FLIGHT TRANSPORTATION LABORATORY
REPORT R96-2

PRESENTATIONS FROM THE 1996 MIT/INDUSTRY COOPERATIVE RESEARCH PROGRAM ANNUAL MEETING

MIT

TABLE OF CONTENTS

RM Research Projects at MIT

- *SWISSAIR:* Development and Testing of Next Generation O-D Control System
- *KLM:* RM System Impacts in a Multiple-Hub Code-Share Network
- *CONTINENTAL:* Boeing/MIT PODS Study of Competitive RM Impacts

Current Thesis Topics (June 96)

- Competitive RM Impacts of Detruncation and Forecasting Methods *(D. Skwarek)*
- Critical Evaluation of Airline Hub and Spoke Operations in Europe *(T. Leiber)*
- RM System Impacts in Multiple-Hub Code-Share Networks *(J. Ferea)*
- Competition Between Traditional and Low-Cost Airlines for Local Hub Traffic *(J. Nissenberg)*

Modeling Passenger Choice of Fare Products Under YM Control

Peter P. Belobaba, MIT
Craig A. Hopperstad, Boeing

INFORMS Washington Meeting
May 6, 1996

Presentation Outline

- Boeing/MIT Passenger Origin-Destination Simulator (PODS) Study
- Modeling passenger choice of paths/fares
- Review of PODS simulation architecture
- Simulation scenario and results:
  - impacts of advance purchase fare restrictions with and without YM controls

Boeing/MIT PODS Study

- Undertaken to better understand interaction of YM actions and passenger choice.
- Provides a test-bed for examining impacts of alternative YM schemes.
- Can be used to evaluate the impacts of fare structures under YM booking controls.

Modeling Passenger Path Choice

- Define passenger "decision window":
  - earliest departure and latest arrival time
  - market time-of-day demand profile
- Eliminate paths with lowest available fare greater than maximum willingness to pay
- Pick best path from remainder, trading off:
  - path quality (number of stops/connects)
  - fare levels and restrictions

Business vs. Leisure Passengers

- Two passenger types defined by:
  - time of day demand and schedule tolerance
  - maximum out-of-pocket fare willingness to pay
  - "attributed costs" associated with path quality, fare restrictions, trip re-planning
- Maximum fares and attributed costs modeled as Gaussian distributions.

Modeling Path/Fare Choice

- Given passenger type, randomly pick for each passenger generated:
  - path quality (stop/connect) costs
  - costs for fare restrictions and "re-planning"
  - maximum "out-of-pocket" willingness to pay
- Screen out paths with unacceptable fares.
- Assign passenger to feasible (remaining) path/fare with lowest total cost.

PODS Simulation Architecture

- Multiple iterations of a single day-of-week.
- Replicates YM system over time, taking into account previous interventions.
- “Historical” booking data is used to generate forecasts for “future” departures.
- YM system only uses data available from past observations.

PODS Demand Inputs

- Total daily demand for an O-D market, by passenger type (business vs. leisure).
- Booking curves by passenger type over 10 booking periods before departure.
- Correlation parameters between passenger types and across booking periods.

“Vanilla” YM System

- Simple “pick-up” forecasts of bookings still to come before departure:
- Unconstraining of closed observations based on booking curve probabilities.
- Optimization is leg-based EMSR seat protection algorithm:
  - Serially nested booking classes.
  - Fare inputs = published fares.

Simulation Questions

- Under PODS representation of passenger choice, what are revenue impacts of:
  - advance purchase restrictions, without YM?
  - YM without advance purchase restrictions?
  - advance purchase and YM combined?
- Are revenue impacts additive, or is there an interaction effect?

Base Fare Structure

Fare Code	Dollar Price	Advance Purchase	Round Trip?	Sat. Night Min. Stay	Percent Non-Refundable
Y	$100	--	--	--	--
B	$80	3 day	Yes	--	50 %
M	$50	7 day	Yes	Yes	100 %
Q	$40	14 day	Yes	Yes	100 %

Simulation Scenario

- Two identical airlines in single A-B market, each with one daily flight at same time.
- Market demand factor 0.9 or 1.2 (Cap=100)
- Examine interaction of pricing and YM:
  - Test BASE fare structure against alternative with no advance purchase restrictions
  - Both airlines use "No Control" (first come, first served --FCFS) or same "Vanilla YM".

Results: Revenue Impacts over No Advance Purchase, No YM

	DF = 0.9	DF = 1.2
Advance Purchase, No YM Control	+12.07%	+7.22%
YM Control Only, No Adv. Purchase	+0.99%	+2.38%
Both Adv. Purchase and YM Control	+20.76%	+47.17%

Fare Mix and Loads (DF=0.9)

	Y	B	M	Q	Total
No ADV, No YM	2	2	0	77	81
Adv. Purchase Only	8	4	3	65	80
YM Control Only	2	3	1	76	81
Both ADV and YM	10	8	8	54	80

Fare Mix and Loads (DF=1.2)

	Y	B	M	Q	Total
No ADV, No YM	2	2	0	88	92
Adv. Purchase Only	6	4	2	80	91
YM Control Only	3	4	1	84	92
Both ADV and YM	15	26	21	27	89

Summary of Findings

- Advance purchase restrictions alone result in larger revenue gain than YM limits alone.
- Revenue gain of restrictions and YM combined exceeds the sum of the two:
  - interaction effect between pricing and YM
  - synergy even greater at higher demand factors
- Relative importance of YM control grows at higher demand factors.

PODS NEXT STEPS: MIT/Boeing Simulation Study

Prof. Peter P. Belobaba
MIT Flight Transportation Lab

AGIFORS YM Study Group 1996
Zurich, Switzerland

PODS Next Steps: O-D Control

- Extend PODS YM simulation capabilities to replicate O-D seat inventory control.
- Develop small network for testing purposes:
  - 6 cities; 2 airlines, competing hubs;
  - simulate passenger choice of alternative paths, schedules, and prices.
- Evaluate benefits and competitive impacts of different O-D control schemes.

"Vanilla" O-D Control Schemes

- Identify several O-D control approaches currently used and/or planned.
- Each generic O-D system includes some combination of 4 components:
  - Historical O-D demand data collection;
  - Forecasting future O-D demands;
  - Optimization based on forecasts;
  - Control of bookings for different O-D's

Historical Data Collection

- PODS structure will be expanded to access historical booking data by ODF.
- Different O-D control schemes make use of historical data by:
  - flight leg and fare type (booking class)
  - flight leg and value class (“virtual” class)
  - pax O-D path and fare type (disaggregate ODF)

O-D Forecasting Options

- PODS YM system uses only historical data from "departed flights" to forecast demand.
- Need for ODF forecasts in some schemes raises several questions:
  - Detruncation of ODF demands -- estimation of ODF "booking curves"?
  - Aggregation of ODF data for forecasting?
  - Forecast model specification?

Optimization for O-D Control

- Network techniques vs. leg-based heuristics
- Leg-based heuristics issues:
  - use of "value classes" for demand aggregation
  - "displacement cost" approximation logic
- Network optimization issues:
  - deterministic vs. stochastic formulations
  - how to use solution outputs (e.g.. "bid prices")

O-D Control Mechanisms

- Choice of method for limiting seat availability to different O-D paths and fares.
- ODF availability determined by explicit booking limits or minimum bid prices?
- If bid price control, trade-off more frequent re-optimization and maximum limits:
  - increasing bid price "slope" with bookings between optimization points?

Example 1: Leg-Based Concept

- YM system "sees" only historical data aggregated by fare class or value class.
- Demand forecasts generated by <u>class</u> on each flight leg, based on history.
- Leg EMSR curve approximates incremental passenger value and displacement costs.
- Heuristic ODF "bid price" derived from leg-based analysis.

Example 2: Network Concept

- YM system has full access to detailed ODF historical booking data.
- Demand forecasts generated for each ODF in airline network on future departure day.
- Network optimization to find bid prices for each leg and/or ODF.
- ODF fare must exceed relevant bid price(s) to receive seat availability.

Questions for PODS O-D Study

- Are the claimed benefits of O-D control achievable, given:
  - realistic data collection and forecasting errors
  - choice of alternative paths on same airline
  - competitor with or without O-D control
- What is "optimal" in O-D control?:
  - no "perfect knowledge" or hindsight
  - might depend on competitive situation

More O-D Control Questions

- Trade-off between forecast aggregation and disaggregate network optimization.
- Is it realistic to de-truncate and accurately forecast demand by ODF and departure?
- Is O-D control itself a "zero-sum" game:
  - across paths offered by the same airline?
  - between airlines with equal YM capabilities?

We Want Your Input

- What are the fairest representations of generic O-D seat inventory control systems?
  - demand aggregation and forecasting methods
  - optimization algorithms
- What other methodological issues are of greatest importance?
- Your comments/criticisms are encouraged!

Outline

- Motivation
- Modeling Sell-Up in EMSRb (briefly)
- The Several Possible Objectives
- Market Description
- Simulation Results:
  - -- base case
  - -- varying demand factor (DF)
  - -- varying price sensitivity

Competitive Impacts of Incorporating Sell-Up Estimates Into Revenue Mangement

Daniel K. Skwarek
MIT Flight Transportation Laboratory

Presentation to the MIT/Industry Cooperative Research Program in Air Transportation Annual Meeting
Cambridge, MA -- May 23, 1996

Study Questions

- In a competitive airline market, how does adjusting the revenue management optimizer for expected sell-up (SU) affect revenues?
- How does choice of estimated SU rate vary under different airline objectives?
- How do these effects vary by demand factor and "actual" sell-up potential?

Modeling Sell-Up

Adjusting EMSRb for Sell-Up:

- Weatherford and Belobaba (1996) modify the EMSRb seat protection model to incorporate estimated SU. Protection levels π_n for fare class n without sell-up are given by solving

$$\overline{P_n}\left(\pi_n\right)=\frac{f_{n+1}}{f_{1,n}}$$

where

f_{n+1} is the fare for the $n+1$ fare class

$f_{1,n}$ is the weighted average fare for fare classes $1 \ldots n$

$\overline{P_n}(\pi_n)$ is the probability of selling π_n seats in fare classes $1 \ldots n$.

- With a sell-up rate of $SU_{n+1,n}$ between fare classes $n+1$ and n, protection levels are now

$$\overline{P_n}\left(\pi_n\right)=\frac{f_{n+1}-f_{1,n}\cdot SU_{n+1,n}}{f_{1,n}\left(1-SU_{n+1,n}\right)}$$

Modeling Sell-Up

Motivation:

- Assuming independent demands by fare class ignores passenger willingness to buy a more expensive fare product if desired fare is unavailable.

- Several factors significantly limit this willingness to sell up:

  -- Availability and knowledge of equivalent fares on competitors' flights

  -- Superior service variables (e.g., frequent flyer program, frequency advantages) which favor one airline over another

  -- Passenger sensitivity to higher fares

- Using PODS to test the revenue advantages of incorporating SU estimates provides important clues about how much airlines may induce sell-up while limiting diversion to the competition.

Modeling Sell-Up

Market Description:

- Consider a one-leg market with

  -- Two carriers, Airline A and Airline B

  -- One frequency each, at equal times

  -- Equal airline preference

  -- Demand Factor (DF) = 0.9

  -- Equal fare class structure as follows:

Fare Class:	*Y*	*B*	*M*	*Q*
Fare	\$100	\$80	\$50	\$40
Adv. Purchase (days)	0	3	7	14

- Airline B always adjusts for SU, while Airline A either does or does not.

  -- If both airlines adjust for SU, they use the same constant estimated SU rate. Our symmetric market conditions therefore imply equal revenues.

Modeling Sell-Up

- Since sell-up rates $SU_{n+1,n}$ are positive and $f_{n+1} < f_{1,n}$, protection levels up to fare class n with incorporation of estimated sell-up will be *higher* than without.

- Our simulations assume for simplicity that sell-up rates *do not vary* between adjacent fare class pairs, i.e., $SU_{n+1,n}$ is constant across all $n+1$, n.

Several Possible Objectives:

- Choosing SU rate to maximize individual gains ignores possibly significant effects on competitors' revenues. We therefore consider three possible objectives:

  -- Maximize *difference* between adopting airline and non-adopting airline incomes.

  -- Maximize *improvement* in adopting airline's revenues over SU = 0.0.

  -- Maximize *improvement* in an individual airline's revenues over SU = 0.0 when both carriers adopt SU.

Sell-Up Base Case

Results

- Introducing sell-up is always beneficial except at extreme SU rates.

- A "jointness effect" prevents adopting carrier from achieving all SU benefits. Typically, *both* airlines must adopt to achieve full individual benefit.

- It is not always in the non-adopting carrier's best interests to also adopt SU.

  -- The result of *diversion* of pax with overprotection by the SU-adopting airline.

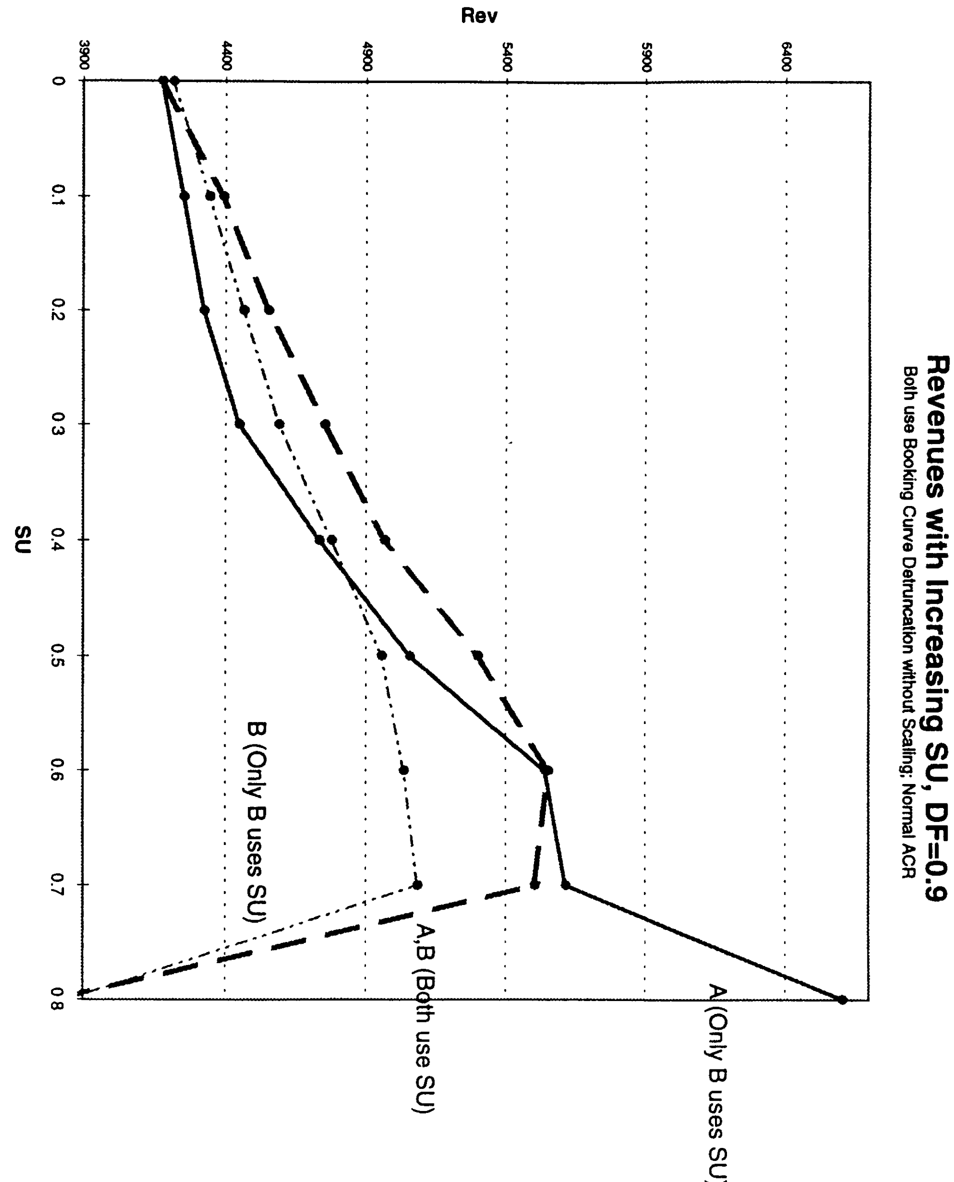
  -- Two critical points:

  (1) Benefit to non-adopting carrier equals benefit to adopting airline

  (2) Benefit to non-adopting carrier equals individual benefit with joint adoption

- Objective Performance:

Base Case Best Estimated SU Rates and % Revenue Improvement			
Airline B's Objective is to Max Difference Between:	Best Est. SU Rate	% Over Base	Base
BRev and ARev	0.3	3.17%	A Rev
BRev(SU) and BRev(no SU); SingleAdoption	0.7	20.54%	BRev(noSU)
BRev(SU) and BRev(no SU); Joint Adoption	0.6	32.98%	BRev(noSU)



Sell-Up under Variable DF

Method

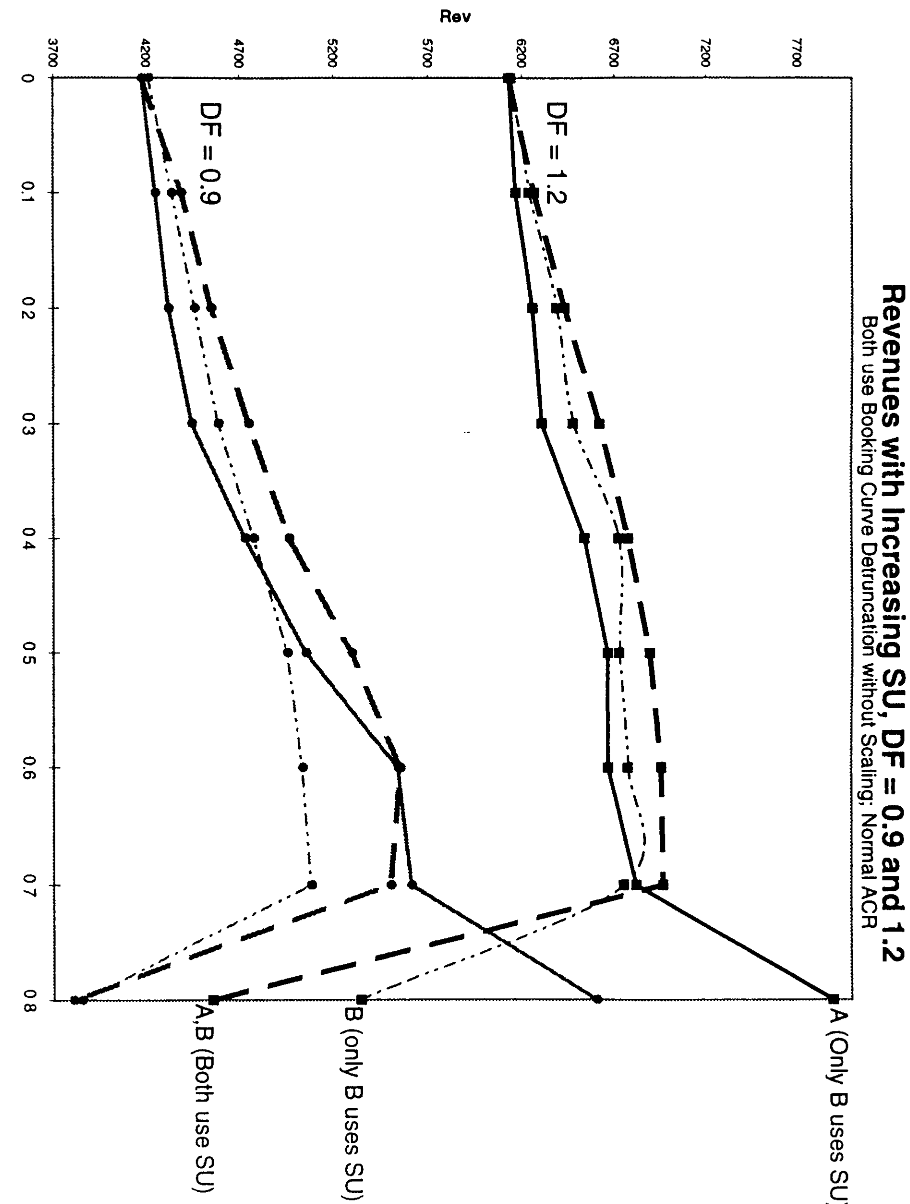
- Keep base conditions except increase demand factor to DF = 1.2.

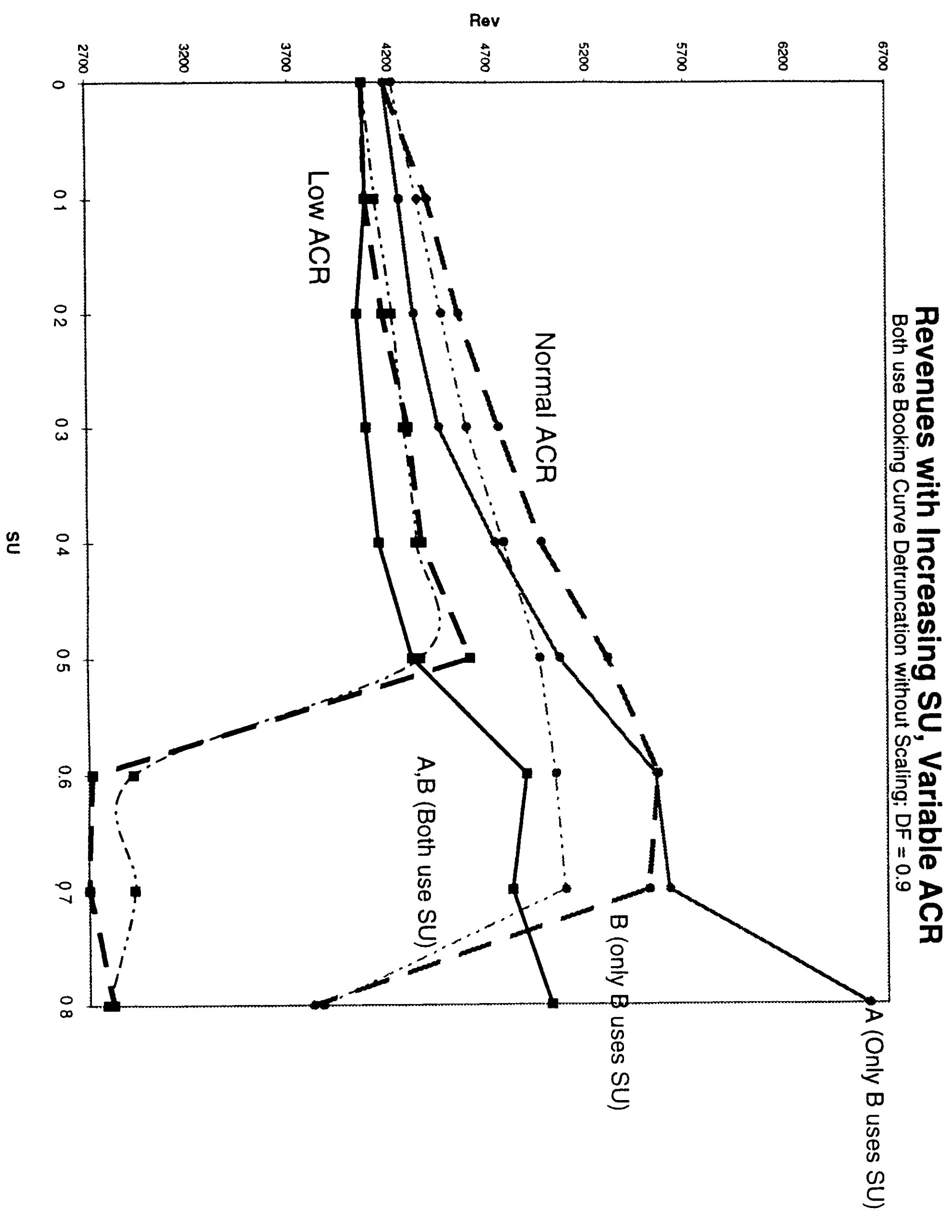
Results

- "Jointness effect" slightly less pronounced: adopting airline achieves most benefits of joint SU adoption.
- Adopting airline enjoys a wider range of SU estimates with superior revenues over non-adopting carrier.
- For both DF, significant deterioration of revenues for adopting carrier/s after SU = 0.7. Suggests "actual" sell-up propensities are significantly lower.
- Objective Performance:

DF = 1.2 Best Estimated SU Rates and % Revenue Improvement			
Airline B's Objective is to Max Difference Between:	**Best Est. SU Rate**	**% Over Base**	**Base**
BRev and ARev	0.4	2.78%	A Rev
BRev(SU) and BRev(no SU), SingleAdoption	0.6	10.31%	BRev(noSU)
BRev(SU) and BRev(no SU); Joint Adoption	0 7	13.64%	BRev(noSU)

-- Percent improvement in objectives over bases is *less* at high DF.





Sell-Up with Variable Price Sensitivities

Motivation

- Price sensitivity indicates changes in passengers' purchasing behavior as price changes.
- The success of a given SU estimate depends on passenger willingness to sell-up, so varying sensitivity should affect revenues.

Method

- PODS implicitly includes sensitivity by passenger type via ACR (Acceptable Cost Ratio).
- ACR is the maximum out-of-pocket cost a passenger is willing to pay over the base Q-fare in the market.

  -- Base ACR are set as follows:
  ACR(business) = 5, ACR(leisure) = 2.

  -- ACR is normally distributed with variation according to a k-factor k_{acr}. Here $k_{acr} = 0.3$.

- Low ACR are defined to be 75% of base, i.e., ACR(business) = 3.75, ACR(leisure) = 1.5.

Conclusions and Summary

- Independently incorporating sell-up estimates is usually beneficial except at high SU.
- Full revenue improvement may depend on whether the competition also incorporates SU estimates.
- Excessive SU estimates overprotect high-valued fare classes, causing diversion of leisure passengers to the competition without commensurate increases in business passengers.
- High demand conditions give an adopting carrier freedom to use higher SU estimates. However, *proportional* revenue gains to SU adoption are less at high DF.
- Lower ACR limits gains to SU.
- Actual airline gains to SU are highly dependent on the particular competitive context.

