaluation*

Route design requires collaborative effort of the airlines and the site. Often the process is iterative. Routes must be constructed that satisfy the needs of both parties, and meet the particular constraints of each. Use of TRUST can facilitate the interaction and can be used to evaluate the performance aspects of the routes.

*Terminal Airspace Design*

Extending or applying the route design capability further, it is clear that automation tools such as TRUST can be used as part of the larger problem of airspace design. The connection or extension of STARS to FMS-like routes would facilitate the simplification of the overall terminal structure.

**Air Traffic Management**

*Passive Mode*

In this mode, the TRUST algorithms require only a one way real time data feed from the Automated Radar Tracking System (ARTS). Live traffic is seen and evaluated by the TRUST automation according to the pre-defined route structure so that schedules and sequences are indicated. This simple level of situational awareness is apparently useful at some sites. In particular this is the design requirement for the Brussels application of TRUST. The ATC operators could use these times to regulate the flow of

traffic in and out of the terminal area to minimize delays at the airport. In effect, a TMC position utilizes the improved view of the evolving traffic for planning purposes resulting in a more efficient operation.

*Arrival and Departure Coordination Mode*

Taking the planning capability one step further, an external processor with a graphical user interface allows interactive operator (typically the TMC) inputs to reserve slots for departures, unmetred aircraft, and missed approaches, as well as display aircraft schedules and en route/terminal transit times. Table 6 illustrates the interface for displaying the schedule.

**Speed Advisory**

This mode, as originally conceived in the ROPAC paper, allows information on speed advisories to be communicated to the controllers through an interface with ARTS. This mode facilitates keeping all aircraft on schedule resulting in a more efficient operation. Controllers can expect equipped aircraft to maintain their route-bound approach, thus reducing the workload to the interaction of speed control for those planes. Meanwhile the controller is free to vector any unequipped aircraft for route conformance. Unequipped aircraft also get speed advisories.

TRUST coordinates the integration of all routes and all aircraft, equipped or not. Computer human interface evaluations are planned to determine how to best present the speed advisory information on the controller displays.

## Summary

The typical TRACON presents challenges with respect to managing the arriving aircraft (and departures) so as to reduce variability, improve predictability, and optimize time-varying demand and capacity. The TRUST concept allows a synergy of available navigation technology (FMS, RNAV, and soon GPS) and new procedures (terminal routes) to facilitate a different and more efficient end state for the TRACON operations. Aircraft self-navigating predefined routes are integrated with unequipped aircraft which receive controller vectors, and all aircraft are monitored with respect to a schedule, with residual timing perturbations mitigated via speed control. A simulation environment has been created to evaluate the possible application(s) of TRUST. A V&V Plan is being followed to determine the conditions under which TRUST can be applied and to demonstrate operational acceptance. Preliminary results indicate that the concept has merit.

## References

[1] Denery, D. G., Erzberger, H., Davis, T. J., Green, S. M., McNally, B. D., *Challenges of Air Traffic Management Research: Analysis, Simulation, and Field Test*, AIAA-97-3832, AIAA Guidance, Navigation, and Control Conference, New Orleans, Louisiana, August 1997.

[2] Erzberger, H., and Nedell, W., *Design of Automated System for Management of Arrival Traffic*, NASA Technical Memorandum 102201, Ames Research Center, June 1989.

[3] Lee, K. K. and Davis, T. J., *The Development of the Final Approach Spacing Tool (FAST): A Cooperative Controller-Engineer Design Approach*, Journal of Control Engineering Practice, Vol. 4, No. 8, August 1996, pp. 1161-1168.

[4] Davidson, T., Letter to Frank Alexander, Chairman of Seattle Flight Management System Demonstration Project, July 12, 1994.

[5] Alexander, F., *Seattle FMS Project Objectives and Benefits*, Northwest Airlines, July 9, 1993.

[6] Forman, J. M., 10 April 1998, *Terminal Area Operations and Needs*, F045-M-022, The MITRE Corporation, McLean, VA.