Sell-Up with Variable Price Sensitivities

Results

- Airline incorporating SU enjoys a slightly wider SU estimate range of revenue superiority over non-adopting carrier.
- Non-incorporating airline achieves superior revenues over joint case at a *lower* SU rate as ACR decreases.
- Negligible jointness effect at low ACR: joint and incorporating airline revenue lines are similar.
- Lower ACR limits individual and joint gains at any SU rate.
- Revenue deterioration point occurs at a *lower* SU rate as ACR decreases. This is consistent with increased price sensitivities at lower ACR.
- Objective Performance:

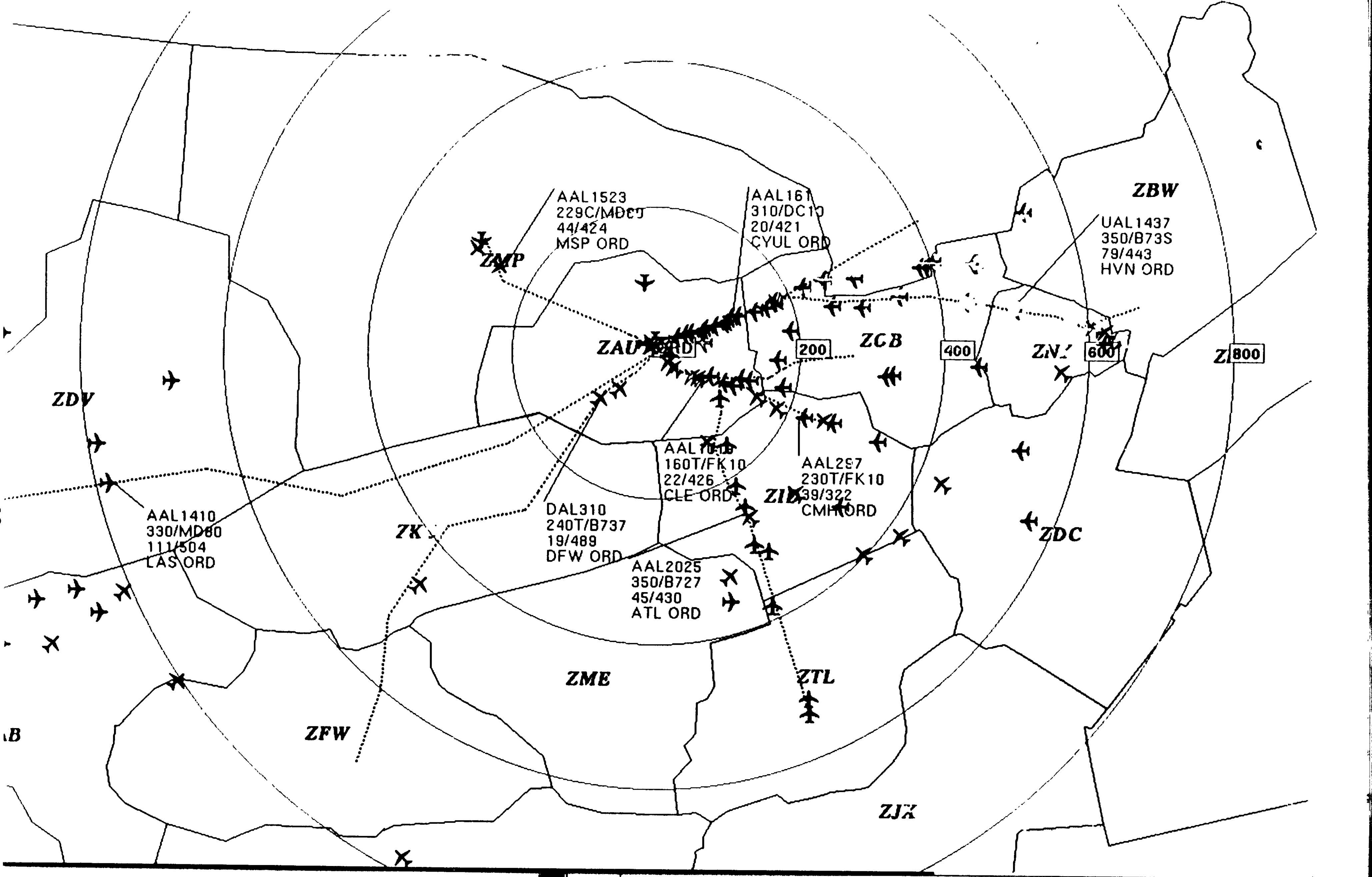
Low ACR Best Estimated SU Rates and % Revenue Improvement			
Airline B's Objective is to Max Difference Between:	**Best Est. SU Rate**	**% Over Base**	**Base**
BRev and ARev	0.3	4.61%	A Rev
BRev(SU) and BRev(no SU); SingleAdoption	0.5	6.83%	BRev(noSU)
BRev(SU) and BRev(no SU); Joint Adoption	0.5	13.10%	BRev(noSU)

DYNAMIC FLOW CONTROL FOR AIRCRAFT ARRIVING AT AN AIRPORT

MAY 1996

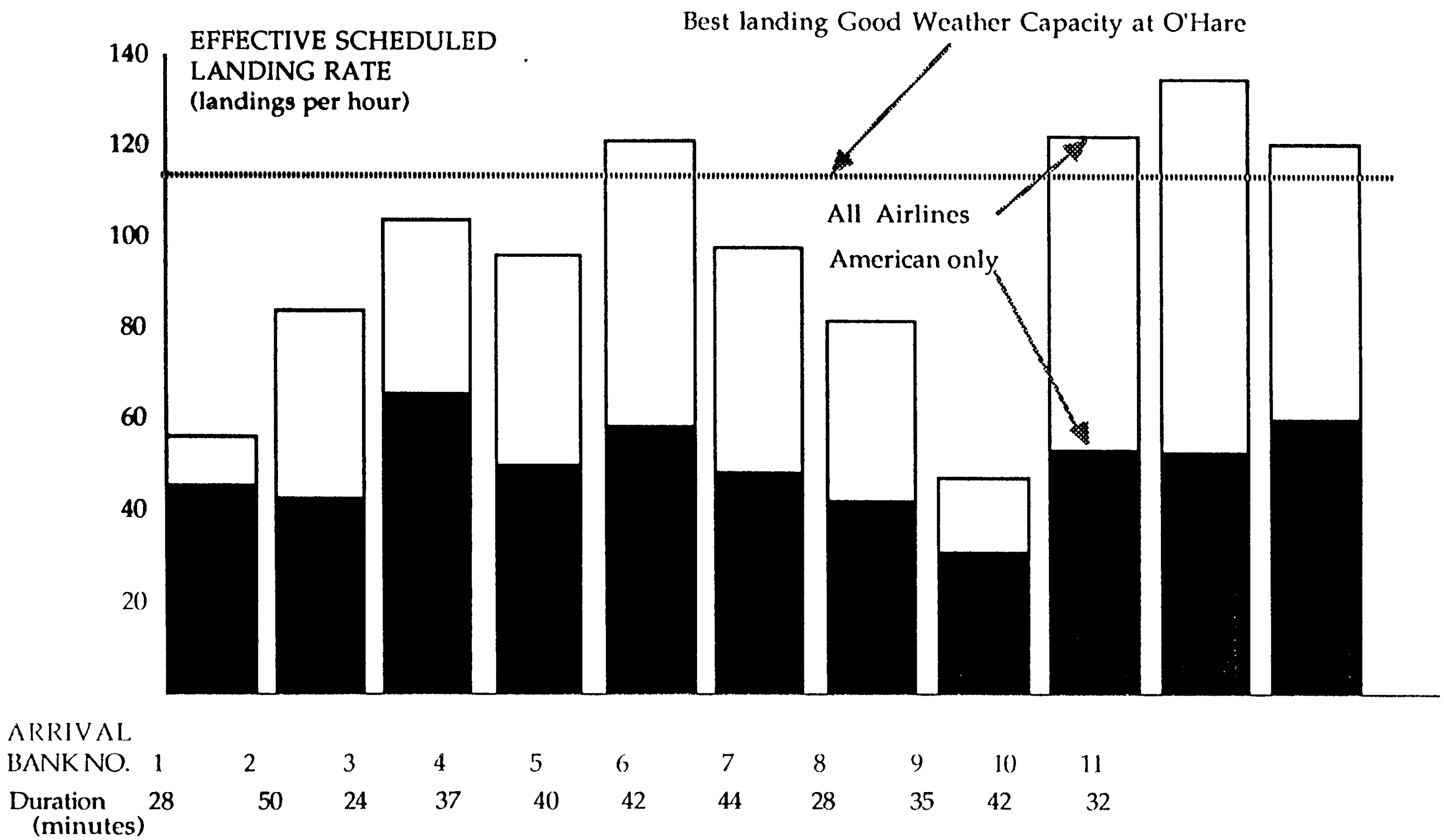
Robert W. Simpson

Flight Transportation Laboratory, MIT



AAL1523
229C/MDC0
44/424
MSP ORD
AAL161
310/DC10
20/421
CYUL ORD
UAL1437
350/B73S
79/443
HVN ORD
ZBW
ZMP
ZAU
ORD
200
ZCB
400
600
800
ZDV
AAL1410
330/MD80
111/504
LAS ORD
DAL310
240T/B737
19/489
DFW ORD
160T/FK10
22/426
CLE ORD
AAL297
230T/FK10
39/322
CMH ORD
ZID
ZDC
AAL2025
350/B727
45/430
ATL ORD
ZME
ZTL
ZFW
ZJX

EFFECTIVE HOURLY LANDING SCHEDULES AT O'HARE (DURING ARRIVAL BANKS OF AMERICAN AIRLINES)



DFC - DYNAMIC FLOW CONTROL

a new concept to control the arrival flow at a single airport which;

1) to ensure coherence with the real world activities, integrates all Traffic Flow Advisories

- Ground Holds, Ground Stops, (internal, first and second tiers, national programs)
- Air Holds (Vertical and Horizontal)
- Enroute Controls (Miles-in-Trail, Cruise Airspeed, Top of Descent, RTA)

2) to handle uncertainties, is updated regularly to account for;

- actual position and groundspeed of airborne aircraft
- new flight plan filings, cancellations, revised departure times
- actual arrival delays at airport
- revised forecasts of Airport Arrival Rate over next few hours

3) to allow interaction by ATM, is interactively responsive to Traffic Flow Managers who can;

- limit flow rates at any Entry Fix
- minimize, limit, or eliminate airborne holding at any Entry Fix
- limit the number of Traffic Flow Advisories issued
- impose ILS Category I,II,III conditions

The Traffic Management Simulator

- Ansi - C language (18000 lines of code, 179,508 bites)
  -> portability on DOS, UNIX and Macintosh platforms.
  Contains a Minimum Cost Flow Algorithm from the MIT Operations Research Center.

- Inputs:
  - *the Airport:* wind forecast, AAR forecast, number of arrival streams, etc.
  - *the Traffic:* Traffic generator for random arrival requests for aircraft of different types (different ranges of cruise speed), from different origins, along different arrival paths, etc.
  - *IIDFC Resolution Logic:* inter-update time period, arcs costs structure and weights, parameters which define the way the network is constructed, etc.

- Dynamic Flow Algorithm exercised every T_{update} (inter-update time period) of simulator time.

- We determine the efficiency achieved by recording the set of commands given to each aircraft, the number of aircraft holding at any time, etc.

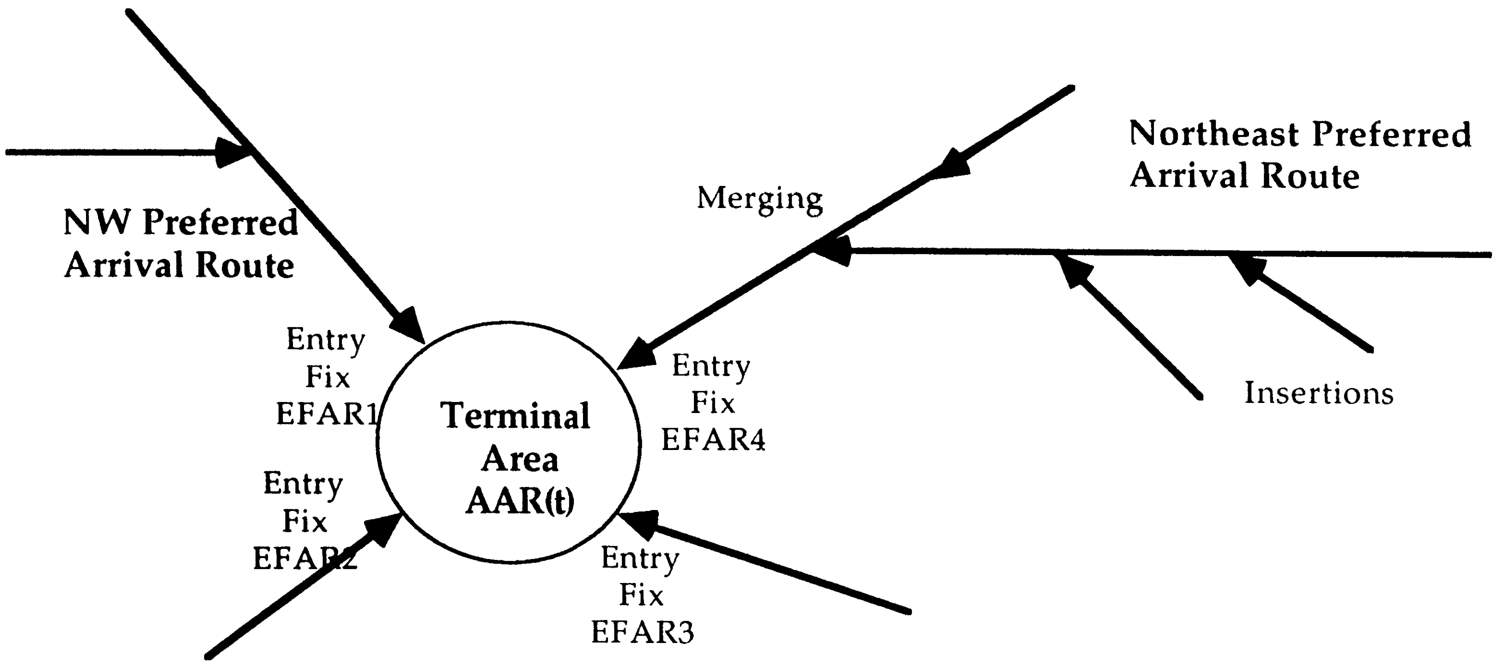
DYNAMIC FLOW CONTROL - SCOPE

ARRIVALS AT A SINGLE AIRPORT

- **forecast of arrival traffic for landing over rest of day by entry fix**
- **forecast of Airport Acceptance Rate AAR(t), time-varying, uncertain times and values**

MULTIPLE ENTRY FIXES

- **multiple arrival streams for several entry fixes to Terminal Area**
- **forecast of Entry Fix Acceptance Rate, EFAR(t) for each fix,**



Algorithm for Optimal Assignment of Delay

If there is accurate updated information on:

1) current aircraft position and speeds
2) updated forecasts of enroute winds
3) current delays at the airport and forecasted acceptance rates
4) new flight plans and cancellations
5) limitations on air holds at destination

Then, we can quickly calculate a new Traffic Flow Plan (TFP) which minimizes the "Costs" of flow management. Costs are expressed in terms of weighted values of:

1) unnecessary delays,
2) fuel burn,
3) traffic management workload

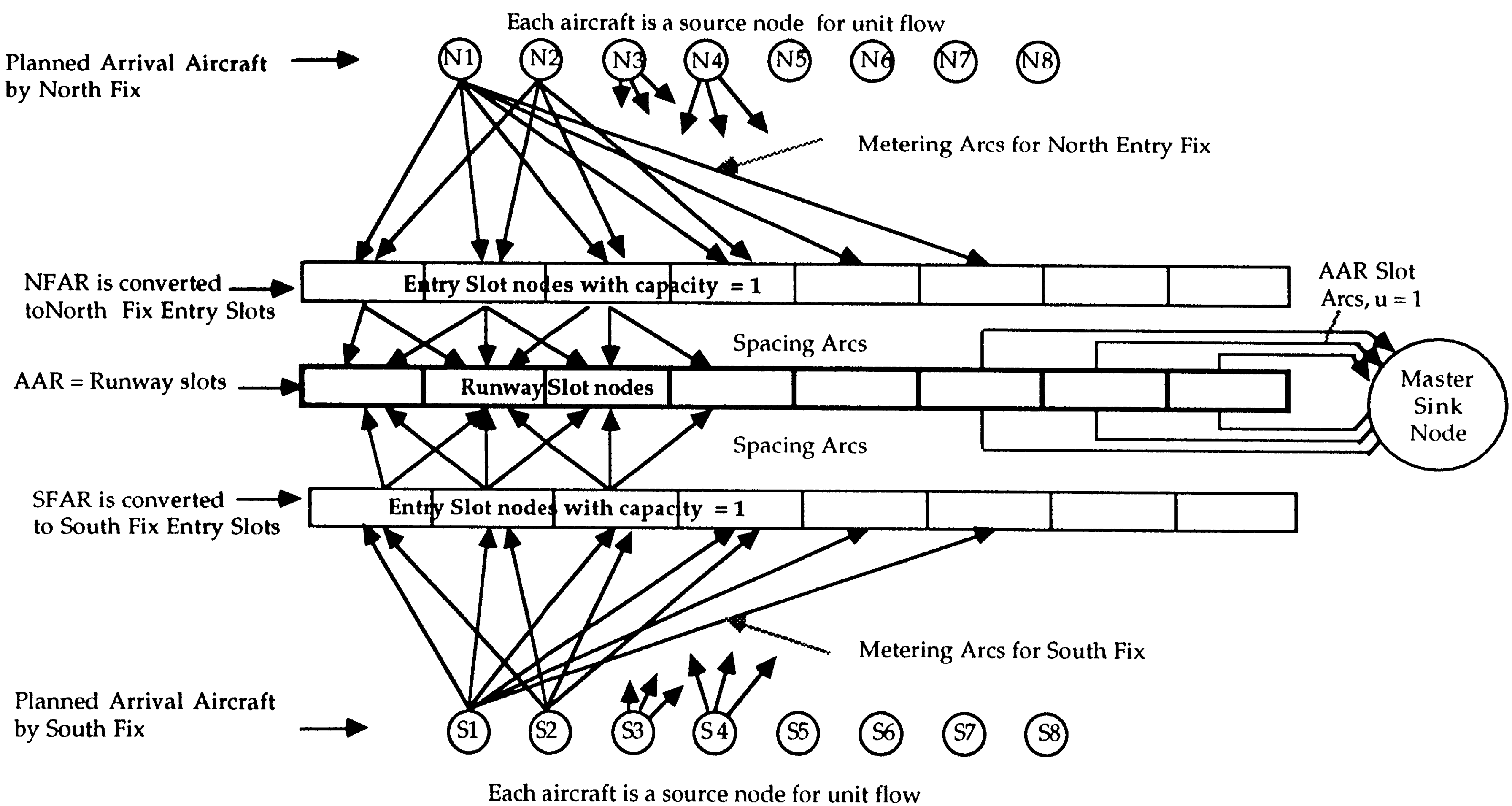
subject to a variety of operational constraints imposed by the Traffic Flow Manager

(eg., limited use of airholding, any cruise speed change is greater than .02 M, all speed changes are monotonic, TOD points within a given range)

The Traffic Flow Plan (TFP) provides;

1) new departure times for some aircraft
2) new cruising speeds for some aircraft (within their stated ranges)
3) planned airholds at every Entry Fix (no. of holding aircraft over time)
4) planned TOD points for all arrivals

Algorithm for Optimal Assignment of Delay - Entry Fix and Runway Slots



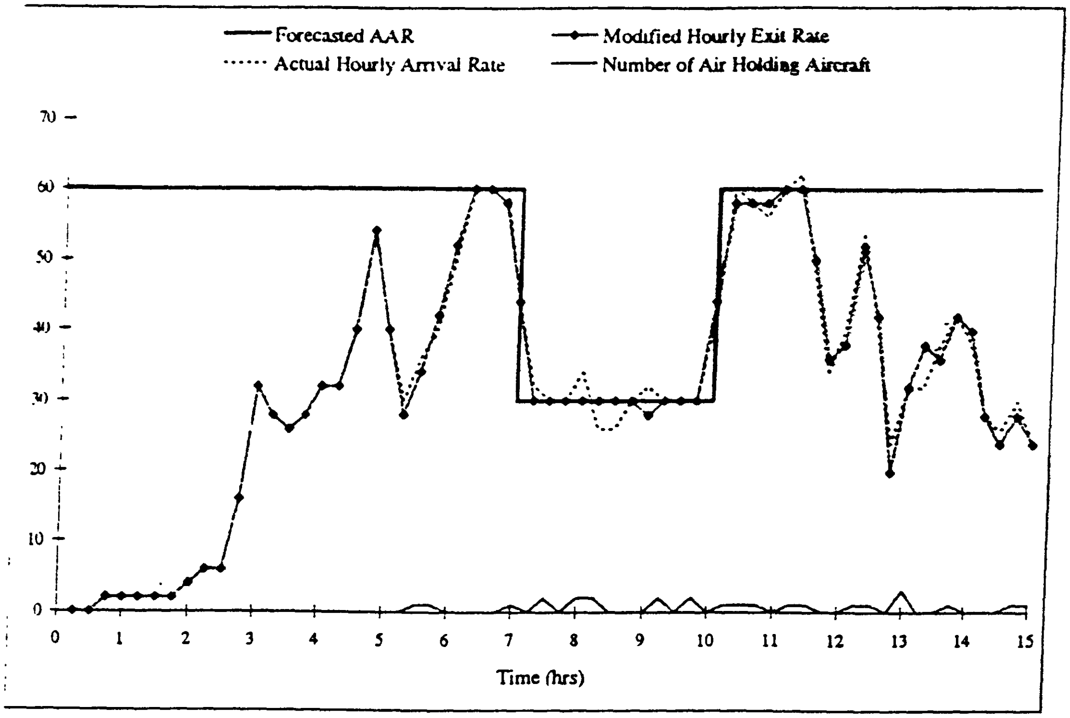


Figure 7-65 : Overall Performance vs. Time

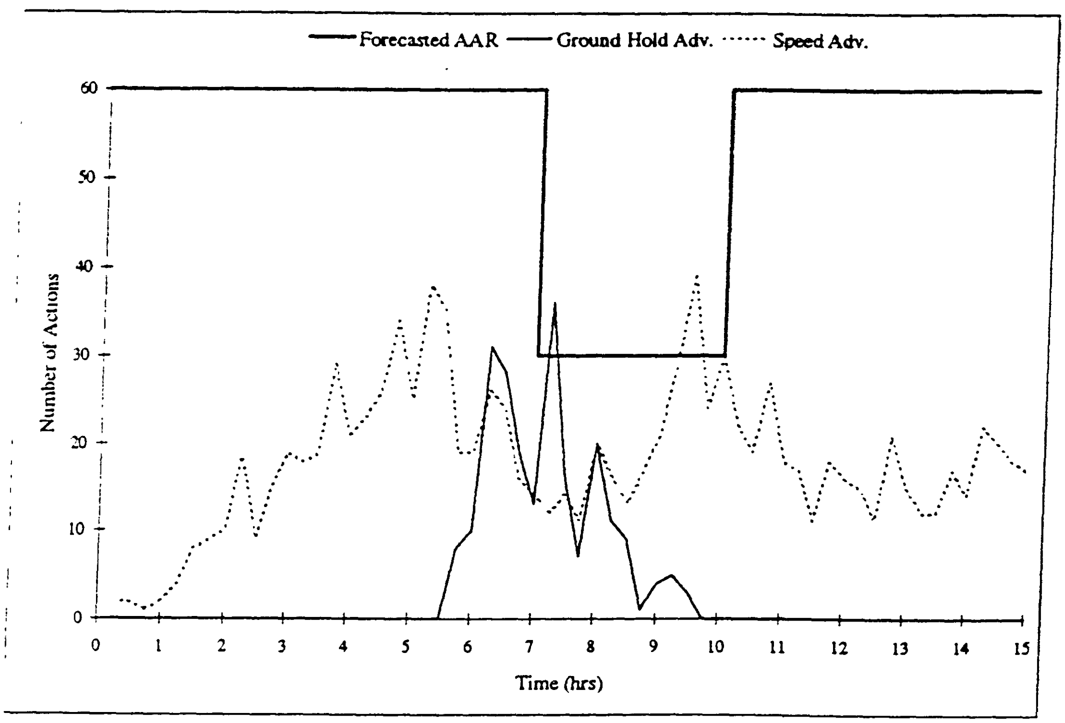


Figure 7-66 : Traffic Flow Management Advisories vs. Time

Scenario 5 : Original Model, Tupdate = 15min.

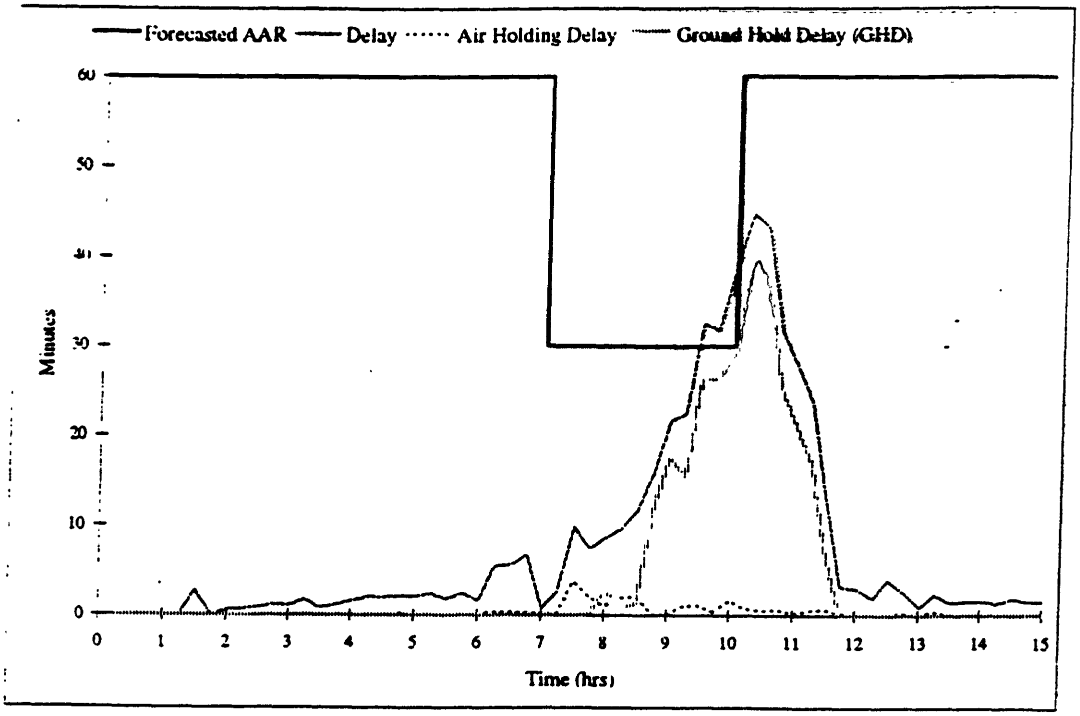


Figure 7-67 : Delays vs. Time

Scenario 5 : Original Model, Tupdate = 15min.

Appendix 5

Summary of Simulation Results from the Original and Modified Model:

Cumulative Delays (min)

	Original Model		Modified Model			
Scenario	*Tupdate = 15min.*	*Tupdate = 30min.*	*Tupdate = 15min.*	*Tupdate = 30min.*	*% Diff (Tupdate=15min)*	% Diff (Tupdate=30min)
1	*5233*	5233	*5233*	5233	----	----
2	*3495*	3695	*3066*	3514	*12.27*	4.90
3	*4406*	4849	*3811*	4470	*13.50*	7.82
4	*4318*	4811	*3947*	4479	*8.59*	6.90
5	*5037*	5142	*3957*	4525	*21.44*	12.00

Ground Hold Advisories

	Original Model		Modified Model			
Scenario	*Tupdate = 15min.*	*Tupdate = 30min.*	*Tupdate = 15min.*	*Tupdate = 30min.*	*% Diff (Tupdate=15min)*	% Diff (Tupdate=30min)
2	*426*	256	*201*	140	*52.82*	45.31
3	*513*	287	*277*	160	*46.00*	44.25
4	*36*	32	*20*	13	*44.44*	59.38
5	*221*	195	*121*	122	*45.25*	37.44

Cruise Speed Advisories

	Original Model		Modified Model			
Scenario	*Tupdate = 15min.*	*Tupdate = 30min.*	*Tupdate = 15min.*	*Tupdate = 30min.*	*% Diff (Tupdate=15min)*	% Diff (Tupdate=30min)
2	*1222*	686	*291*	180	*76.19*	73.76
3	*1140*	675	*128*	87	*88.77*	87.11
4	*961*	629	*137*	114	*85.74*	81.88
5	*1074*	641	*116*	87	*89.20*	86.43

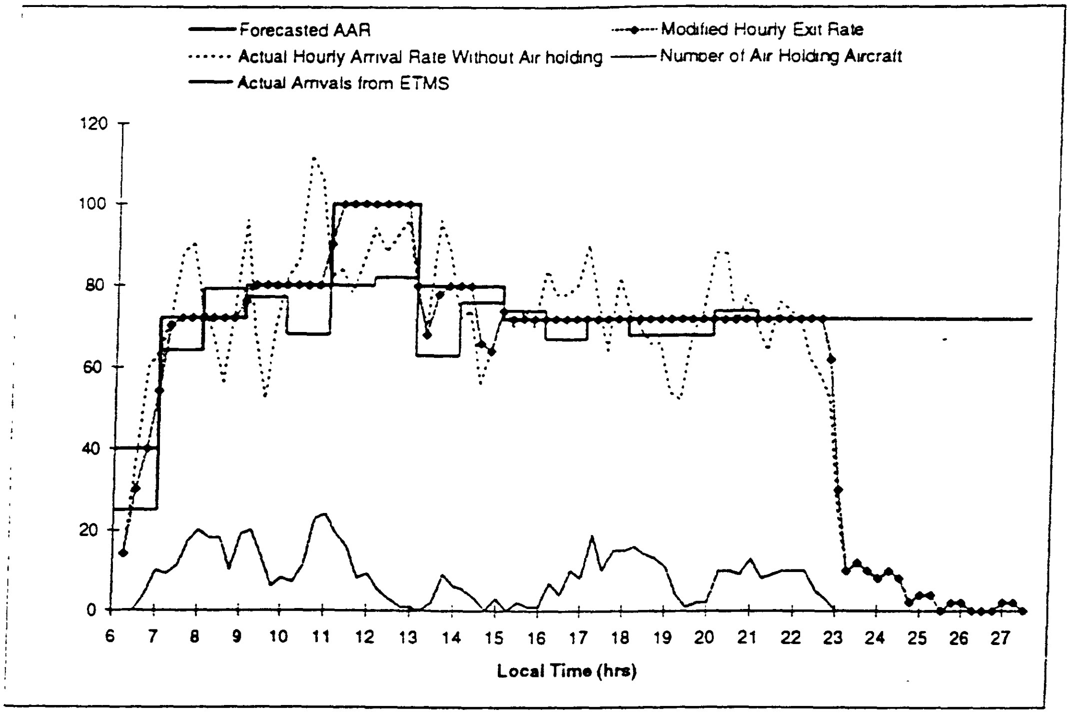


Figure 7-84 : Overall Performance vs. Local Time

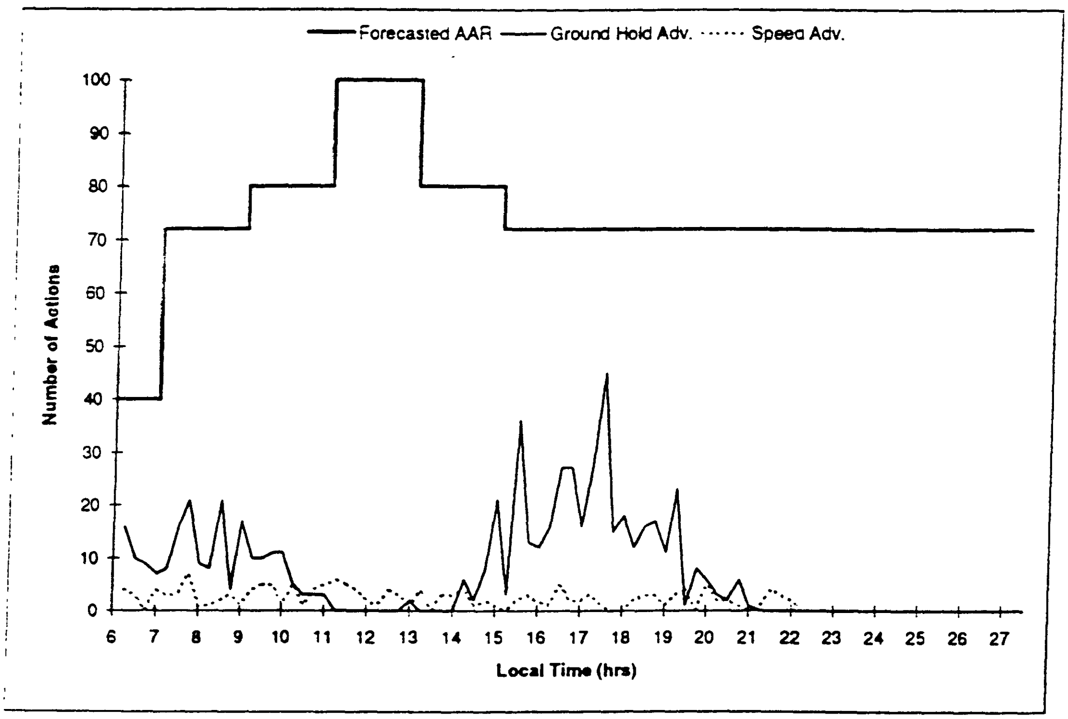


Figure 7-85 : Traffic Flow Management Advisories vs. Local Time

Scenario 5 : Modified Model, Tupdate = 15min, Actual ORD Flight Data (10/31/95), CSA Window = 12knots

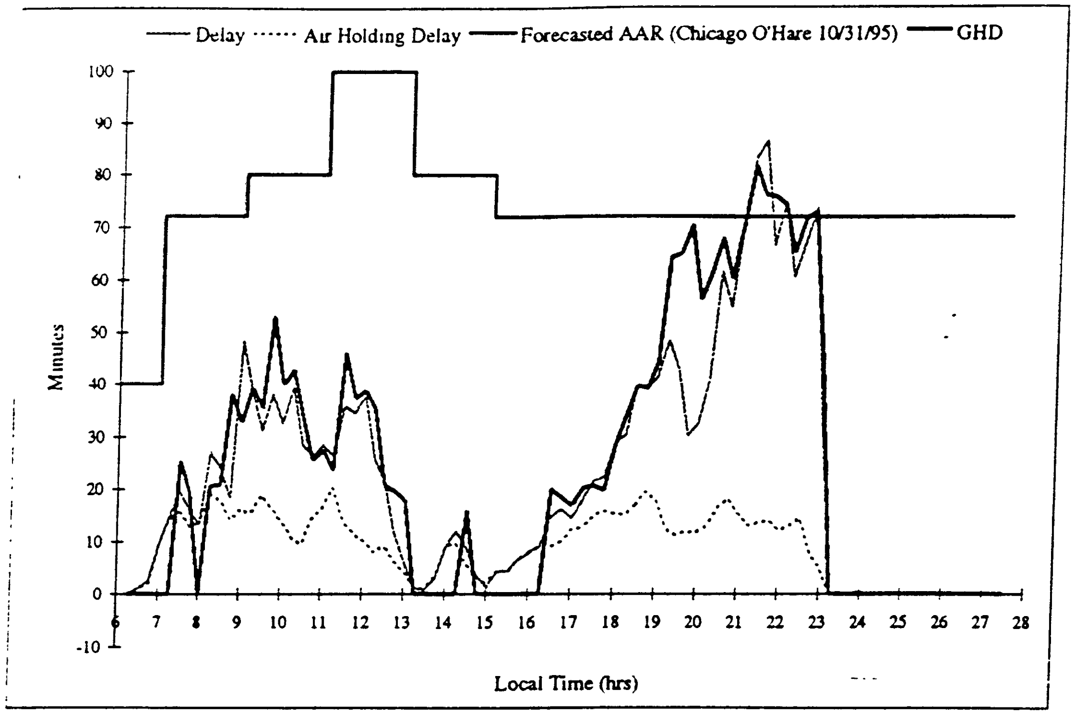


Figure 7-86 : Delays vs. Local Time

Scenario 5 : Modified Model, Tupdate = 15min, Actual ORD Flight Data (10/31/95), CSA Window = 12knots

Summary - DFC Simulation Experiments

Conclusions

1. DFC is able to perform at a typical large US airport in handling the volume of information and quickly producing a new Traffic Flow Plan.

2. The number of Traffic Flow Advisories of any type which are issued by DFC can be easily controlled by the Traffic Flow Managers.

3. The efficiency of the TFP does not degrade significantly when the Update time is increased to 30 minutes from 15 minutes.

4. The number of aircraft air holding at any Entry Fix can be controlled by using both Ground Holding Advisories and Airspeed advisories.

Future Work

1. Expand the TFP algorithms to control the EFAR (Entry Fix Acceptanc eRate) at all fixes

2. Improve the user interfaces on the DFC simulator to allow real time demonstration and participation by Traffic Flow Managers

3. Modify the simulator to integrate the use of the most common method of Traffic Flow Management called m-i-t (miles- in-trail) as practiced at particular airports.

Competition Between Traditional and Low-Cost Airlines for Local Hub Traffic

James Nissenberg
MIT Flight Transportation Lab

MIT/Industry Cooperative Research Program
Presentation
May 23, 1996

Presentation Outline

- Research objectives
- Significance of local hub market traffic to traditional and low-cost airlines
- Modeling local hub market traffic
- Case study: America West versus Southwest Airlines at Phoenix, Arizona
- Phoenix demand model results:
  - comparison of elasticity coefficient estimates

Research Objectives

- Use econometric models to estimate the demand for traditional and low-cost airlines in local hub markets
- Interpret the differential coefficient estimates using airline economic theory
- Study how coefficient estimates change depending on type of competitive scenario

Definitions of Local, Traditional and Low-Cost

- Local Hub Traffic:
  - passengers whose origin and destination correspond to a hub and a spoke airport
  - market traffic is defined bi-directionally
- Traditional Airlines:
  - major hub-and-spoke airlines
- Low-Cost Airlines:
  - Southwest, Valujet, RenoAir, etc.

Local Hub Traffic Significance

- Typically represents 30-35% of traditional airline hub airport traffic
  - Fills empty seats after higher-revenue connecting traffic has been accommodated
  - Hubs without significant local traffic rarely survive (e.g. Raleigh-Durham, Nashville, San Jose)
- Typically represents 60-65% of low-cost airline hub airport traffic
  - Most low-cost airline traffic is local
  - Smaller percentage of operations between hub and spoke airports

Major Determinants of Airline Demand in a Local Hub Market

- Socioeconomic
  - Population
  - Per Capita Income
- Passenger Choice
  - Airfares
  - Flight Frequencies
  - Flight Time (or distance)
  - Endpoint Dominance

Modeling Local Hub Market Traffic

1. <u>Functional Form</u>

- Demand modeled as a multiplicative function of socioeconomic and passenger choice variables
  - allows for interaction among explanatory variables
  - estimates constant variable elasticities

Modeling Local Hub Market Traffic

2. <u>Explanatory Variables</u>

- Population base of spoke city/region
- Per capita income of spoke city/region
- Average quarterly fare paid*
- Estimated quarterly nonstop frequencies*
- Scheduled flight time*
- Average quarterly cross-fare*
- Average quarterly cross-frequencies*

* By market/airline

Case Study: America West vs. Southwest Airlines at PHX

- 11 Short-haul markets
  - average market distance 500 miles
- 8 Quarters
  - 2nd quarter 1993 through 2nd quarter 1995
- 80 Quarterly market observations
- Analysis confined to duopoly markets
  - where America West and Southwest carry over 90% market share combined

Conclusions

- Variation in socioeconomic factors has a greater effect on the number of traditional carrier passengers
  - population more important than fares
  - per capita income and business travel
- Passengers choose the low-cost carrier for its fares, but fares matter less as market distance increases
- The effect of additional flights does not seem to depend on the type of carrier
- Price and frequency matching makes cross-variable interpretation difficult

Revenue Management in a Multiple-Hub Alliance Network

MIT Flight Transportation Lab

Prof. Peter Belobaba & Jim Ferea

May 22, 1996

Project Objectives

- Examine different revenue management schemes in KLM/NW alliance network.
- Extend previous research to include:
  - large scale multi-hub network evaluations
  - simulation of alternative passenger path choice
- Identify revenue and traffic interaction effects when carriers use different RM approaches.

Seat Inventory Control (RM)

- Seat inventory control establishes booking limits to differentiate among passenger requests and maximize revenues.
- We simulated and compared two common RM approaches:
  - EMSR Fare Class Control
  - Stratified Bucketing/Virtual Class Nesting

Fare Class Control

- O-D itineraries/fare combinations (ODFs) grouped by fare type (yield) into “fare classes” for control purposes.
- RM system collects data, forecasts and optimizes fare class limits on each leg.
- EMSRb model for nested classes used in calculating fare class booking limits.

Fare Class	Fare Product
C	Business Class
Y	Full Fare
B	7 Day AP One-Way Discount
M	14 Day AP Sat. Night Stay Non Refundable
H	21 Day AP Sat. Night Stay Non Refundable
Q	"Sale" Fares
V	Special Promotions

Table 2.1 A theoretical fare class hierarchy defined by restrictions.

Fare Class Control Limitations

- Traditional approach to RM, protects seats for late-booking, high yield passengers on each flight leg.
- Multi-leg ODFs must find requested fare class available on each leg of itinerary.
- Approach will reject long-haul "discount" requests (with higher total revenue) in favor of short-haul "full-fare" passengers.

Virtual Nesting by ODF Value

- Hidden "virtual" classes are defined by revenue value range on each flight leg.
- Each ODF is "mapped" to a virtual class based on its total itinerary revenue value.
- Seat availability determined by availability of corresponding virtual classes.
- Approach gives priority to highest revenue ODFs, regardless of yield.

OD Market Revenue Tables

Long Haul Class	Fare
C	1339
Y	899
B	649
M	499

Short Haul Class	Fare
C	399
Y	299
B	249
M	189

Connection (CN) Class	Fare
C	1499
Y	999
B	699
M	549

Network Virtual Mapping of ODFs

Virtual	Virtual Range	ODFs
V1	$700 +	C Long, Y Long, C CN, Y CN
V2	$500 - $699	B Long, B CN, M CN
V3	$410 - $499	M Long
V4	$350 - $409	C Short
V5	$310 - $349	
V6	$240 - $309	Y Short, B Short
V7	$180 - $239	M Short
V8	$145 - $179	
V9	$85 - $144	
V10	$0 -$84	

Example 2.2 Mapping of ODFs into a virtual class structure.

Network vs. Leg Virtual Classes

- Network-wide virtual classes:
  - same virtual class revenue ranges defined for all flight legs in network
  - based on equal distribution of network ODFs among, for example, 10 virtual class ranges
- Leg-specific virtual classes:
  - virtual class revenue ranges defined separately for each flight leg in network

Virtual Nesting Limitations

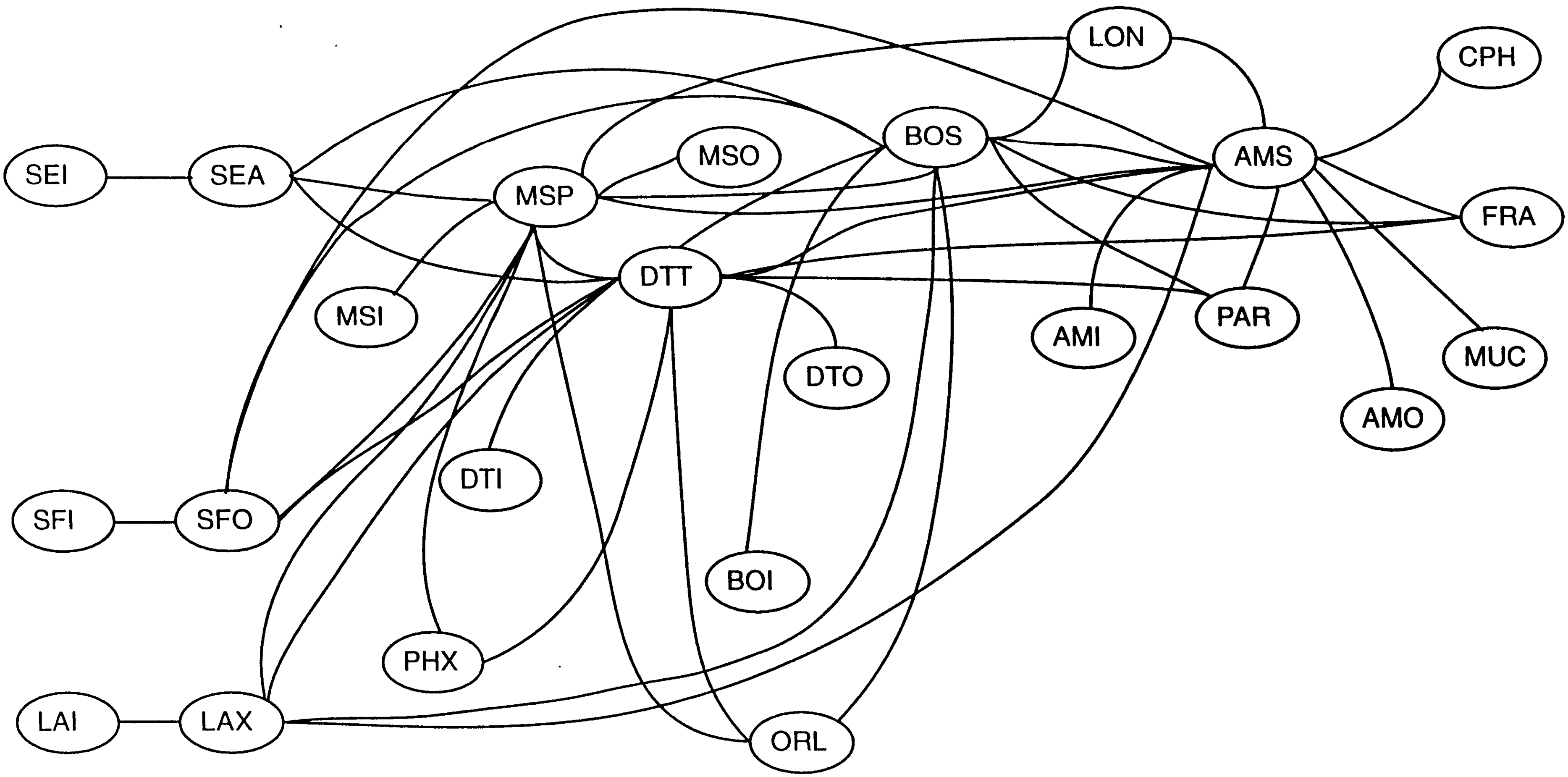
- Protection of seats for highest revenue ODFs favors connecting long-haul requests.
- "Greedy" approach can result in rejection of two local (one-leg) passengers with higher combined revenue.
- Seamless CRS communication necessary since ODF mapping must be "de-coded" by airline.

Simulation: KLM/NW Network

- Representative trans-Atlantic sub-network:
  - Eastbound flows on typical peak summer day
  - 46 KL+NW flight legs connected by 4 hubs
  - 237 O-D routings using 7 fare classes
  - "dummy" legs represent flights not included in sub-network
  - demand factors (demand/capacity) on each leg range from 0.69 to 1.89

KLM/NW Multiple Hub Network for August 1994

System Map



Simulation Program

- Integrated RM optimization and booking process simulation developed at MIT:
  - each iteration represents one departure day
  - booking limits calculated at each revision point based on future demand inputs
  - passenger requests accepted/rejected between revision points
  - 16 booking periods for each departure day

Simulation Characteristics

- 25 repetitions of booking process for each scenario.
- Demands randomly generated in Poisson process, given input demand data.
- Booking curves ensure that most low-fare requests occur early, and most high-fare passengers request seats closer to departure.

Alternative Path Choice

- Previous simulations limited to single-hub networks with one ODF path option.
- In multi-hub network, some will accept 2nd choice path when 1st choice not available.
- We incorporated multiple paths and a "recapture probability" into the simulation:
  - likelihood of accepting next best path choice.

Base Results: One Path Choice

- Both carries use same RM system.
- Multiple demand scenarios created by adjusting data by 0.80, 0.90, 1.10 and 1.20
- Fare Class Control increases total network revenue over “first come, first served”:
  - 7% revenue increase at 80% load factor
  - 15% revenue increase at 92% load factor

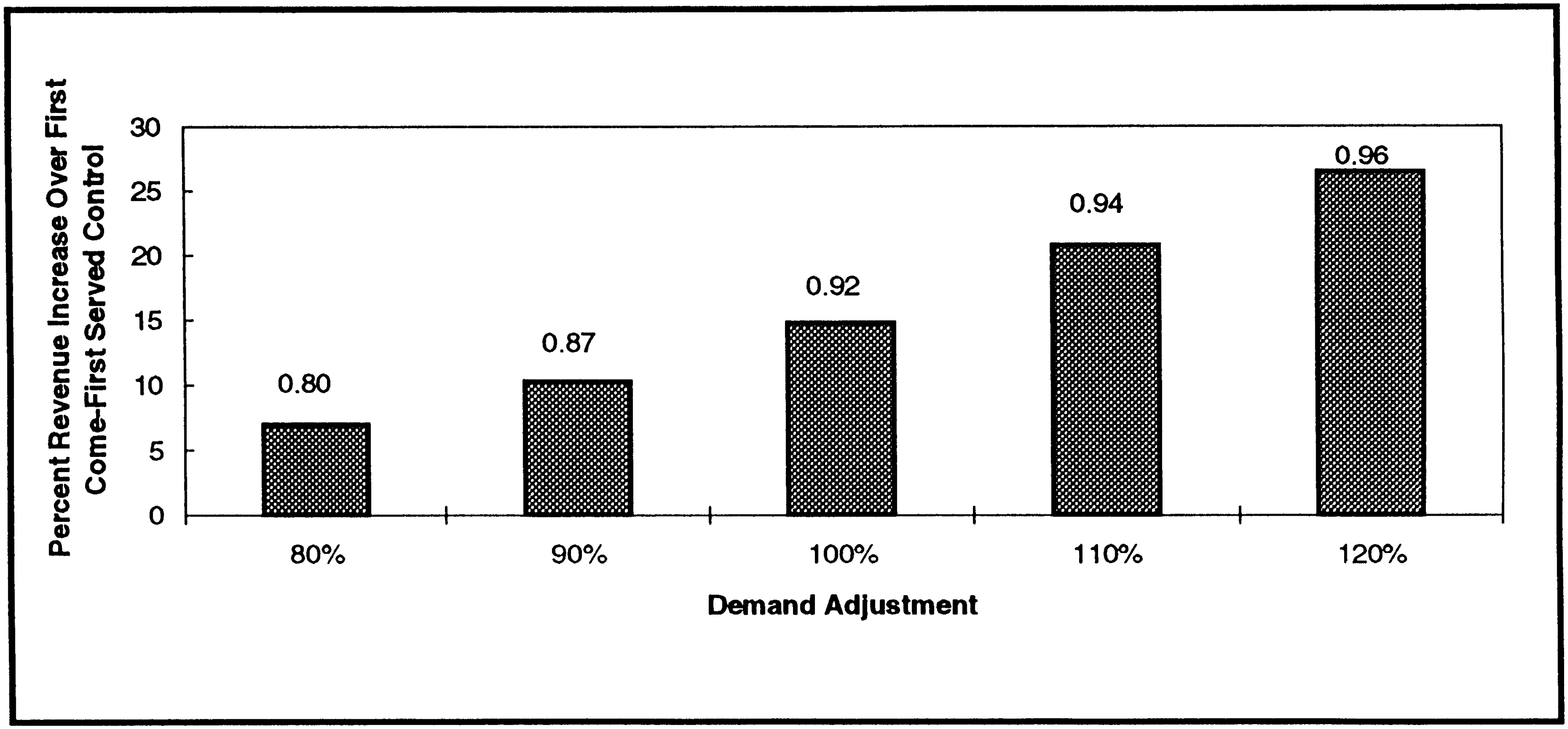


Figure 3.1 Expected Revenue Gains from an EMSRb fare class control system over a First Come-First Served system with no control. Average leg load factors for EMSRb fare class control are indicated for each demand level.

Base Results: Virtual Nesting

- Base case simulation (one path choice) of virtual nesting shows additional revenue gains over EMSRb fare class control:
  - almost 0.50% at 81% network load factor
  - 1.25% incremental gain at 91% load factor
- Network vs. leg virtual nesting:
  - network-wide better at lower demands
  - leg-specific better at higher demands

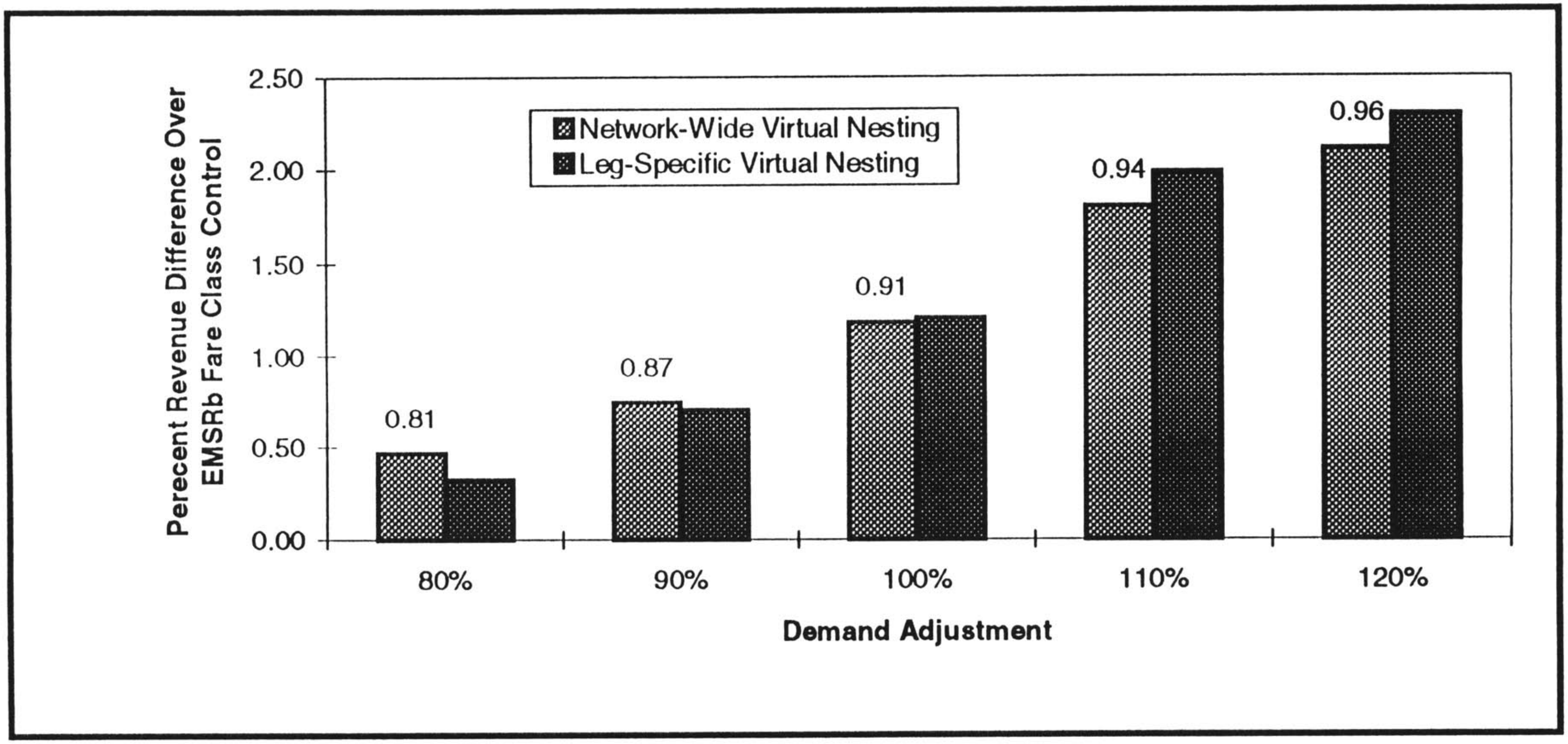


Figure 3.2 Revenue comparison of virtual nesting over EMSRb fare class control. The average leg load factor for the simulation is included shown at each point and is relatively the same, regardless of virtual class determination.