[7] Mohleji, S. C., June 1989, *Route Oriented Planning and Control for Terminal Automation*, MTR-88W00223, The MITRE Corporation, McLean, VA.

[8] Mohleji, S.C., 1996, *A Route-Oriented Planning And Control Concept for Efficient Flight Operations At Busy Airports*, Control Engineering Practice, Vol. 4, No. 8, pp. 1143-1151.

[9] Barker, D. R., Becher, T. A., Chase, S. P, and Harding, J. H., September 1997, *Flexible Terminal Routing: Concept Description and Prototype Design*, MTR-97W0000108, The MITRE Corporation, McLean, VA.

[10] Boan, L. M., Sanders, S. and Mohleji, S. C., 1998, *FMS/GPS/RNAV Routes in the Transition Airspace Briefing Book*, WN-98W0000052, The MITRE Corporation, McLean, VA.

[11] Hunter, G., et. al., July 1996, *CTAS Error Sensitivity, Fuel Efficiency, and Throughput Benefits Analysis*, Seagull Technology, Inc., Cupertino, CA.

[12] Defense Modeling and Simulation Office, 1996, *Verification, Validation, and Accreditation Recommended Practices Guide*, U.S. Department of Defense, Washington, D.C.

[13] Becher, T. A. and Barker, D. R., September 1997, *Flexible Terminal Routing: Concept Validation and Prototype Verification Plan*, MTR-98W0000029, The MITRE Corporation, McLean, VA.

[14] Taraken, R. M., Huang, C. L., Pollio, C. L., 1992, *Integration and Interaction Laboratory Initial*

*Experimentation Capability: Terminal/TASF*, MTR-92W0000192, The MITRE Corporation, McLean, VA.

[15] Harding, J. L., and Chase, S. P., September 1996, *Transition from En Route to Terminal Airspace: Operational Concept Exploration*, WN960000120, The MITRE Corporation, McLean, VA.

[16] Etkin, B., 1972, *Dynamics of Atmospheric Flight*, New York, Wiley.

[17] Law, Averill M. and W. David Kelton, 1991, *Simulation Modeling and Analysis*, Second Edition, McGraw Hill, Chapter 5.

[18] Sargent, Robert G., 1992, *Validation and Verification of Simulation Models*, Proceedings of the 1992 Winter Simulation Conference, ed. J.J. Swain, D. Goldsman, R. C. Crain, and J. R. Wilson, p.104ff.

[19] Lee, K., K., Sanford, B. D., and Slattery, R. A., August 1997, *The Human Factors of FMS Usage in the Terminal Area*, AIAA Modelling and Simulation Technologies Conference, New Orleans, LA.

[20] Harding J. L., September 1998, *Results of Verification of Terminal Routes Using Speed-control Techniques (TRUST) Laboratory Prototype*, MTR-98W0000123, The MITRE Corporation, McLean, VA.

[21] Barker, D. R., December 1998, *Personal Computer Based Simulation of Terminal Routing Using Speed-control Techniques*, MTR-98W000130, The MITRE Corporation, McLean, VA.

[22] Barker, D. R., T. A. Becher, September 1998, *Transmittal of Supplemental Deliverable "Trip Report: Visit to Seattle-Tacoma International Airport,"* F045-L-076, The MITRE Corporation, McLean, VA.

[23] Vandevenne, H. F. and Andrews, J. W., 1993, *Effects of Precision and Terminal Controllability on Runway Throughput*, Air Traffic Control Quarterly, Vol. 1(3), John Wiley & Sons, Inc.

[24] Hunter, George, January 1992, *Aircraft Flight Dynamics in the Memphis TRACON*, Seagull Technology, Inc., Sunnyvale, CA, TM92120-01.

[25] Becher, T. A., September 1998 *Aircraft Performance and TRUST Route Design*, F045-M-045, The MITRE Corporation, McLean, VA.