Simulation with Path Choice

- Both carriers still use same RM method.
- Incorporate up to 3 paths possibilities for each ODF on the KLM/NW sub-network.
- Recapture rates of 100%, 70% and 50%.
- Test against base case with only one path:
  - expect overall passenger spill to decline
  - expect total network revenues to increase

Simulation Results: Path Choice

- For fare class control, results as expected:
  - reduced network spill and higher revenues
  - higher recapture rate, bigger revenue increase
- For virtual nesting, revenue gain decreases at higher demand levels:
  - recaptured multiple-leg passengers displace more local passengers (in lower virtual classes)
  - multi-leg passengers tend to book earlier

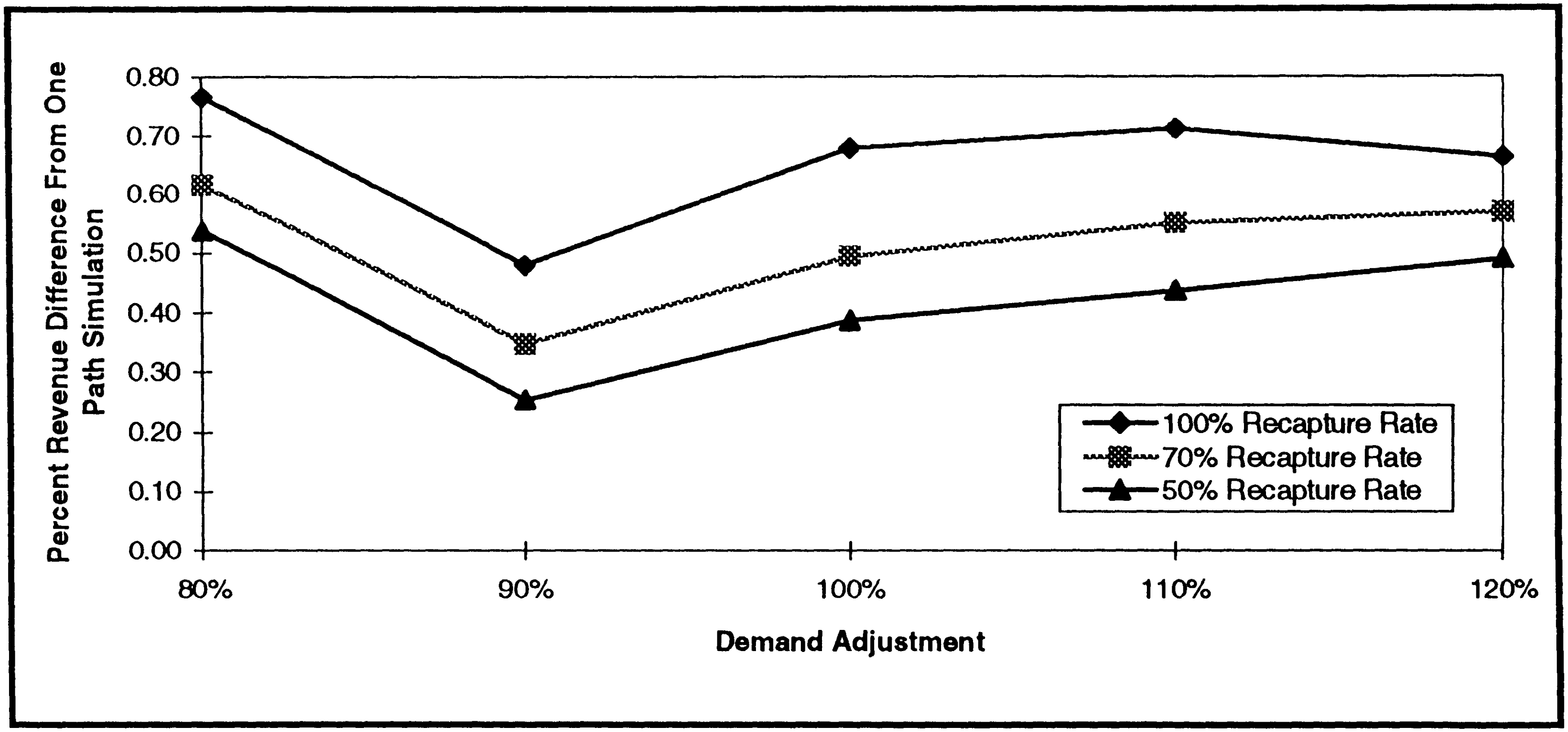


Figure 3.5 Revenue performance for EMSRb fare class control with three available paths compared to one available path.

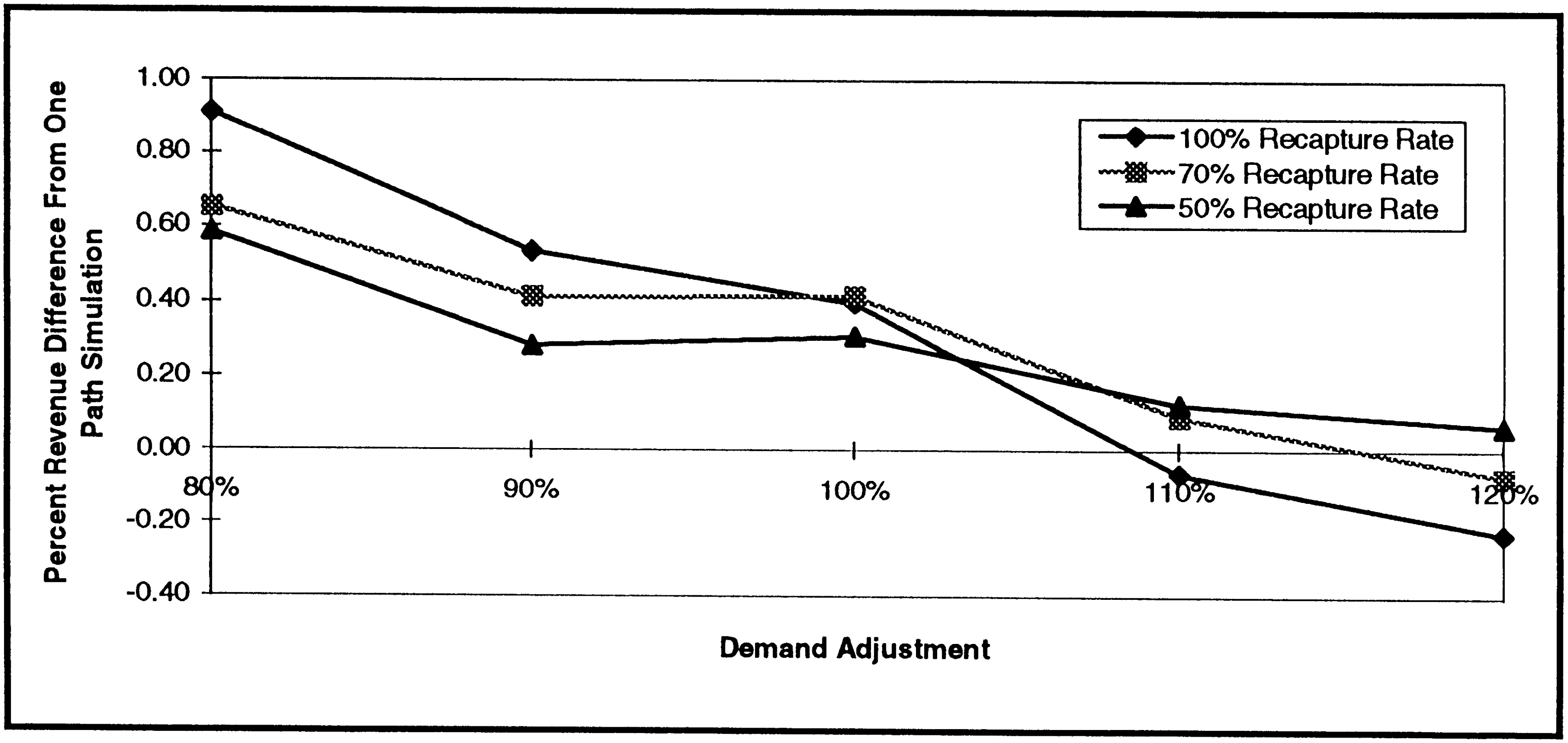


Figure 3.6 Revenue performance for leg-specific virtual nesting with three available paths compared to one available path.

Summary: Path Choice Findings

- More realistic representation of multi-hub alliance network suggests revenue gains of passenger re-capture.
- Demonstrates importance of modeling recapture to revenue impact analysis.
- Different RM methods respond differently under varying recapture assumptions.

Summary of Findings

- Revenue performance of RM methods can differ in large multi-hub networks.
- Inclusion of path choice and passenger recapture in simulation suggests benefits of KLM/NW alliance.
- Use of different RM systems by alliance carriers can lead to unexpected revenue and traffic/spill outcomes.

Schedule Planning and Operations Control

Technologies for Surviving Competition in the Airline Industry

Dr. Dennis F. X. Mathaisel

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Department of Aeronautics & Astronautics
MIT

AGENDA

1. Overview of available models and computer packages for airline schedule planning and airline system operations control

   1.1 Strategic

   1.2 Tactical

   1.3 Operational

2. Systems Development: Approach

   2.1 General Strategies

   2.2 The Airline Scheduling Workstation (ASW)

   2.3 Two Stages of Development

3. Expected Benefits for an ASW

4. Summary and Conclusions

Strategic	• Fleet Planning • Fleet Assignment • Network Optimization/Evaluation
Tactical	• Timetable Construction • Traffic Allocation and Network Evaluation • Aircraft Assignment • Aircraft Routing • Aircraft Swapping (Switch and Save) • Airline Schedule Development GUI's

Operational	• System Operations Control
	  • Operations Manager
	  • Irregular Operations
	  • Crew Management
	  • Flight Dispatch
	  • Aircraft Routing to Maintenance
	  • Aircraft Situation Display
	• Ground Handling and Manpower Planning
	• Passenger Services
	• Catering

STRATEGIC

Fleet Planning - Cell

- Find optimal (maximum operating income) schedule of aircraft acquisition and retirements over a series of future years

- Use aggregate route/market clusters ("cells")

- Introduce financial parameters and constraints purchase vs. lease options

- Linear Programming techniques

STRATEGIC

<u>Fleet Assignment – FA-4</u>

- Uses large scale LP technique to find "best" allocation of available fleets to feasible, desirable aircraft routings on a network of services
- Maximize Operating Income
- Detailed schedule of departure/arrival times not considered
- Given:
  - O-D market demand function (not fixed)
  - Multi-stop routings
  - Limits on available daily fleet hours
  - Limits on onboard load factors achievable
  - limits on Max-Min desired daily market services
- Results
  - Routes to be flown
  - Frequency by type of aircraft

STRATEGIC

Network Evaluation and Competitive Analysis - TALLOC

- Simulation of an airline's competitive environment at the schedule level of detail
- Given
  - O-D demands
  - Schedules of your airline and your competition
  - Passenger behavior parameters
  - Costs and fares
- Results
  - Composition of onboard segment traffic
  - Market analysis
  - Profitability analysis

TACTICAL

Timetable Construction – REDUCTA

- Shifts flights within a specified time window with the objective of increasing the efficiency of the schedule

- Given:
  - Set of services which must be flown
  - Time window for each service
  - Minimum turn times
  - Curfews

- Results:
  - Re-optimized time schedule for the services

TACTICAL

Timetable Construction – INSERT

- Algorithm for building aircraft (or ground vehicle) itineraries based on the demand for service
- Builds routes and schedules through a sequential "insertion" of services into the system
- Structured decision rules
    - Choice of aircraft type
    - Hubbing decision rules
- More useful for special operations than for scheduled services

TACTICAL

Traffic Allocation and Network Evaluation - TALLOC

Given

- Forecasts of O-D demands for all markets
- Schedules for your airline and your competition
- Passenger behavior parameters

Results

- Segment analysis
- Composition of onboard segment traffic
- Market analysis

  Services provided in each market and the traffic carried on each flight

Very detailed evaluation of a schedule in a competitive environment

- Simulates passenger booking process
- A link between scheduling and revenue and capacity management (?)

Thru - Flight Optimization Module

- Analyzes thru-flight vs. connecting flight possibilities

TACTICAL

Aircraft Assignment

- Optimal assignment of aircraft types to a fixed schedule
- Uses very large scale integer linear programming techniques
- Constraints
  - Minimal set of crew constraints
  - Minimal set of maintenance constraints
- Integration with revenue management systems (?)

TACTICAL

Aircraft Routing - MRS

Objective

Find good set of turns between arrivals and departures at a station to form routings

Given

- Desire for through service in certain markets
- Maintenance planning constraints

Output

- Rotations, daily/weekly lines of flying
- Gate occupancies at stations
- Routings to planned maintenance checks

Uses tree-construction techniques, and forward and reverse tree search.

TACTICAL

Switch and Save – SWITCH (David L. Johnson)

Objective

Maximize operating income by switching aircraft types to match capacity with demand

Given

- Set of scheduled services for any two fleet types with fixed operating times and known net operating income
- Aircraft operating costs

Find

- All possible ways of switching aircraft types and select the fleet assignment with maximum total profit

Note:

For planning purposes it is not necessary to specify the starting location of aircraft. They can be positioned at any station the planner chooses.

TACTICAL

Airline Schedule Development GUI's

- Standalone or client-server architecture
- Multiple users
- Interactive graphics editor
- Unlimited number of aircraft, segments, rotations, stations
- Flexible setup, filtering, sorting, scaling
- Multiple windows

  Lines of flying

  Aircraft rotations

  Station activity

  Gate assignment

  Timetable

  Geographic map view

- Frequency-based and fully-dated schedules

ASD -- cont.

- Rule-based constraint checker

  Crew requirements

  Maintenance requirements

  Operations (ground times, station continuity, curfews, etc.)

- Librarian: merging and splitting schedules

- Interfaces to existing algorithms

- Connection Generator (PATH)

- Automatic flight numbering

- Import and export functions: read and write data files to mainframe

- Interfaces to DBMS

- Printed reports

- Runs on any UNIX workstation or PC supporting UNIX

OPERATIONAL

System Operations Control

- Operations Manager
- Irregular Operations
- Crew Management
- Flight Dispatch
- Aircraft Routing to Maintenance
- Aircraft Situation Display

Ground Handling and Manpower Planning

Passenger Services

Catering

OPERATIONAL

System Operations Control GUI's

- Flight following
- Real-time graphical user interface
- Embedded icons show the current status

    Cancellations

    Changes in ETA/ETD

    Maintenance

    Weather forecasts

    Crew information

    Passenger loads

  Aircraft/airport status

  Built-in "flagging" system for warnings

  "What-if"

- Client-server architecture
- Multiple users

DFXM-96-16

OPERATIONAL

Systems Operations Control GUI's - cont.

- Flexible setup, filtering, sorting, scaling
- Marketing schedule display to compare planned and actual Imbedded icons
- Cancellations, changes in ETA/ETD, overfly, etc.
- Maintenance problems
- Weather forecasts
- Crew information
- Passenger loads
- Interactive graphics editor
- Modify ETAs/ETDs
- Swap equipment
- Cancellations
- Overfly or add additional stop
- Popup menus to edit mainframe transaction commands before transmission
- Popup menus to retrieve aircraft, station, flight information
- Messaging system
- Interactive "what-if": evaluate alternative plans
- Interfaces to existing algorithms
- Import and export functions: read and write data files to mainframe
- Printed reports

TACTICAL

Aircraft Routing - MRS

Objective

Find good set of turns between arrivals and departures at a station to form routings

Given

- Desire for through service in certain markets
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Output

- Rotations, daily/weekly lines of flying
- Gate occupancies at stations
- Routings to planned maintenance checks

Uses optimal tree-construction techniques, and forward and reverse tree search.

OPERATIONAL

Resource Allocation and Manpower Planning - RAMPS (ADDAX)

- Assigns agents to ramp services
- Translates real-time operations information into the tasks required for each aircraft's movement
- Management policies and standards programmed into the system
- Includes ramp agent selection criteria and shift break schedules

OPERATIONAL

Passenger Service Agent Allocation System - PSAAS (ADDAX)

- Monitors and assigns passenger service agents to tasks
- Based on real-time flight information, PSAAS matches agents to appropriate jobs throughout the day
- Management policies and standards programmed into the system
- Assignments based on:
    - Job classification
    - Skills
    - Time lapsed since last assignment
    - Travel time to assignments
    - Workload balancing

OPERATIONAL

Catering Allocation Planning Equipment Routing - CAPERS (ADDAX)

- Dispatches catering personnel to tasks
- Translates real-time flight information into the catering tasks required for each aircraft's movement
- Management policies and standards programmed into the system
- Monitors and tracks
  - Job skills for each employee
  - Daily rosters
  - Equipment availability
  - Loading dock schedules

2. Systems Development Approach

2.1 General Development Strategies

- Involve schedulers at all development stages -- (there will be cultural and organizational shock)
- Provide familiar systems and reports to ensure that the new system will not preclude doing certain schedule sub-processes by old methods
- Expect changes in organization and procedures as workstation capabilities are perceived
- Establish a local area network of workstations in scheduling area, capable of interfacing with the airline's existing mainframe system.
- Develop transportable, modular, object-oriented code
- Extendible
- Easily supported
- C, C++
- Efficient data structures
- Common graphical user interfaces to all sub-systems
- Common DBMS platforms
- Common hardware platforms

2.2 The Airline Scheduling Workstation (ASW)

A Computer Tool for Airline Schedulers

1. Desk top Engineering Workstations running UNIX on a local area network interfaced with existing airline mainframe systems.

2. Large (19 inch), high-quality color displays with interactive, instantaneous, manipulation of schedule graphics information using a "mouse".

3. Object-oriented C programming to provide modular code, easily extendible to handle time-varying scheduling constraints, policies, etc., and to reduce programming support.

Two Stages of Development

Stage 1 – Introduction of a Manual, Interactive Graphics Scheduling System

a) Provide computer graphic displays of schedule information

- Instantaneously modifiable by mouse, global data base modification
- Selectable screen data -- by fleet, station, time, schedule period
- Save alternate solutions
- Auditable differences
- Memo pad for scheduler
- Keyed to input data, and assumptions used
- Automated search routines, etc. to minimize keyboard and mouse work

b) Provide instantaneous error flagging (even if error occurs off-screen)

- e.g., insufficient gates, flow imbalance, double crew layover, violation of turnaround or transit times, insufficient aircraft

Stage 1 -- cont.

c) Integrate initial crew, gate, maintenance schedule planning with aircraft schedule planning

   – e.g., rough initial schedules for crews, gates, station personnel)

d) Provide familiar printed reports and graphics for distribution around airline

e) Provide interface to mainframe data system to maintain current scheduling processes

f) Centralize data bases

Two Stages of Development

<u>Stage 2 – Introduction to Automated Decision Support</u>

- Algorithms to assist human schedulers optimize sub-problems

- Eliminate manual effort at certain steps of the process

- Broaden search for optimal or good solutions to scheduling sub-problems

- May introduce large scale optimization algorithms

Summary
State-of-the-Art in Computerized Scheduling

Conclusions

1. We cannot create one analytical model which is adequate to describe mathematically the complete airline scheduling problem.

2. We can provide quick, accurate answers to many sub-problems which occur in the complete scheduling process, but we need an environment which allows these techniques to be available to human schedulers. This environment is now available in the form of a network of computer workstations.

3. It is attractive to consider a single, integrated system to be used by various airline personnel as the scheduling process moves from initial planning to final execution.

4. People will remain an important part of the airline scheduling process. They are responsible for generating good schedules, and need "decision support" in their activities. There never will be a "fully-automatic" scheduling system.

5. The desired approach is incremental introduction of computerized assistance via graphic workstations. The strategy should be to create evolutionary stages:

   Stage 1 – Introduce the Scheduling Workstations
   Stage 2 – Introduce Automated Decision Support

Summary
State-of-the-Art in Computerized Scheduling -- cont.

6. The scheduling process is not permanent

   – As time goes by the problems change, (perhaps temporarily), and the markets evolve, and there will be emphasis on different aspects. It will not be possible to create a completely automated decision maker which keeps up with changes.

7. As these tools are developed, they have their impact on the Scheduling Process

   – It will change in its flow of information, the sequence of processing will change, and eventually the airline's organizational structures will change. The introduction of computer automation must be adaptive to allow these changes to occur.

8. Every airline will have to develop its own automated scheduling system and manage the evolutionary impact on its operations. There is no single, turnkey solution to be provided by outsiders. A conceptual, long term plan is needed to direct the evolutionary effort and prevent building an incoherent set of sub-systems.

Aircraft Routing to Maintenance

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May 1996

Objective

Find good set of turns between arrivals and departures at a station to form routings

Given

- Desire for through service in certain markets
- Maintenance operational constraints

Output

- Rotations, daily/weekly lines of flying
- Gate occupancies at station
- Routings to planned maintenance checks

CONSTRAINTS TO THE OBJECTIVE

Maintenance to be performed

A - check: every 50 hours, 3 hour check

B -

C -

D - check: every 500 hours, 3 day check

Bases

1-4 maintenance stations
some stations specialize, such as electronics or engines

Scheduling

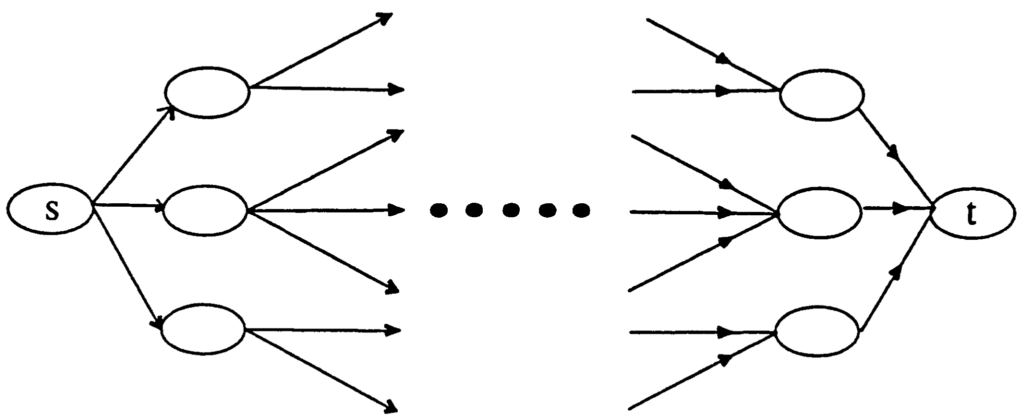
Workload balancing

Irregular Ops

3-5 percent of an airline's fleet require unscheduled maintenance

APPROACH

Tree Search Techniques

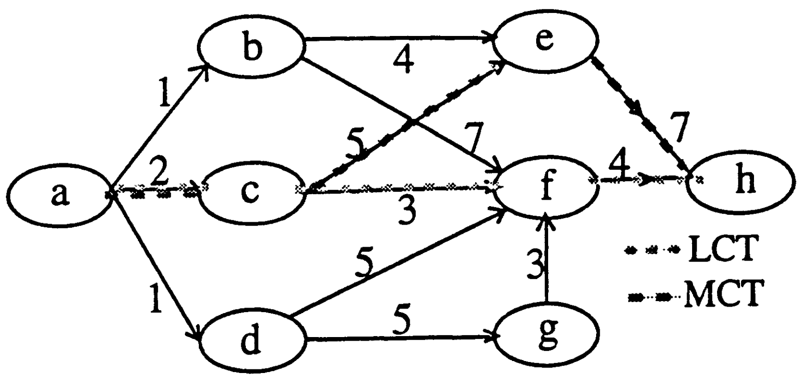


A network consisting of nodes and arcs directed from **s** and to t.

Shortest Path SP (s,t) $\equiv$ LCT (s,t) = $LCT^F + LCT^R$

Longest Path LP (s,t) $\equiv$ MCT (s,t) = $MCT^F + MCT^R$

Where "cost" is the flight time.



The LCT and MCT of a simple, non-negative cost, network. The numbers represent each arc's "cost", in this case flight hours.

SP (a,h) = (ac, cf, fh)

LP (a,h) = (ac, ce, eh)

LCT^F (a,h): $\pi_h = 9$

MCT^F (a,h): $\pi_h = 14$

LCT^F - MCT^F gives bounds on costs from a to h

e.g. (ad, df, fh) gives $\pi_h = 10$

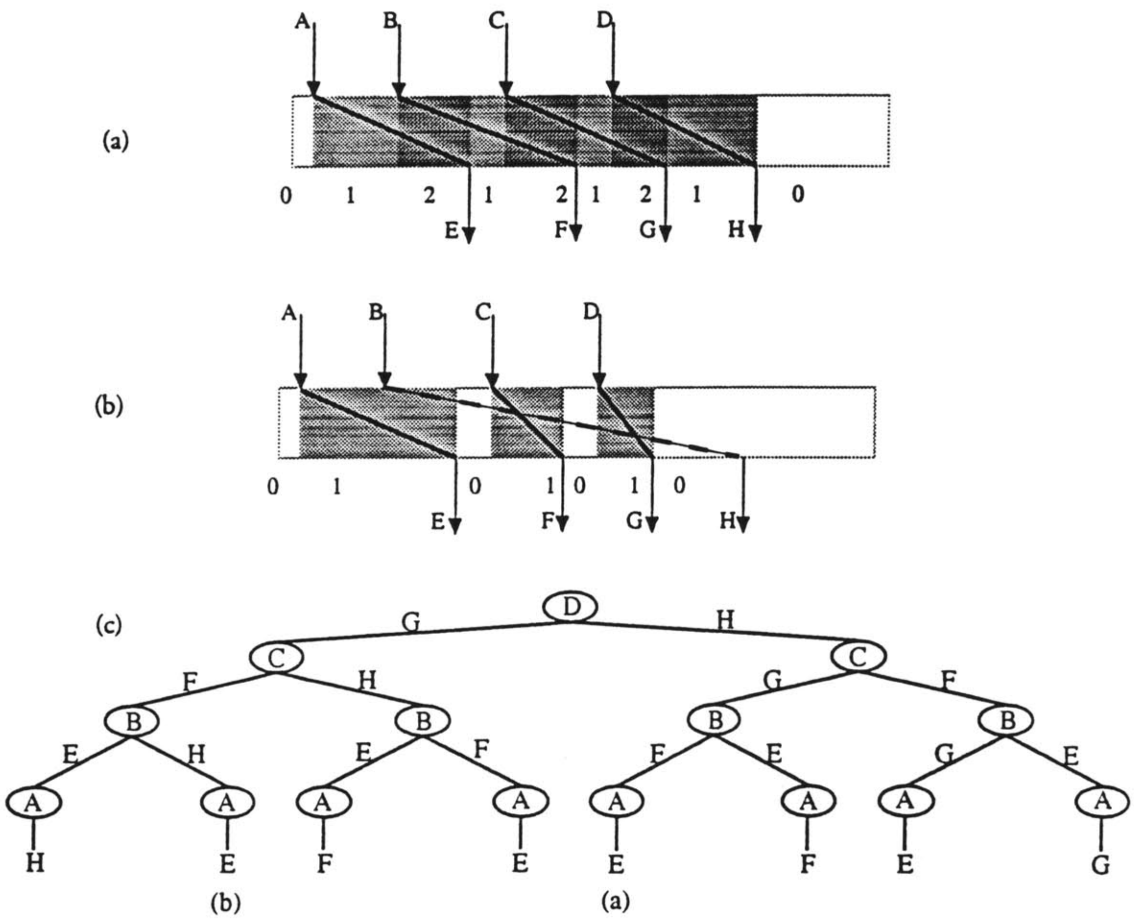
Similarly:

LCT^R (h,a) gives $\pi_a = 9$

MCT^R (h,a) gives $\pi_a = 14$

Aircraft "Switches"

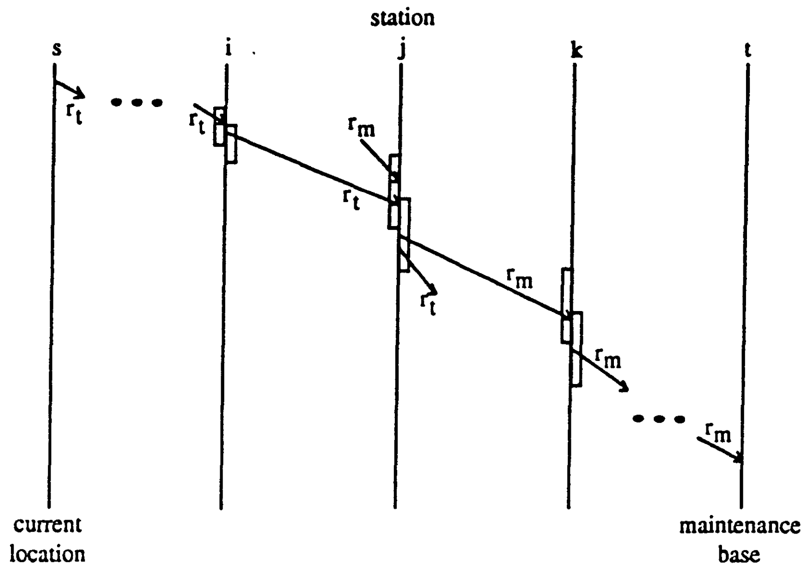
Switching aircraft types at stations for routings in order to connect forward and reverse trees.



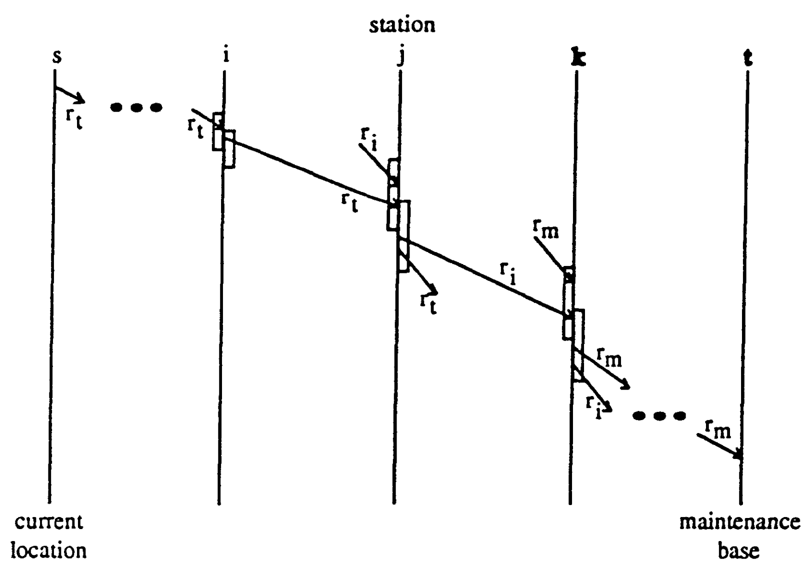
(a) Cluster using a FIFO turn scheme. (b) Only possible turns if B turns to H assuming no late flights. (c) Turn Tree for this cluster.

Clusters and Switches

It is necessary to globally view the schedule when considering switches.

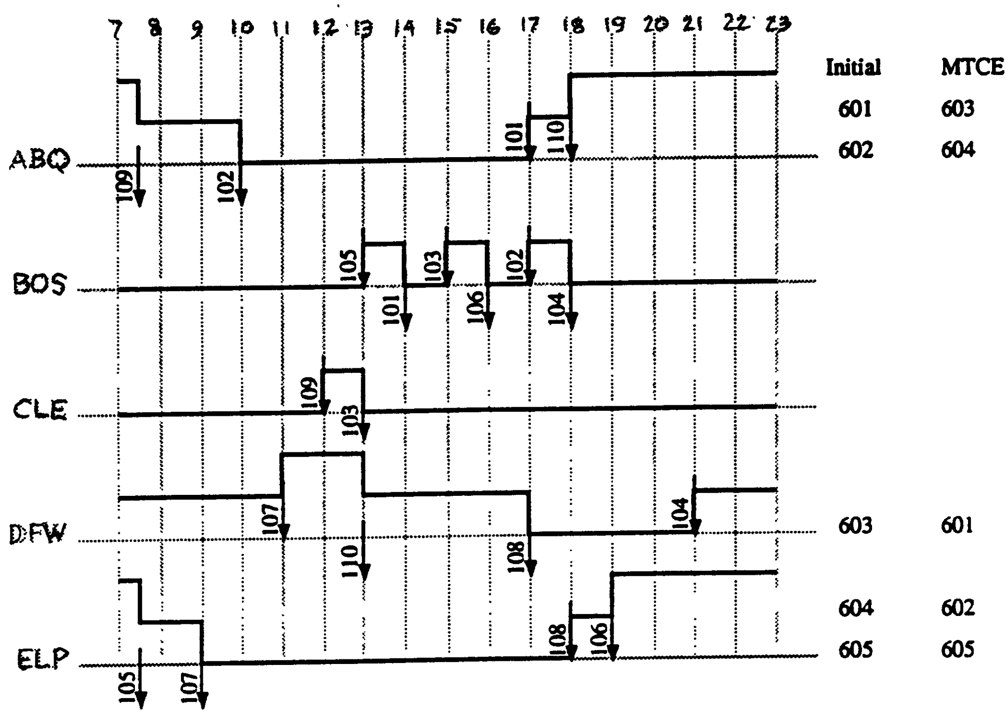


Intersection of the target aircraft's rotation r_t and the rotation, r_m, of another TN which is directed to the maintenance base.



An intermediate rotation, r_i, is required to direct the target aircraft to the rotation directed to the maintenance base.

Implementation



Schedule Map of the Base Schedule.

TN rotations determined by the Forward Tree search.

Day	TN601 -- 4	TN602 -- 3	TN603 -- 5	TN604 -- 1	TN605 -- 2
5	102 104	109 103 106	108	105 101	107 110
6	108	105 101	107 110	102 104	109 103 106
7	107 110	102 104	109 103 106	108	105 101
8	109 103 106	108	105 101	107 110	102 104
9	105 101	107 110	102 104	109 103 106	108
10	102 104	109 103 106	108	105 101	107 110
11	108	105 101	107 110	102 104	109 103 106
12	107 110	102 104	109 103 106	108	105 101
13	109 103 106	108	105 101	107 110	102 104
14	105 101	107 110	102 104	109 103 106	108
15	102 104	109 103 106	108	105 101	107 110
16	108	105 101	107 110	102 104	109 103 106
17	107 110	102 104	109 103 106	108	105 101
18	109 103 106	108	105 101	107 110	102 104
Tr after 18 days	-40:10	-31:40	-19:40	-9:30	-6:20

CONCLUSIONS

- Using LCT and MCT approach is a powerful way to consider alternative aircraft paths

- Each tree has a min cost and max cost bounds

- to accomplish a switch, nodes must be visualized as a cluster

- Ability to switch depends on the size of the cluster

- The algorithm successfully computed alternative rotations to accommodate the maintenance requirements

Development of Heuristic Procedures for Flight Rescheduling in the Aftermath of Irregular Airline Operations

Presenter: Michael Dudley Delano Clarke
Research Assistant
MIT Flight Transportation Laboratory
International Centre for Air Transportation

Presentation: FTL Annual Cooperative Meeting
May 23, 1996

Presentation Outline

- Introduction /Motivation
- Background
- Statement of the Problem
- Important Research Issues
- Model Development
- Problem Formulation
- Proposed Research Program
- Summary and Conclusions

Motivation of Research

- Significant Impact of Irregularities on an Airline's Flight and Resource Schedules
- Efforts spent to Optimize Schedules in Strategic phase are lost
- Available Information Flow
- Available Computer Technology

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Motivation of Research

- Effects of Irregularities on Airline Operating Expenses
- Site examples
  - Blizzard in the Northeast (January 1996)
  - Hail storm at Dallas/Ft. Worth (August 1995)
- Current Resolution Approaches
  - Manual decision making
  - Cancellation planning

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Airline Operations Control

- Purpose of Airline Operations Control Centre

  Execution Scheduling, the process of executing the system resource schedules on a daily basis

- Functional Groups within the AOCC
  - Airline Operations Controllers
  - Flight Dispatch Group
  - Crew Operations Group

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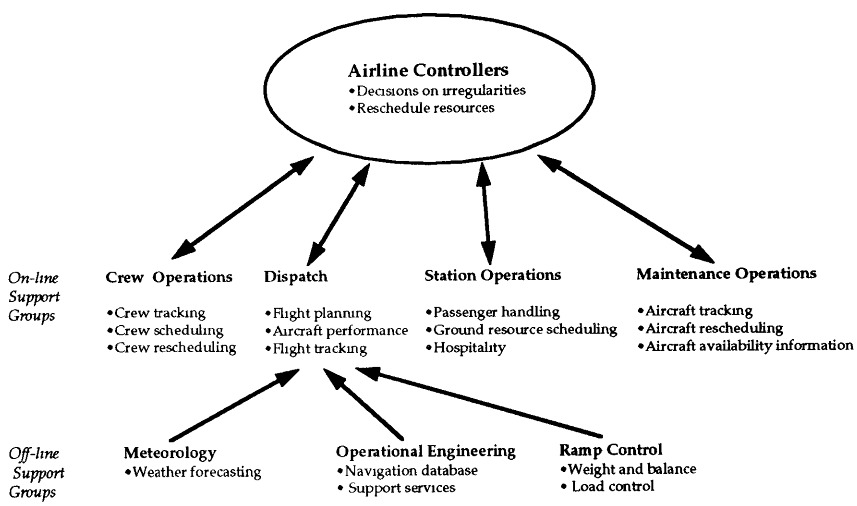
Information Flow within AOCC



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Problem Statement

- Definition of Irregular Operations

Aftermath of unexpected variations in operations which have a significant impact on the carrier's schedule

- Primary Causes of Irregularities

Severe weather patterns, delays in ATC systems, airport closures, aircraft breakdowns, lack of adequate crews, problems in ground handling and support services

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Problem Statement

- Impact on the Schedules of an Airline
  - Aircraft rescheduling and rerouting
  - Flight delays and cancellations
  - Maintenance scheduling
- Three Dimensional Assignment Problem
  - Assignment of each aircraft to most "profitable" flights
  - Assignment of each aircraft to an aircraft rotation to satisfy maintenance requirements

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Important Issues

- Isolation of the "problem" Airport
- Multi-fleet Switching Capability
- Crew considerations
- Aircraft maintenance considerations
- Combined Cancellation and Delays Ability

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Important Issues

- Practicality of DSS system
- Real-time Solution Capability
- Current Activities in AOCC
- Solution methodology

  Optimization versus Heuristic

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Model Development

- Establish the Overall Framework of the Problem, Operational Requirements
- Develop a series of Mathematical Models, Algorithms and Procedures, Computer Implementation
- Validate Algorithms with Actual Operations data from a major US domestic carrier

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Problem Formulation

- Conventional
  - Fleet assignment solved before the aircraft routing
- New Approach
  - hybrid of the fleet assignment and aircraft routing problems
  - additional constraints for crew availability, ATC dynamic slot allocation issues, and passenger flow
  - Iterative sub-problems

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Problem Formulation

- Decision Variables

X_{ijk} = 1 if flight (i,j) is assigned to aircraft k, 0 otherwise
Y_{ij} = 1 if flight (i,j) is cancelled, 0 otherwise
Z_k = 1 if aircraft k is assigned to maintenance, 0 otherwise
S_{ij} = amount of spilled passengers from flight (i,j)

- Known Variables

D_{ij} actual passenger demand for flight (i,j)
f_{ij} net fare per passenger on flight (i,j)
t_{ij} flight time for flight (i,j)
C_{ijk} operating cost of assigning aircraft k to flight (i,j)

Problem Formulation

- Known Variables

C_{ijo} cost of cancelling flight (i,j)
M_{it} maintenance/ground capacity for station i at time t
CAP_k seating capacity of aircraft k
T_k amount of legal flight time available on aircraft k before maintenance
$CYCLE_k$ maximum number of flight cycles allowed on aircraft k

- Indices

F set of all flights
F(j,k) subset of flights that can be assigned to aircraft k at station j
F(i,p) subset of flights departing from station i in time period p
K set of all aircraft in the fleet
K(i,j) subset of aircraft considered for flight (i,j)

Problem Formulation

- Constraints
  - flight covering $\sum_{k \in K(i,j)} X_{ijk} + Y_{ij} = 1 \forall ij$
  - aircraft utilization $\sum_{(i,j) \in F(k)} t_{ij} \times X_{ijk} \leq T_k \forall k$
  - aircraft covering $\sum_{(i,j) \in F(k,p)} X_{ijk} \leq 1 \forall k, \forall p$
  - leg based demand covering

$$\sum_{k \in K(i,j)} \left(D_{ij} - CAP_k\right) X_{ijk} - S_{ij} = 0 \forall ij, S_{ij} \geq 0$$

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Problem Formulation

Constraints (cont'd)

- crew availability $\sum_{(i,j) \in F(i,p)} \sum_{k \in K(i,j)} X_{ijk} \leq CREW_{i,p} \forall i, p$
- ATC slot allocation $\sum_{(i,j) \in F(i,p)} \sum_{k \in K(i,j)} X_{ijk} \leq S_{i,p} \forall i, p$
- Conservation of flow $\sum_{(i,j) \in F(i,k)} X_{ijk} - \sum_{(i,j) \in F(j,k)} X_{ijk} + Z_{k,j} = 1 \forall k, j$

- Objective Function

$$\min \sum_{(i,j) \in F} \sum_{k \in K(i,j)} C_{ijk} X_{ijk} + \sum_{(i,j) \in F} C_{ijo} Y_{ij} + \sum_{(i,j) \in F} f_{ij} S_{ij}$$

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Solution Methodology

- GENERATE
  - Potential aircraft rotations using modified tree search algorithms on a sub-graph of the overall network schedule map
- ASSIGN
  - Aircraft rotations to each operating aircraft while optimizing specified objective (eg. max profit). If there are less aircraft than rotations, some flights will be assigned to "cancellation" rotations
- REVISE
  - Overall network structure, adjusting scheduled arrival and departure times of each flight, reflecting the output of the ASSIGN module

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Research Timetable

- Phase 1
  - Problem Formulation
  - September 1995 through June 1996
- Phase 2
  - Computer Implementation
  - June 1996 through December 1996
- Phase 3
  - Validation of Algorithms and Procedures
  - January 1997 through May 1997

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Research Facilities

- Computer Hardware
  - IBM R/S 6000
  - Sun SparcStation 5
- Software
  - OSL (Optimization Subroutine Library)
- Data Requirements
  - Operational data from a major US carrier

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Summary

- Primary goal to Develop Algorithms and Procedures that can in Implemented in a Robust Real-time Decision Support System in the Airline Operations Control Centre
- Target date of completion June 1997

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Background

- Airline Scheduling Process
  - ° Overview of the primary phases
- Airline Operations Control
  - ° Purpose of AOCC (Operations Control Centre)
  - ° Functional Groups within the AOCC
  - ° Information Flow Diagram (Requirements)
  - ° Interaction with External Sources

Aircraft Scheduling Process

- Fleet Assignment Problem

  Given the flight schedule, determine which fleet (type of aircraft) is assigned to each flight

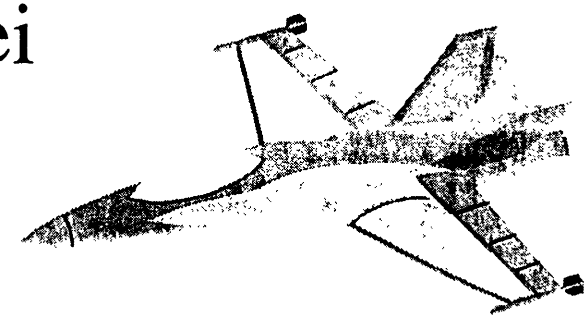
- Aircraft Routing/Rotation Problem

  Given the output of the assignment problem, determine which flights are flown by each aircraft of a given fleet (solved separately for each fleet)

Logan Airport with A New Runway

Husni Idris

Yuanyuan Wei



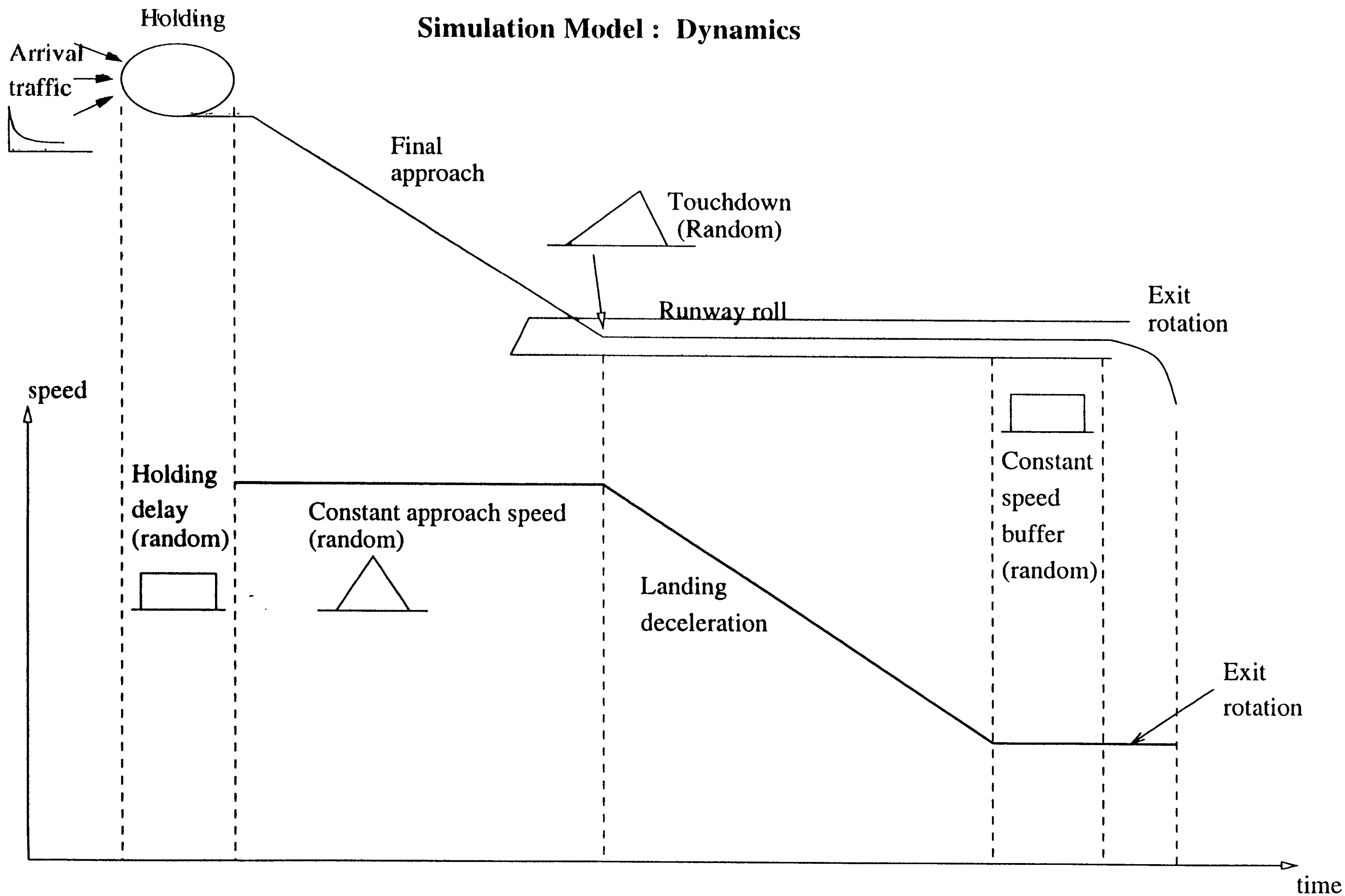
Objectives:

- Conduct a case analysis using an airport environment simulation and editor.
- Assessment of Logan airport capacity with the new runway.
- Comparison of queuing analysis and simulation analysis.

Methodology:

- Two methods for runway system capacity analysis:
  - Queuing analysis
  - Simulation analysis
- Estimate the runway system capacity using queuing analysis.
- Calibrate the simulation by comparing the two methods under the same assumptions.
- Estimate the runway system capacity under different assumptions using the simulation.

Simulation Model : Dynamics

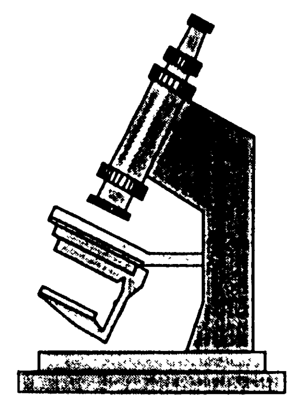


Simulation Model: Operations

- Arrival/departure traffic:
  - Poisson process (similar to queuing analysis).
  - OAG schedule for a busy day (plus a random delay).
- Landing/takeoff sequence:
  - FCFS (similar to queuing analysis).
  - FCFS with takeoff insertion between landings.
  - Landing priority.
- Two runway operation:
  - The two runways are independent.
  - Jets on the long runway and non-jets on the short runway.
  - The short runway is used for either landings or takeoffs (due to noise).
  - Unbalanced operations on the two runways.

Experimental Procedure

- Simulation Calibration
  - Capacity Calibration
  - Delay Calibration
- Case Study
  - Two-Runway Configuration
  - One-Runway Configuration



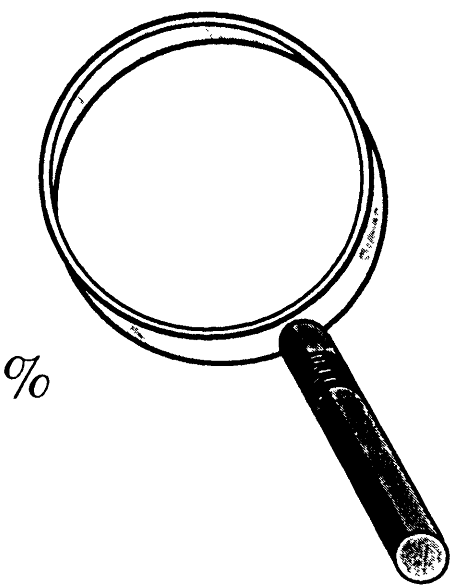
Calibration of the Simulation: I (Conditions)

- Seperation Matrix:

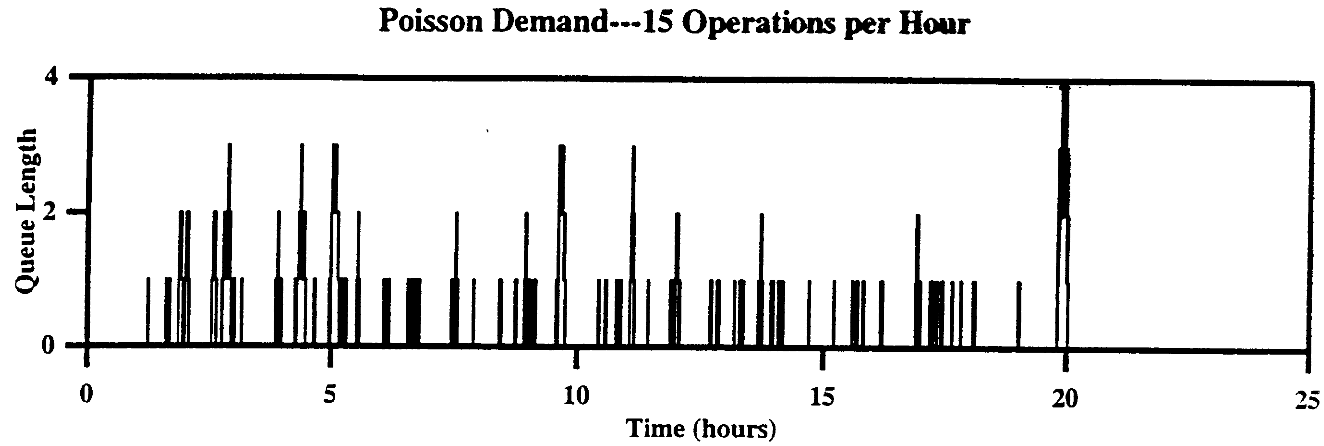
$$
\begin{array}{c c}
 & \begin{array}{cccc} H & L & M & S \end{array} \\
\begin{array}{c} H \\ L \\ M \\ S \end{array} & \left[\begin{array}{cccc} 4.0 & 5.0 & 5.0 & 6.0^{*} \\ 2.5 & 2.5 & 2.5 & 4.0^{*} \\ 2.5 & 2.5 & 2.5 & 4.0^{*} \\ 2.5 & 2.5 & 2.5 & 2.5 \end{array}\right]
\end{array}
$$

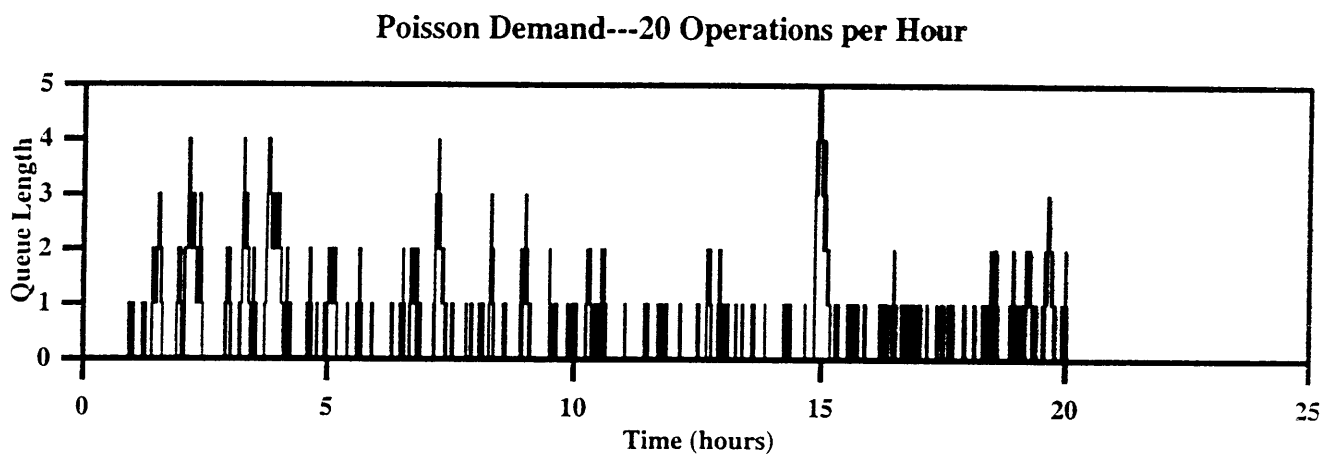
- Aircraft Mix:

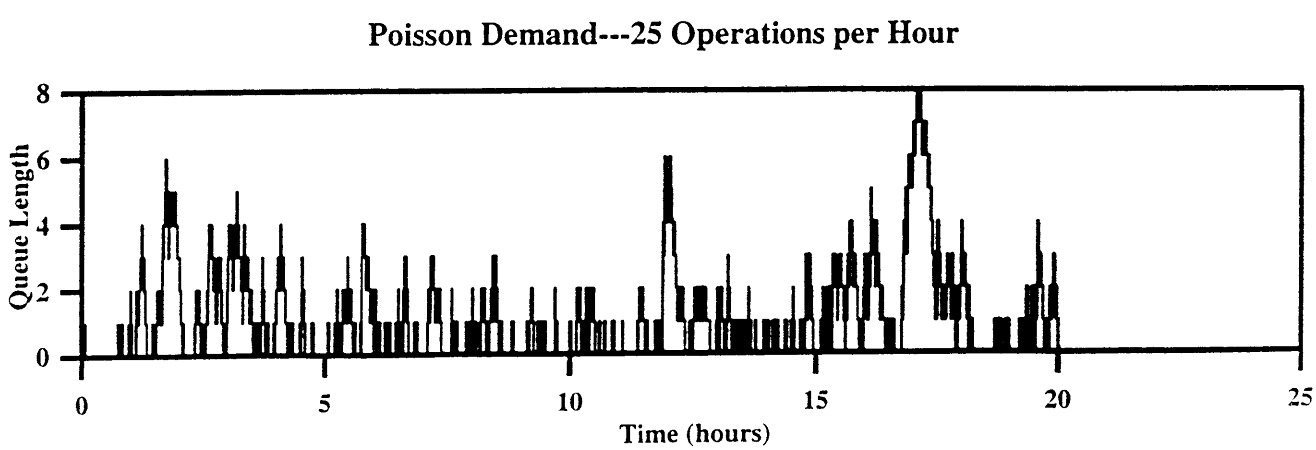
H = 5%   L = 45%   M = 45%   S = ~~4~~5%



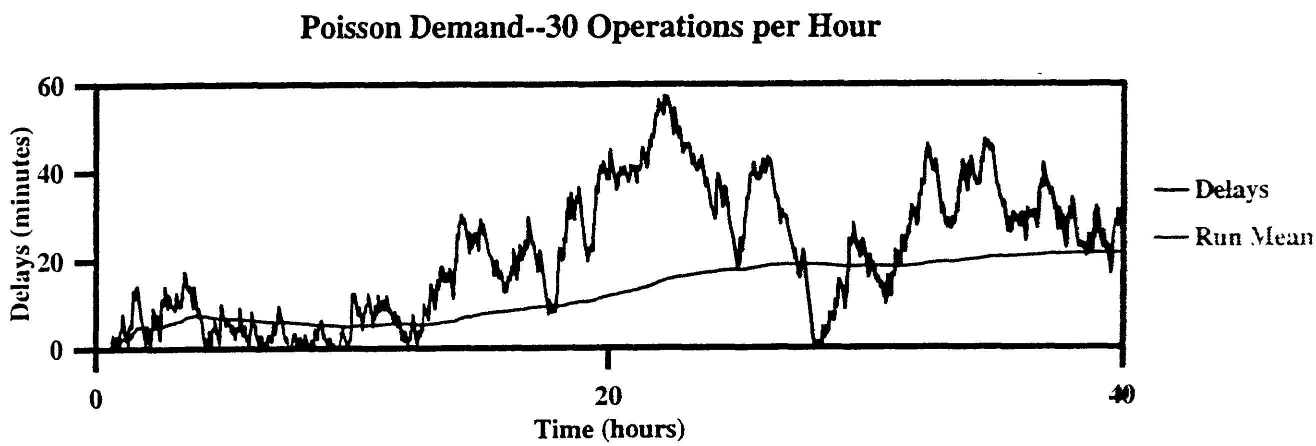
Calibration of the Simulation

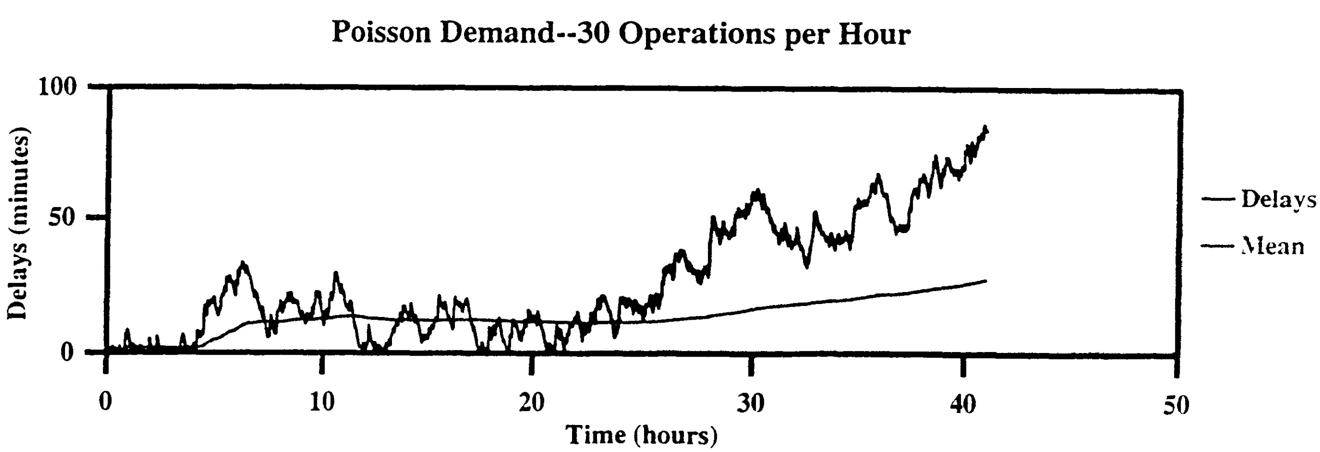


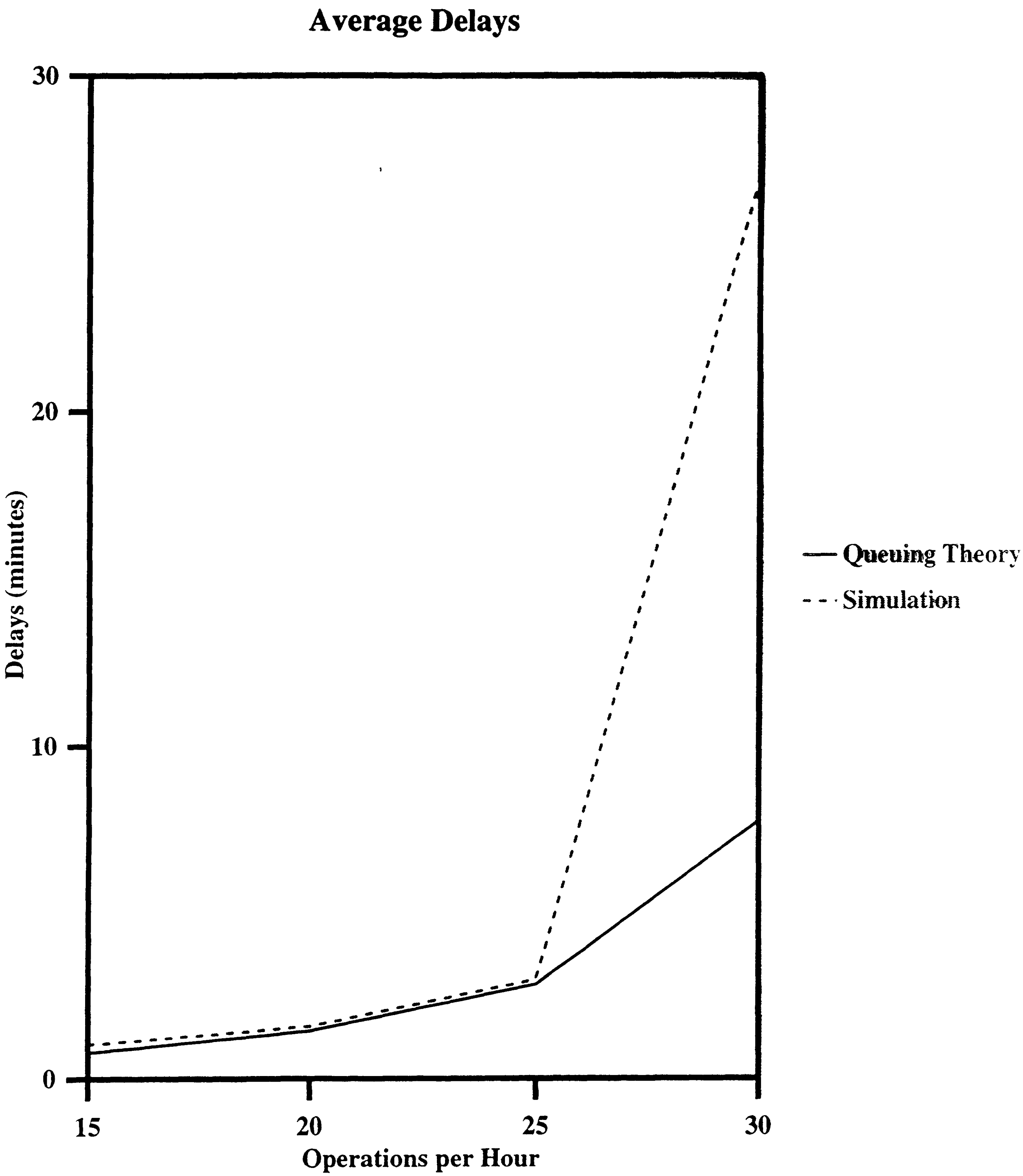




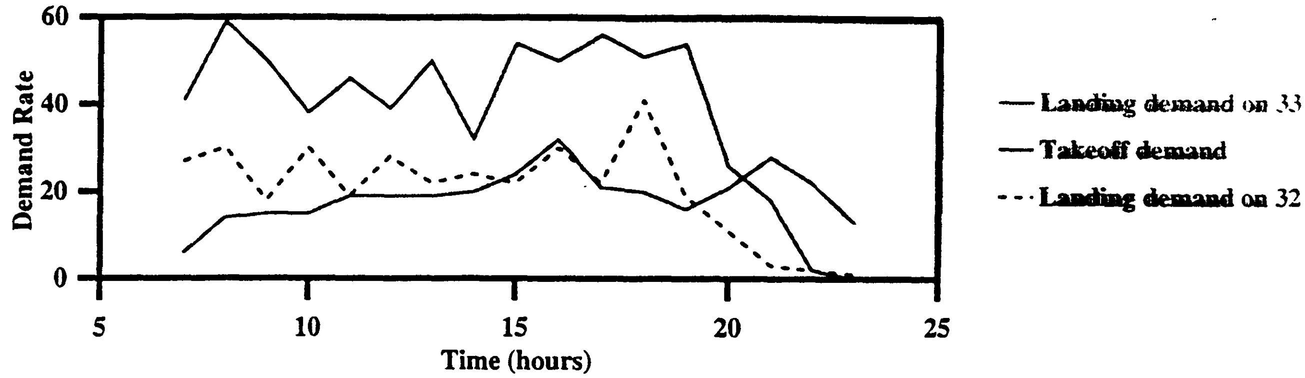
Calibration of the Simulation



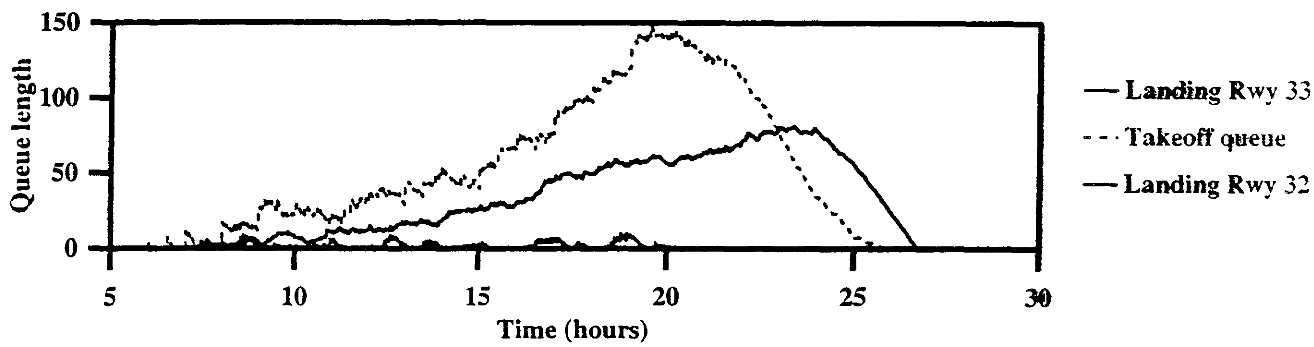



Average Delays
30
20
10
0
Delays (minutes)
15
20
25
30
Operations per Hour
Queuing Theory
Simulation

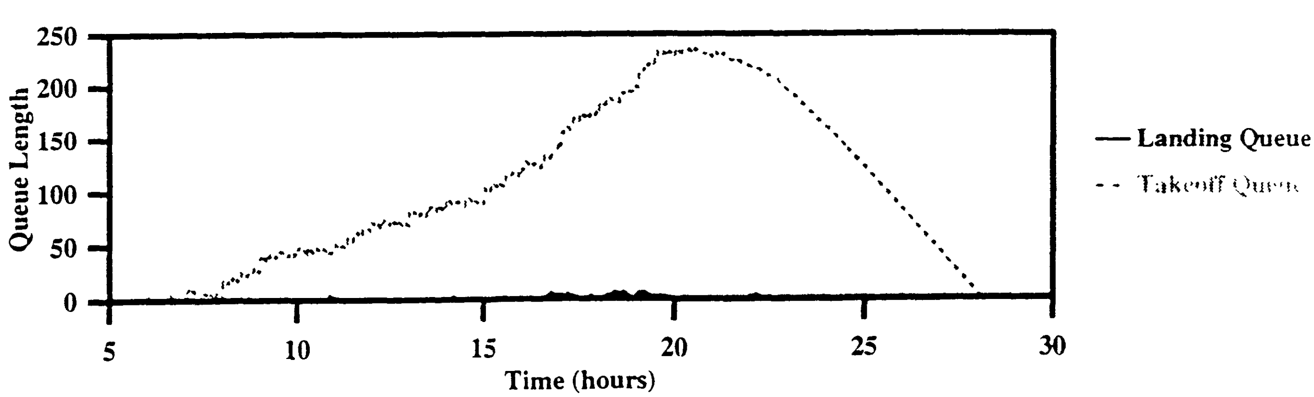
100% OAG Traffic



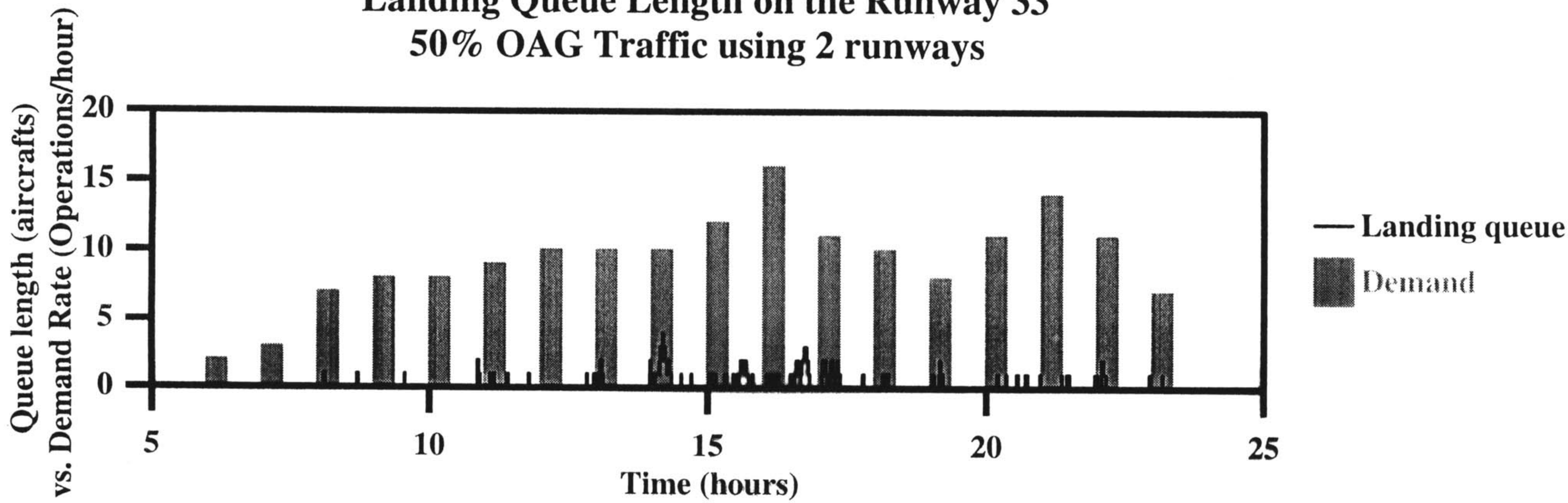
Queue length with 100% OAG Traffic using 2 Runways

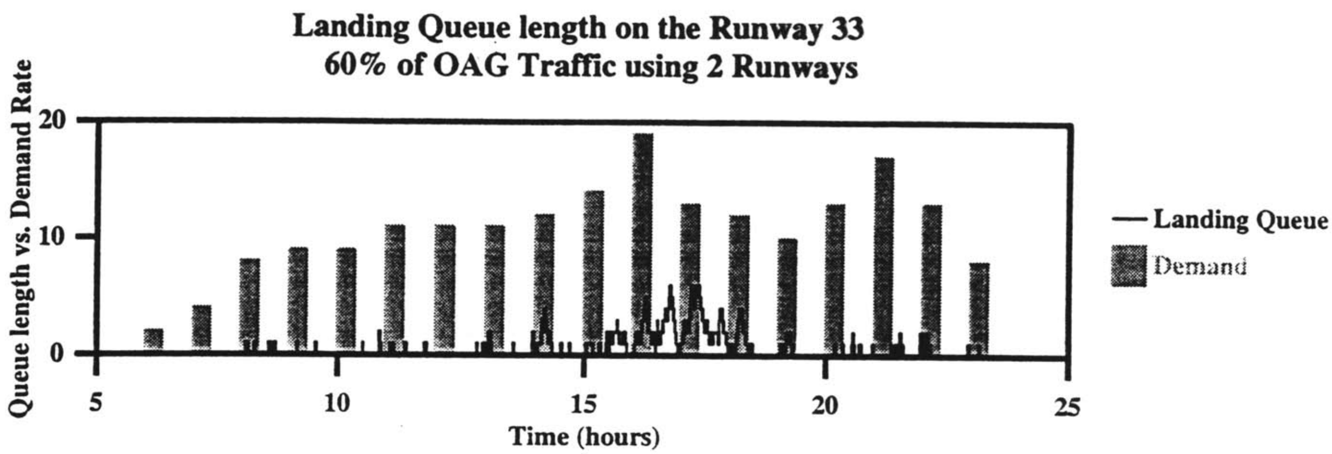


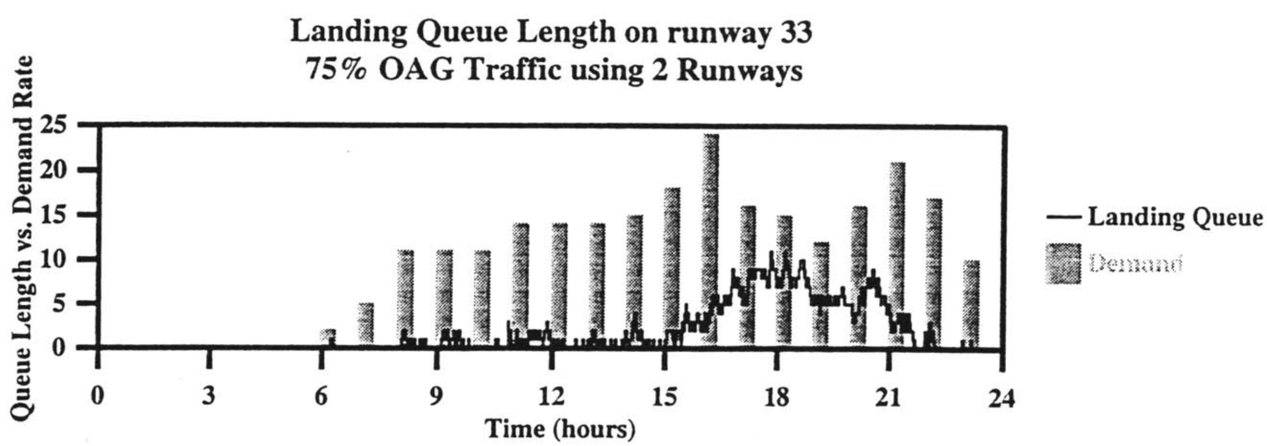
Queue length on runway 33 with landing priority



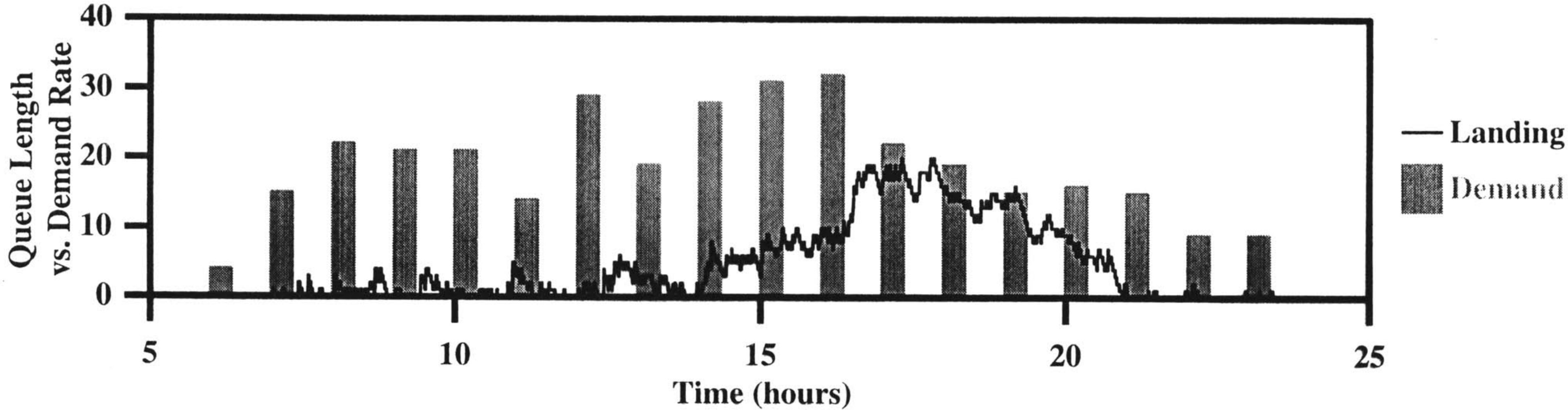
Landing Queue Length on the Runway 33
50% OAG Traffic using 2 runways

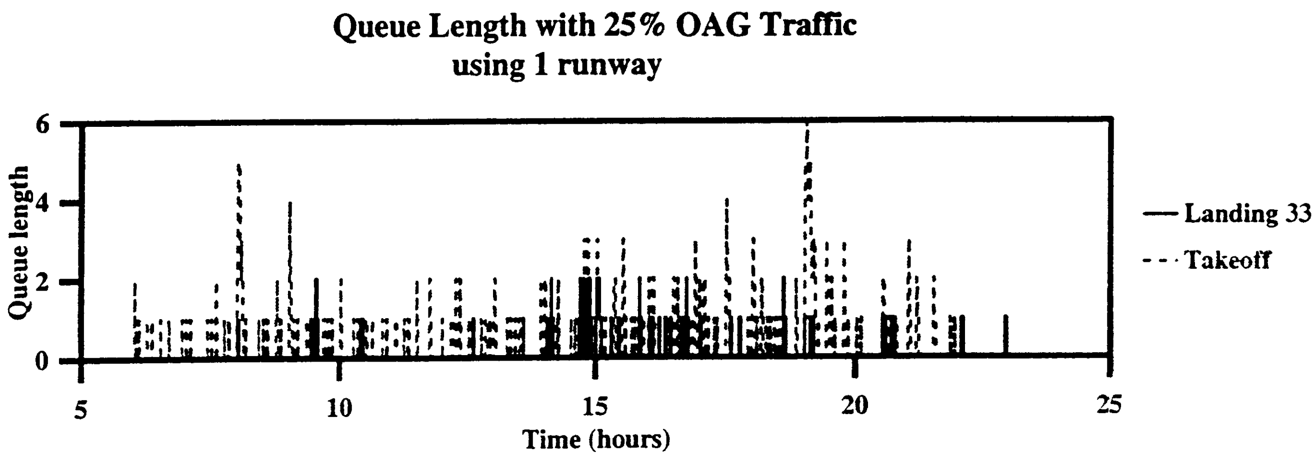


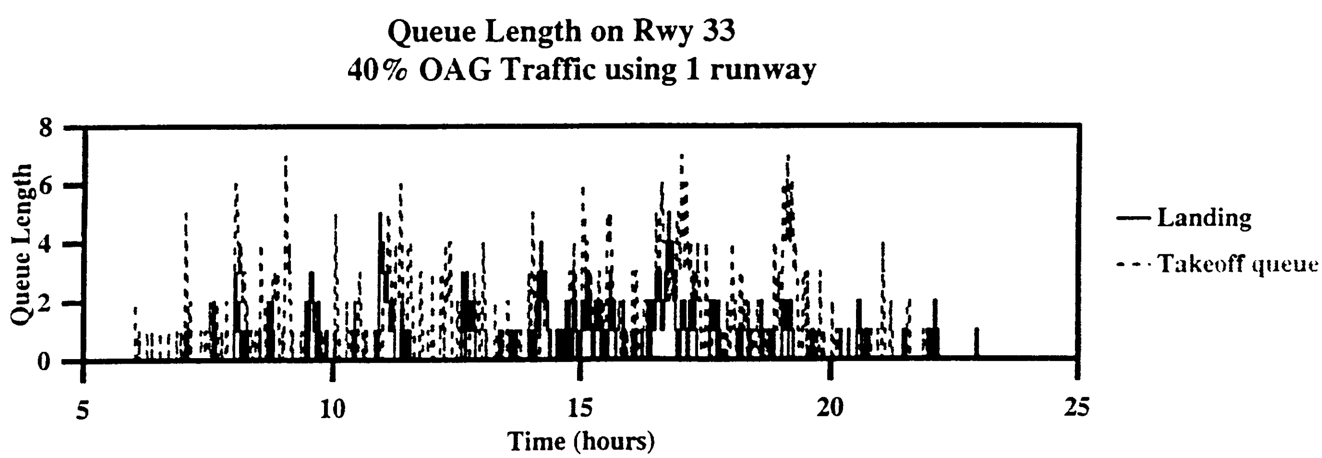

Landing Queue length on the Runway 33
60% of OAG Traffic using 2 Runways
Queue length vs. Demand Rate
20
10
0
5
10
15
20
25
Time (hours)
Landing Queue
Demand


Landing Queue Length on runway 33
75% OAG Traffic using 2 Runways
Queue Length vs. Demand Rate
25
20
15
10
5
0
0
3
6
9
12
15
18
21
24
Time (hours)
Landing Queue
Demand

Landing Queue Length on Runway 33 with 50% of OAG scheduled Traffic Using one runway




Queue Length with 25% OAG Traffic
using 1 runway
Queue length
6
4
2
0
5
10
15
20
25
Time (hours)
— Landing 33
- - · Takeoff


Queue Length on Rwy 33
40% OAG Traffic using 1 runway
Queue Length
8
6
4
2
0
5
10
15
20
25
Time (hours)
— Landing
- - · Takeoff queue

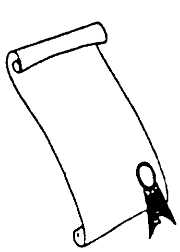
Results of Case Study

TABLE 1. Two Runways

OAG Percentage	**50%**	**60%**	**75%**	**100%**
Demand Rate	60	72	90	120
Average Queue Length	0.167	0.5	2.2	34
Max Queue Length	4	6	11	82
Average Delay	1.25	2.1	6.16	64.27
Max Delay	7.57	14.0	24.5	217

TABLE 2. One Runway

OAG Percentage	**25%**	**40%**	**50%**
Demand Rate	30	48	60
Average Queue Length	0.06	0.45	4.87
Max Queue Length	2	5	20
Average Delay	1.12	1.95	14.5
Max Delay	7.5	9.1	51.24



Accomplishments

- Enhance Ground Motion Simulator
- Calibrate the simulation against queuing theory
- Reconfigurate Logan airport with a new runway using GMS Editor
- Simulate the operations in Logan with this new runway

Traffic Organization Using Intermediate Slot Markers

Scheduling and Simultaneous Conflict-free Path Planning for All Aircraft in The Terminal Area

Implementation working report

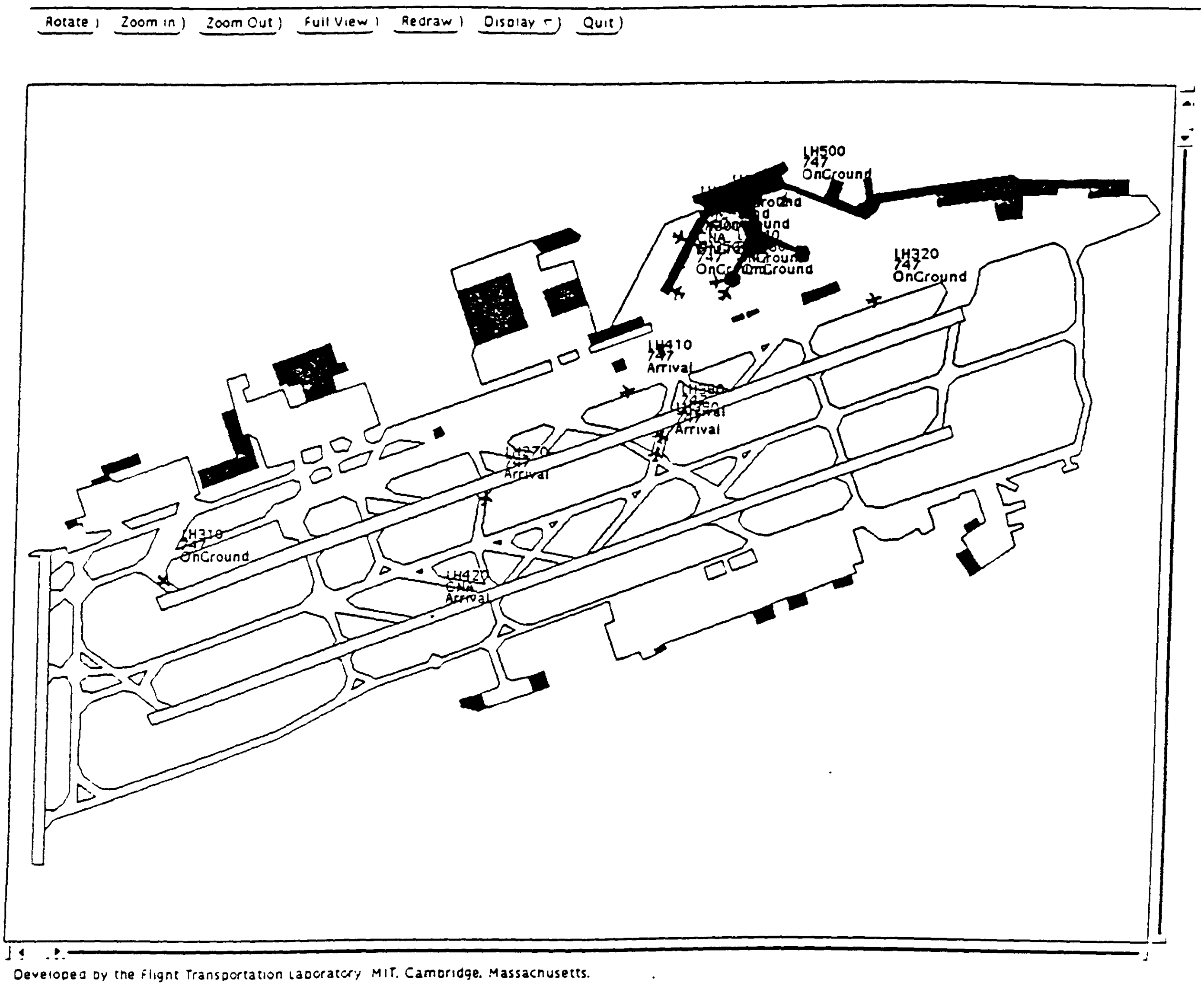
by

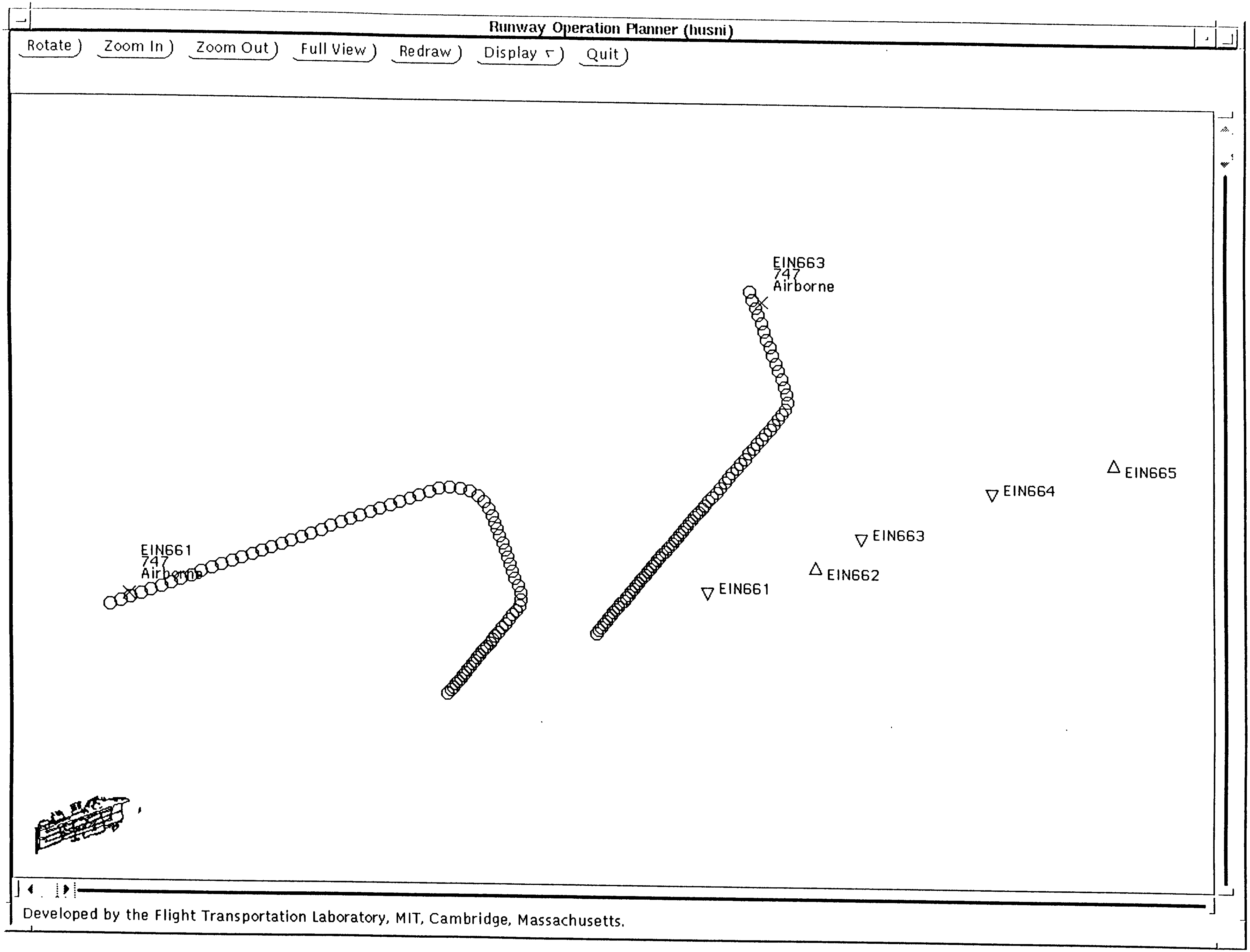
Husni Idris
Flight Transportation Laboratory
MIT
January 30, 1996

1

ATC Operations in the Terminal Area:

- Upstream of entry points:
  - Flight management
  - Flow control
- Runway scheduling
- Approach path generation
- Conformance monitoring
- Hazard monitoring


Rotate
Zoom in
Zoom Out
Full View
Redraw
Display
Quit
LH500
747
OnGround
LH320
747
OnGround
LH410
747
Arrival
Arrival
LH370
747
Arrival
LH310
747
OnGround
LH420
CNA
Arrival
Developed by the Flight Transportation Laboratory MIT, Cambridge, Massachusetts.


Runway Operation Planner (husni)
Rotate
Zoom In
Zoom Out
Full View
Redraw
Display
Quit
EIN663
747
Airborne
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Airborne
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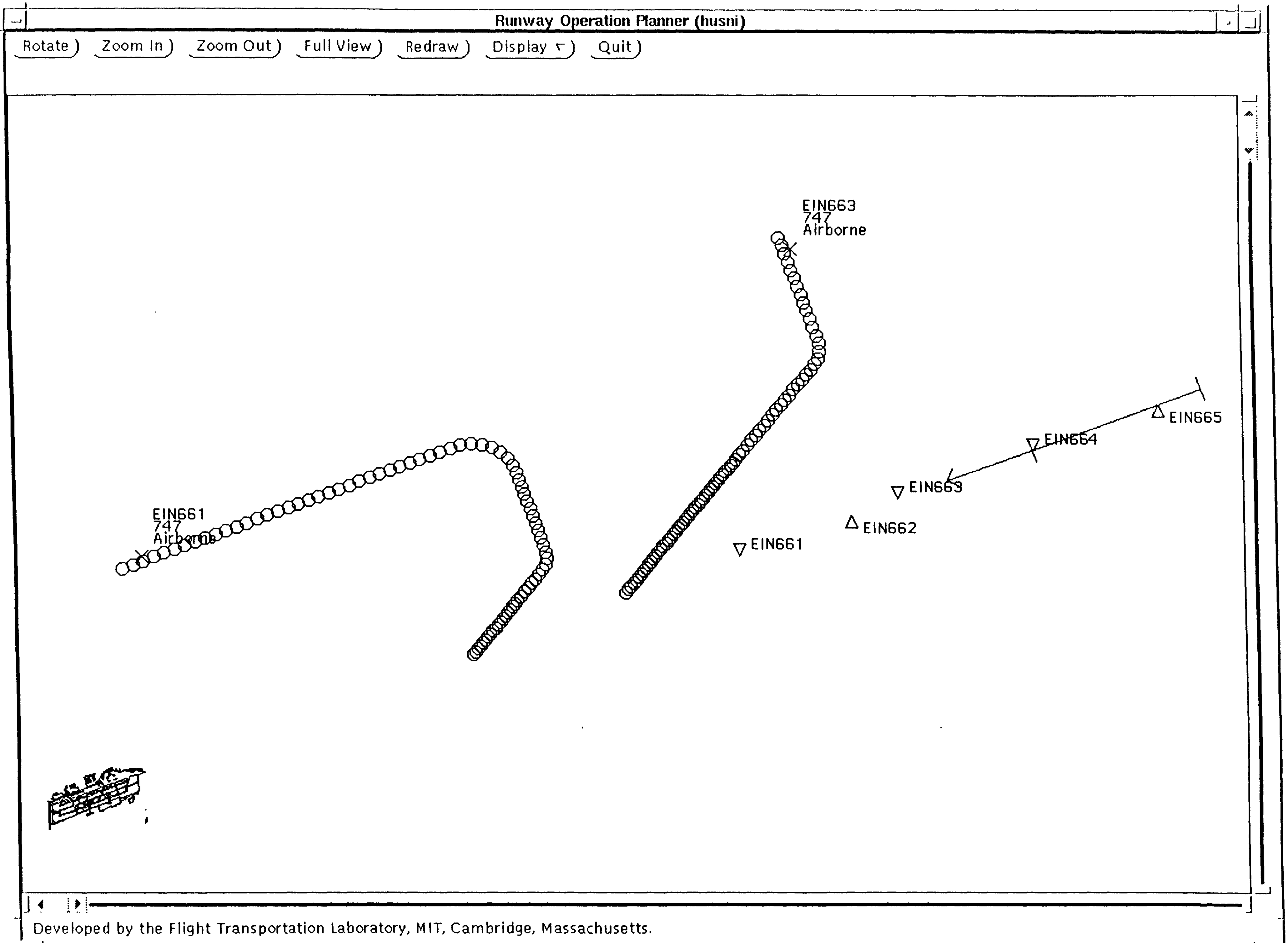
EIN661
Developed by the Flight Transportation Laboratory, MIT, Cambridge, Massachusetts.


Runway Operation Planner (husni)
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Airborne
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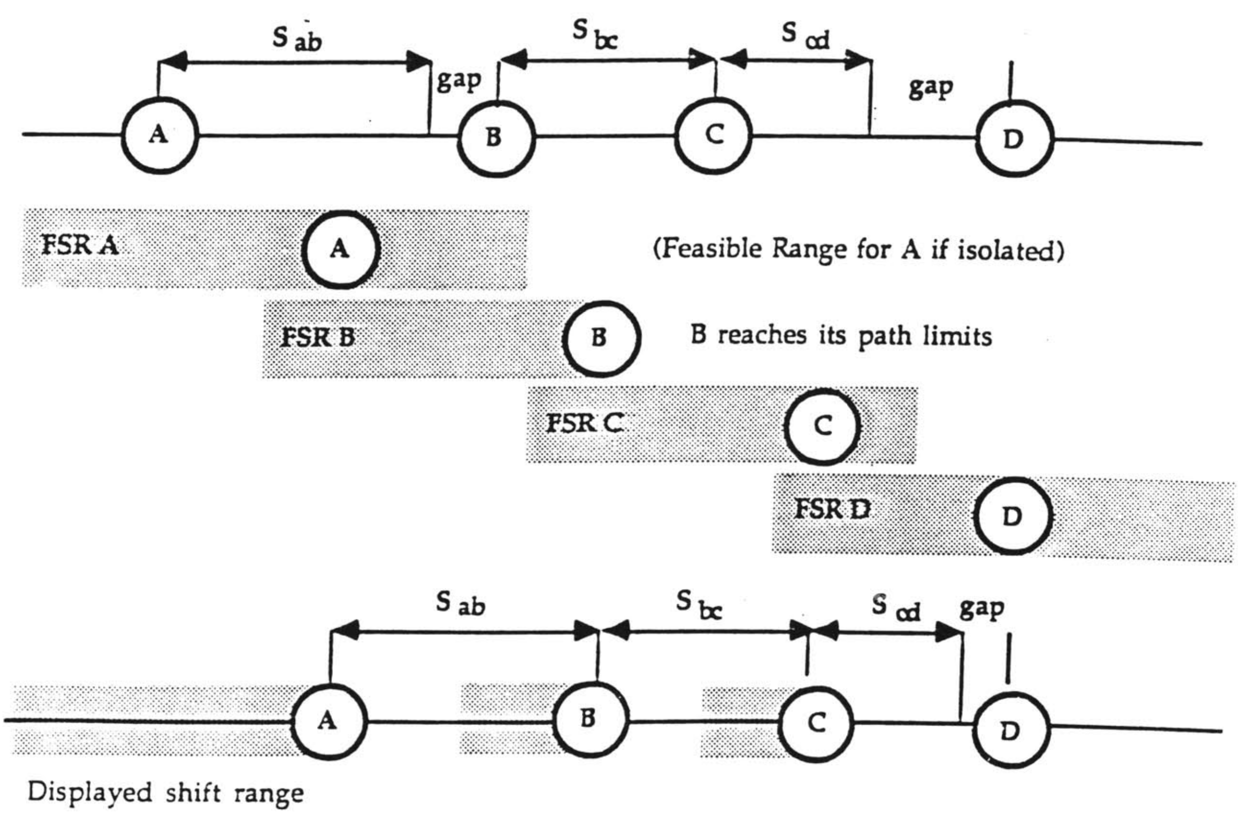
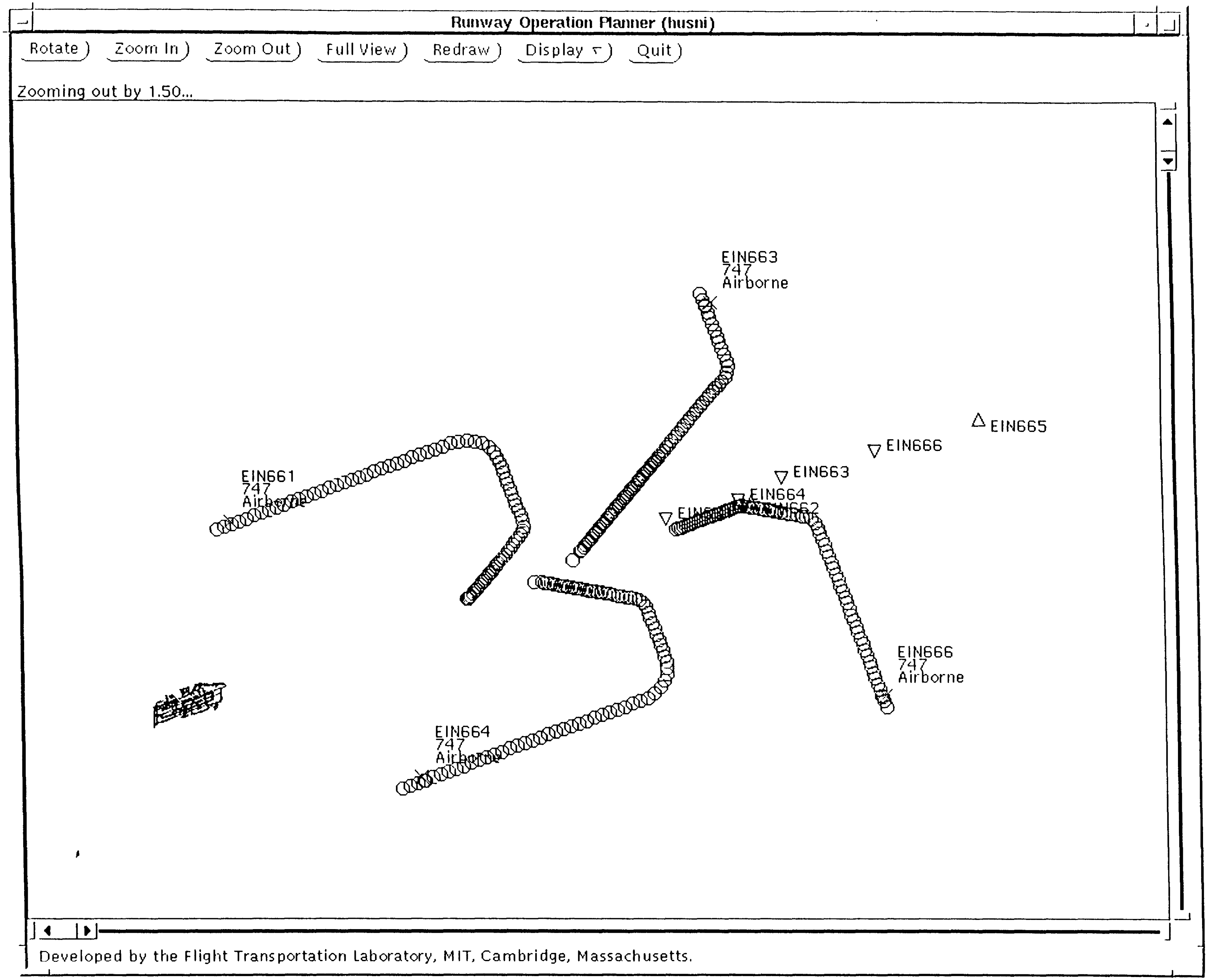
EIN661
Developed by the Flight Transportation Laboratory, MIT, Cambridge, Massachusetts.

Automatic Rearward Shifting of Slots (ARS)

Example:

If an attempt is made to shift A rearwards, it cannot reach the limit of its feasible range because it must maintain a separation Sab from B; and when B reaches the limit of its range, A cannot be moved further and maintain separation from B. As B moves rearward, C is also moved since it is tight in the original spacing, but when B reaches its limit, C stops moving rearward and since there still is excess spacing from D, it turns out that D does not have to be shifted. The shift range shown to the controller will instantly show how far each aircraft can be shifted in any situation so that the complexity of the shifting need not be known.




Runway Operation Planner (husni)
Rotate
Zoom In
Zoom Out
Full View
Redraw
Display
Quit
Zooming out by 1.50...
EIN663
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Airborne
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Airborne
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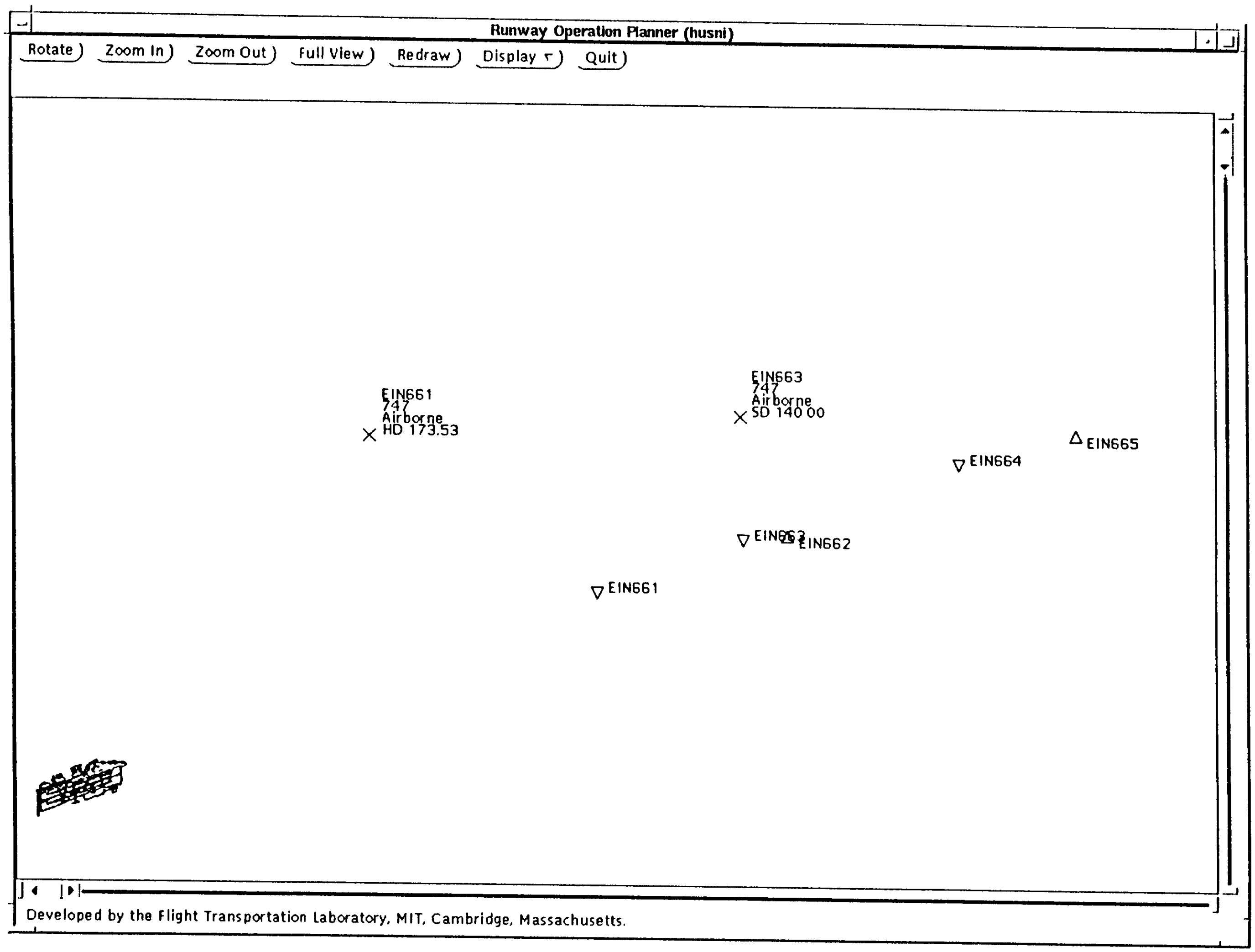
747
Developed by the Flight Transportation Laboratory, MIT, Cambridge, Massachusetts.


Runway Operation Planner (husni)
Rotate
Zoom In
Zoom Out
Full View
Redraw
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EIN661
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Airborne
HD 173.53
EIN663
747
Airborne
SD 140.00
EIN665
EIN664
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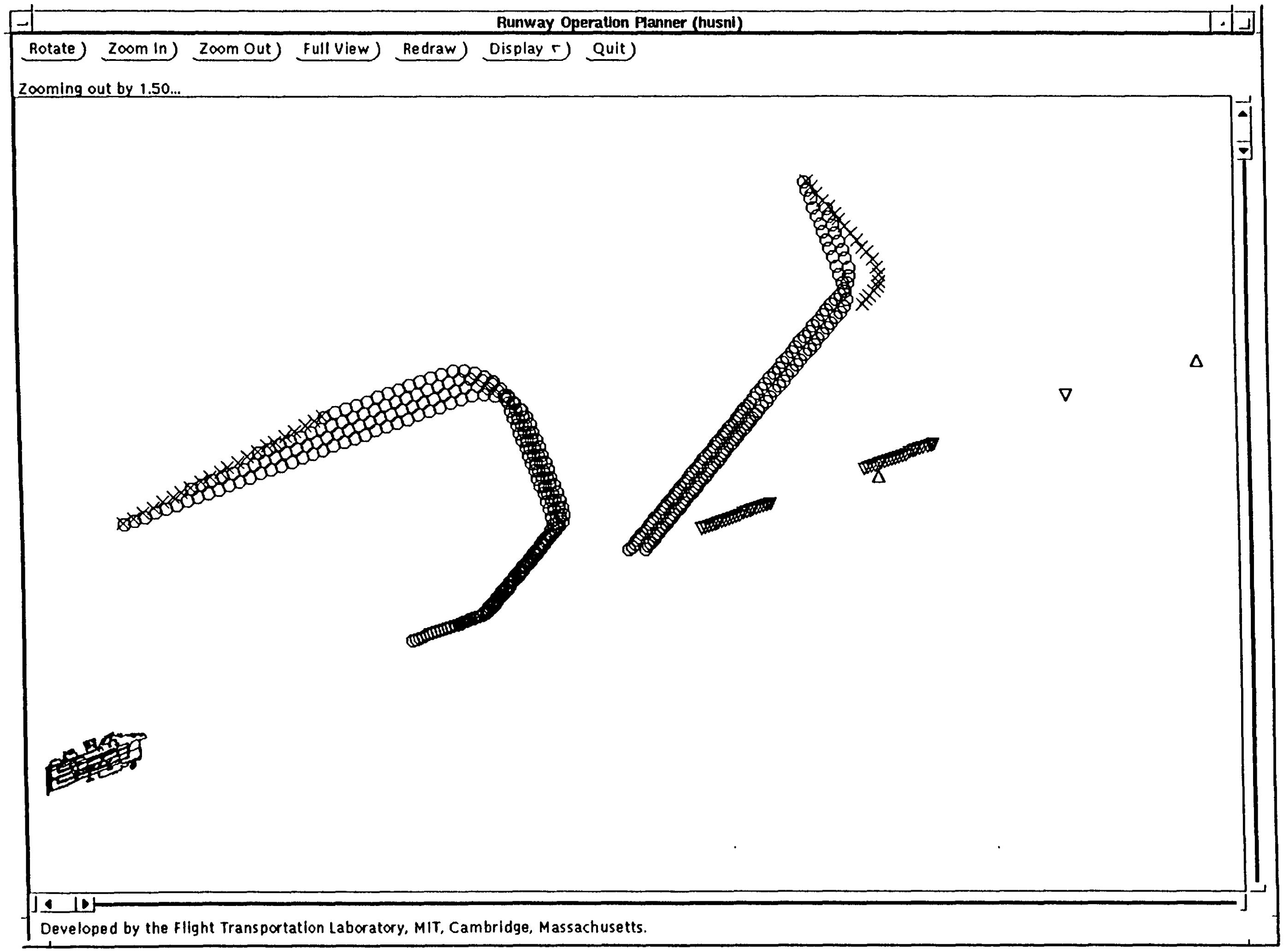
Developed by the Flight Transportation Laboratory, MIT, Cambridge, Massachusetts.



Runway Operation Planner (husni)
Rotate
Zoom In
Zoom Out
Full View
Redraw
Display
Quit
Zooming out by 1.50...
Developed by the Flight Transportation Laboratory, MIT, Cambridge, Massachusetts.

ASLOTS: a human-centered automation system for terminal area operations

- **Runway scheduling:**
  - Manual change of schedule within a limited range: moving the slot markers
  - Manual resequencing of landings: moving the slot markers
  - Manual insertion of takeoffs between landings: using the slot markers
  - Automatic update of the schedule after a manual change: automatic rearward shifting
  - Automatic update of the schedule after a centerline interception error: centerline adaptation
- **Approach path generation:**
  - Automatic assignment of patterns
  - Automatic approach path generation: providing cues for appropriate clearances
  - Manual delivery of clearances following the automatic cues

- **Conformance monitoring:**
  - Automatic regeneration of the approach path after a conformance error
  - Automatic regeneration of the approach path after moving the slot marker
- **Hazard monitoring:**
  - Automatic maintenance of the minimum separation between aircraft on the centerline: automatic rearward shifting and centerline adaptation

The path generation steps:

- Choose the pattern: Such as trombone or direct. This defines the shape of the path in terms of legs and segments.
- Choose the geometry: Such as the angles of the different legs, the altitude, and the offset from the runway centerline (where applicable).
- Choose dynamic parameters: Such as the speed, deceleration, descent rate, and turn rate of the aircraft.
- Choose the time duration of the path segments: find the feasible path in terms of clearances (i.e. when should the clearances be delivered).

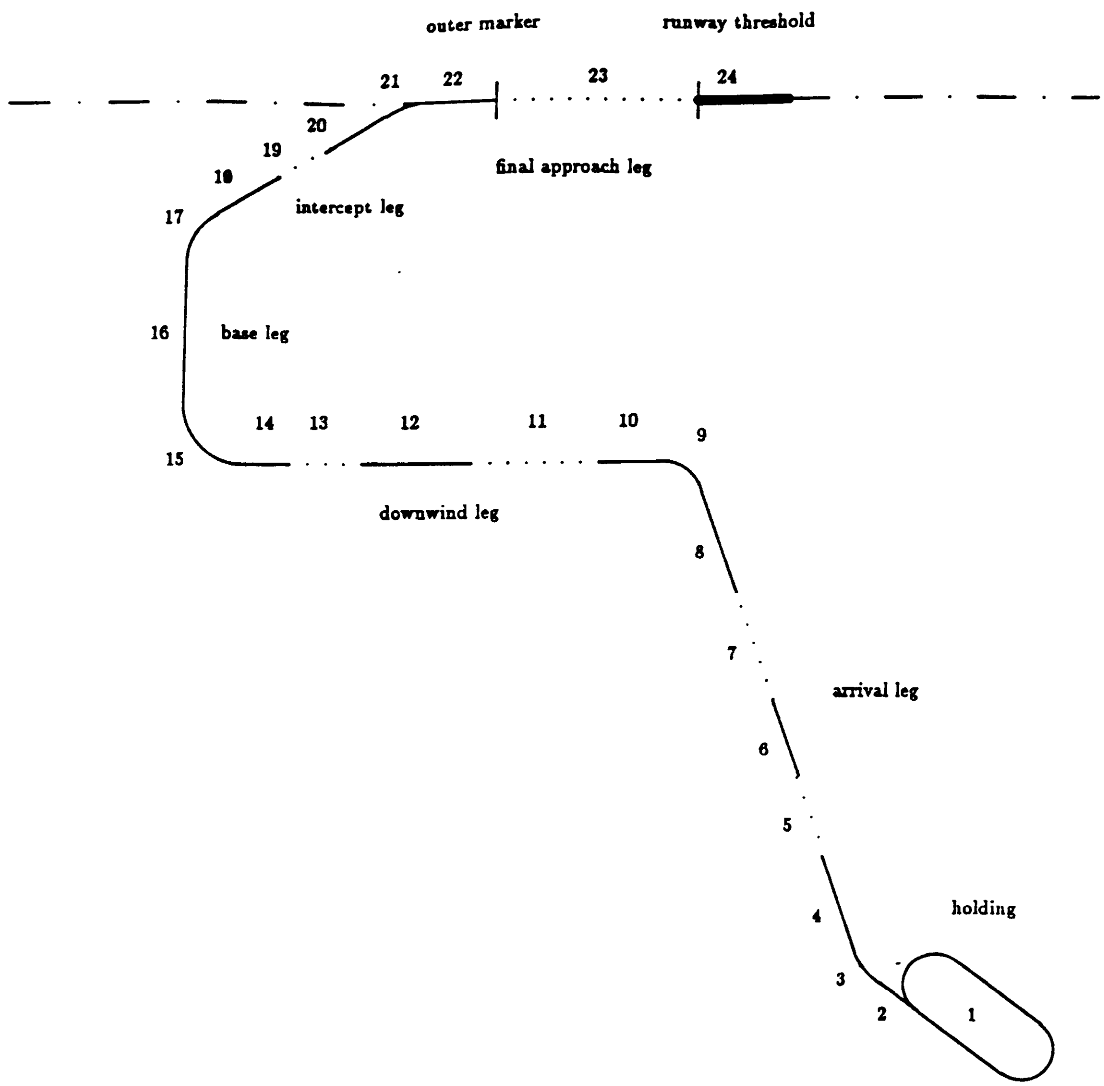


Figure 4.1: "Arrival-Trombone" Pattern

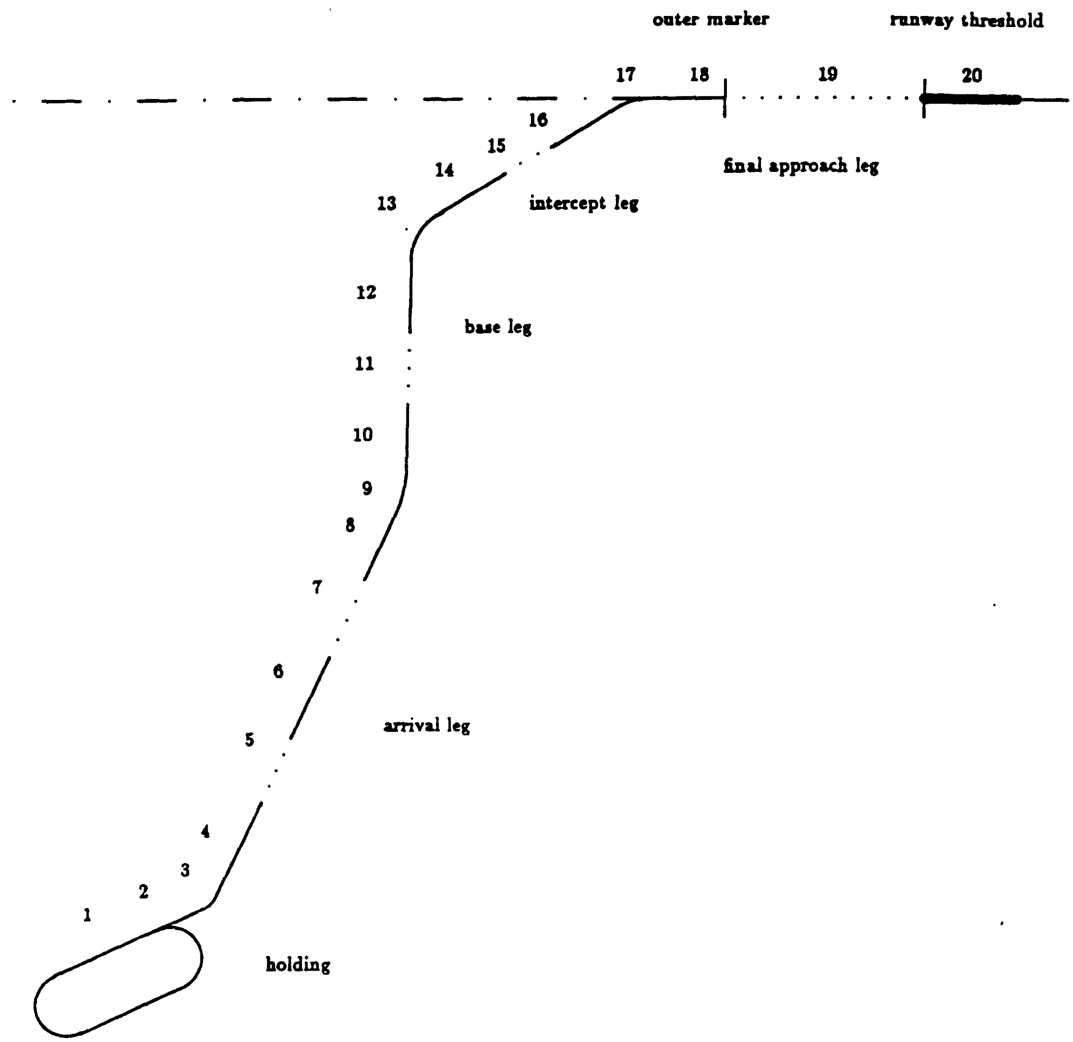


Figure 4.9: "Arrival-Direct-to-Base" Pattern

The constraints of the path generation problem

- Constraints imposed by space management
- Constraints imposed by aircraft capabilities
- Constraints imposed by human pilot capabilities
- Constraints imposed by the runway operation schedule
- Constraints imposed by conflict avoidance

Flexibility as an objective

- Choose the center of the solution set

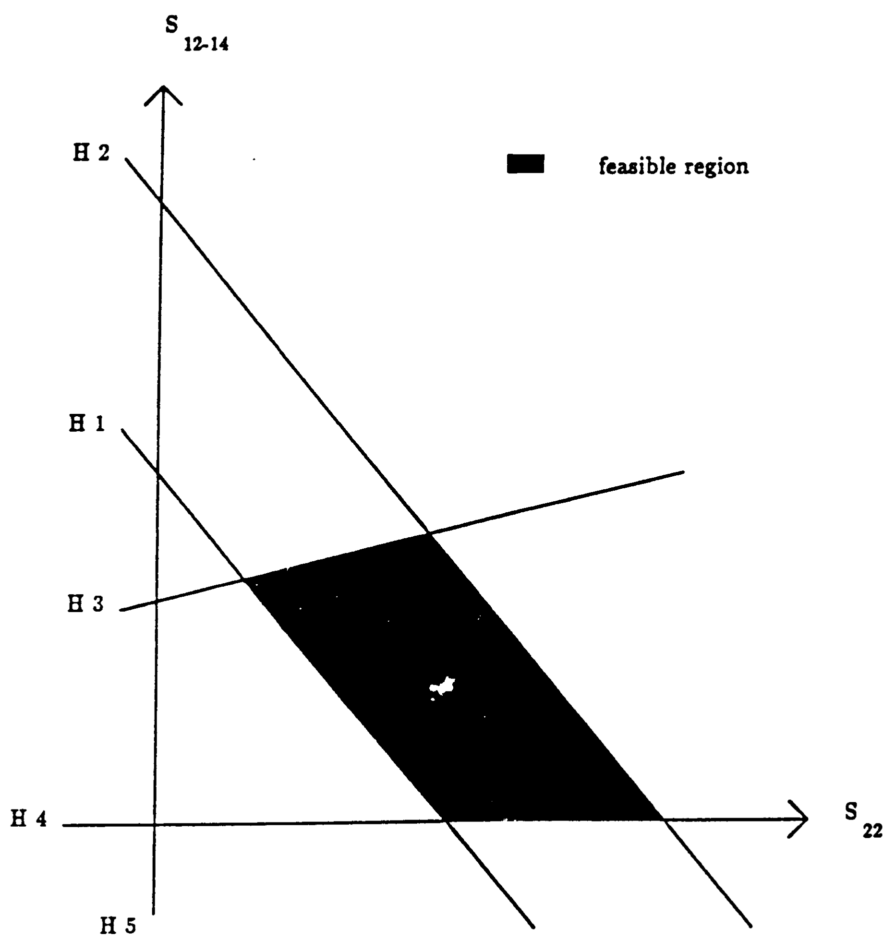
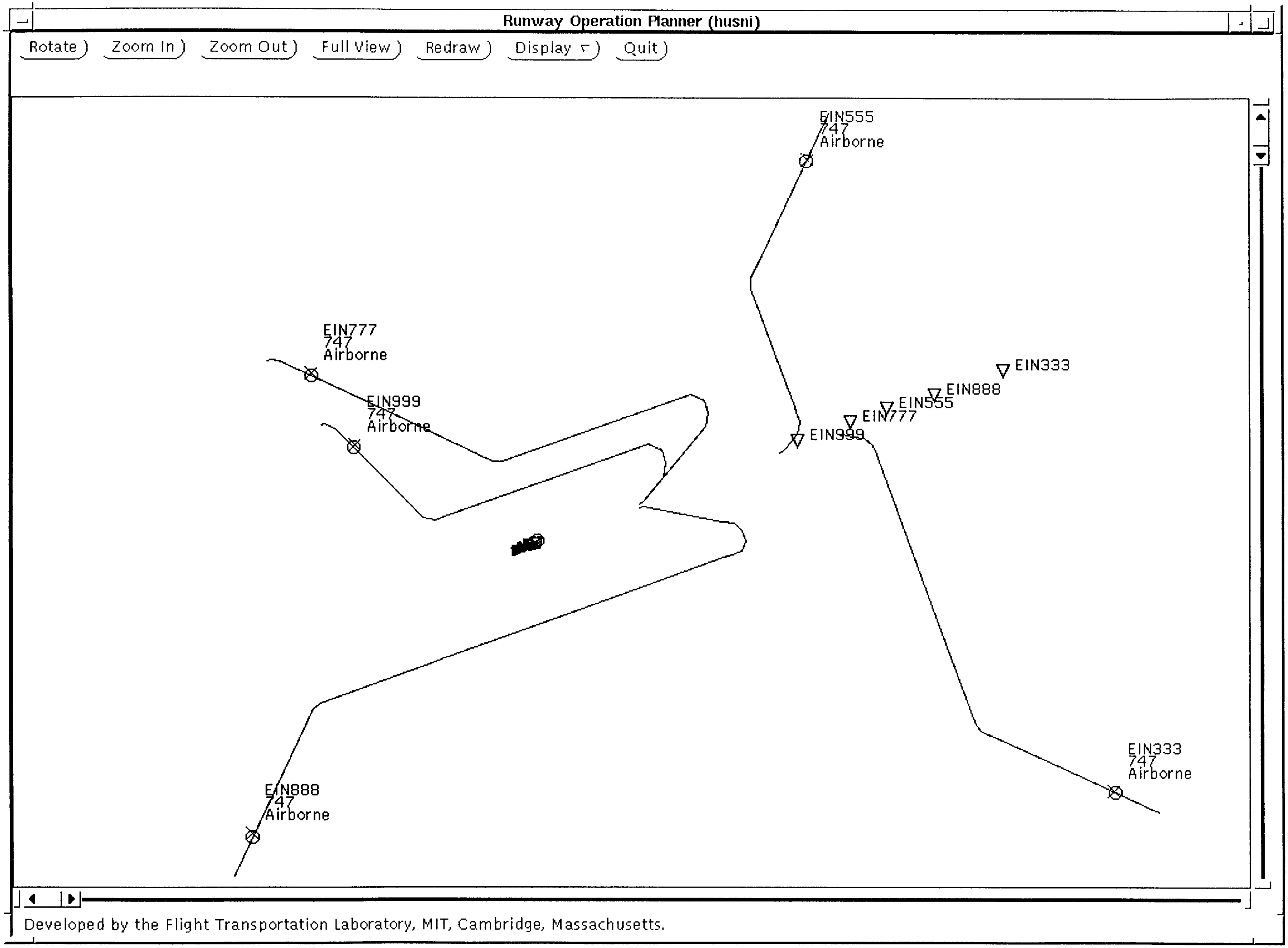


Figure 4.4: Feasible region


Runway Operation Planner (husni)
Rotate
Zoom In
Zoom Out
Full View
Redraw
Display
Quit
EIN555
747
Airborne
EIN777
747
Airborne
EIN999
747
Airborne
EIN333
EIN888
EIN555
EIN777
EIN999
EIN333
747
Airborne
EIN888
747
Airborne
Developed by the Flight Transportation Laboratory, MIT, Cambridge, Massachusetts.

Automation of the conflict avoidance task

- Monitor the conflicts manually, with ASLOTS providing graphical tools such as path previews
- Automated conflict avoidance:
  - Sadoune's generate-and-test scheme
  - Integrate conflict avoidance as constraints in the path generation problem

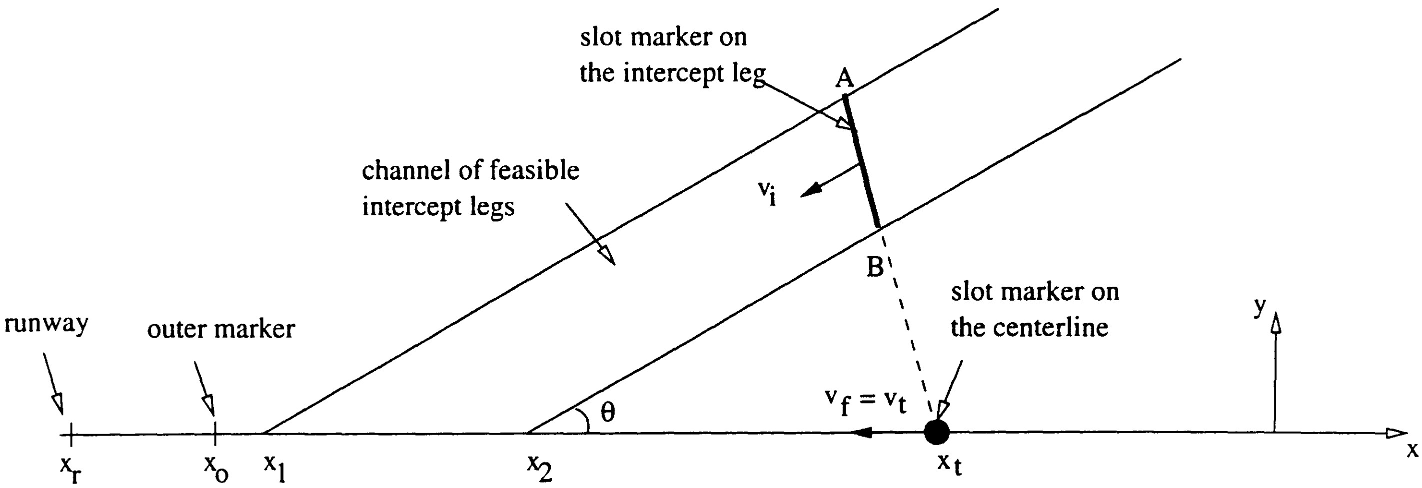


Figure 1: The slot marker on the intercept leg with one intercept speed

$$x + v_i cos(\theta)t = x_t + v_t t$$

$$y + v_i sin(\theta)t = 0$$

$$x = \left(\frac{v_i cos(\theta) - v_t}{v_i sin(\theta)}\right)y + x_t$$

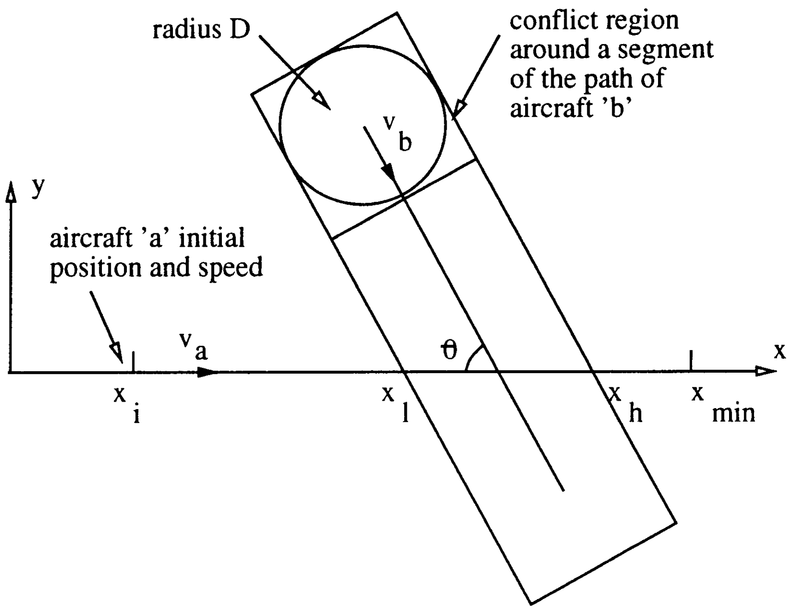


Figure 1: A generic conflict on one leg

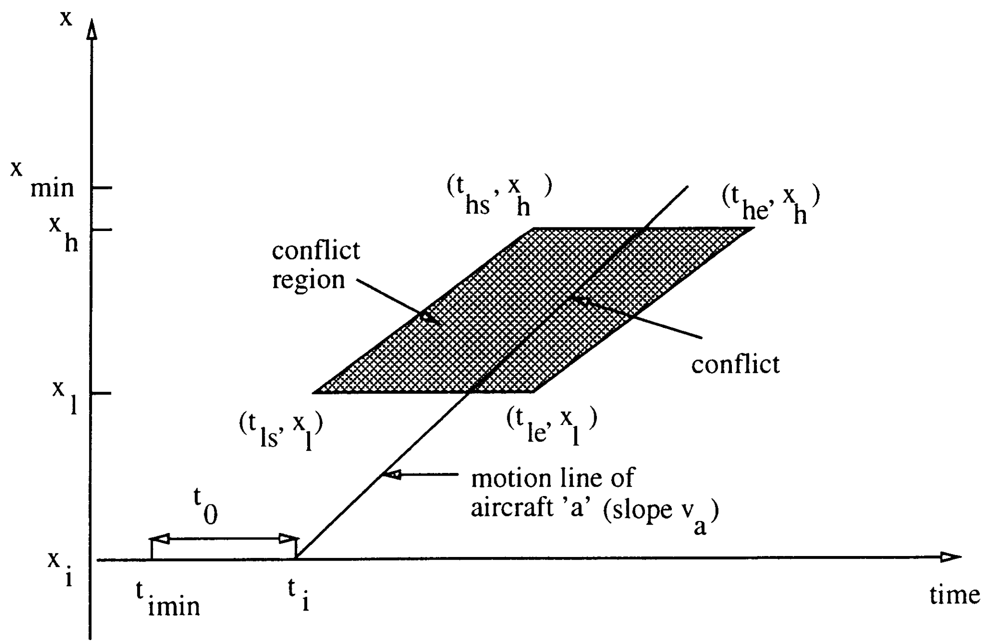


Figure 2: The conflict region in the time-x space

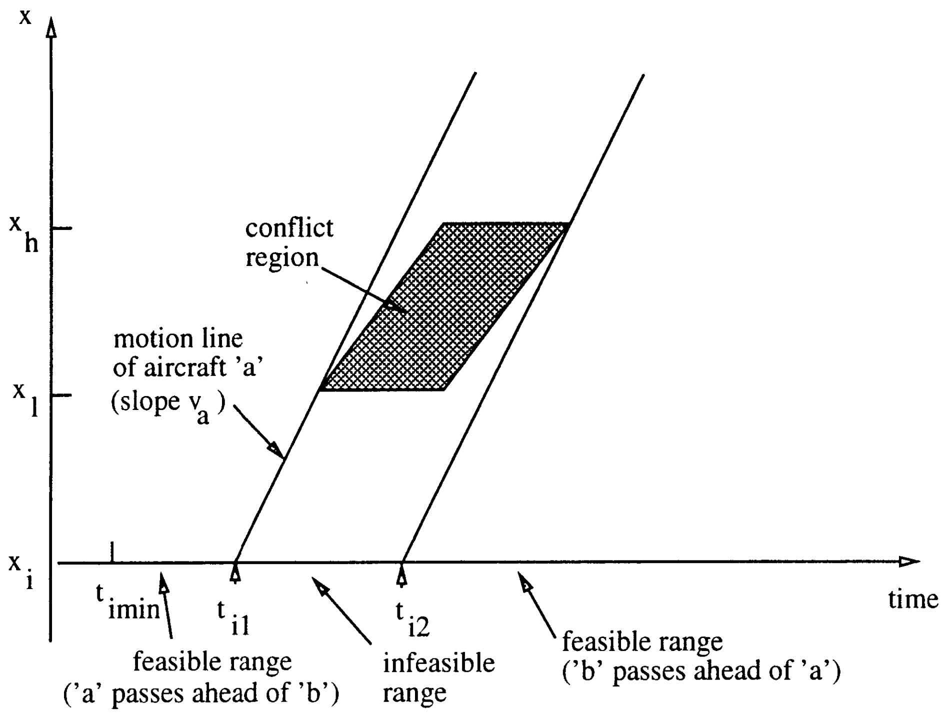


Figure 3a: Conflict resolution, both aircraft with one speed
($v_a > v_b \cos(0)$)

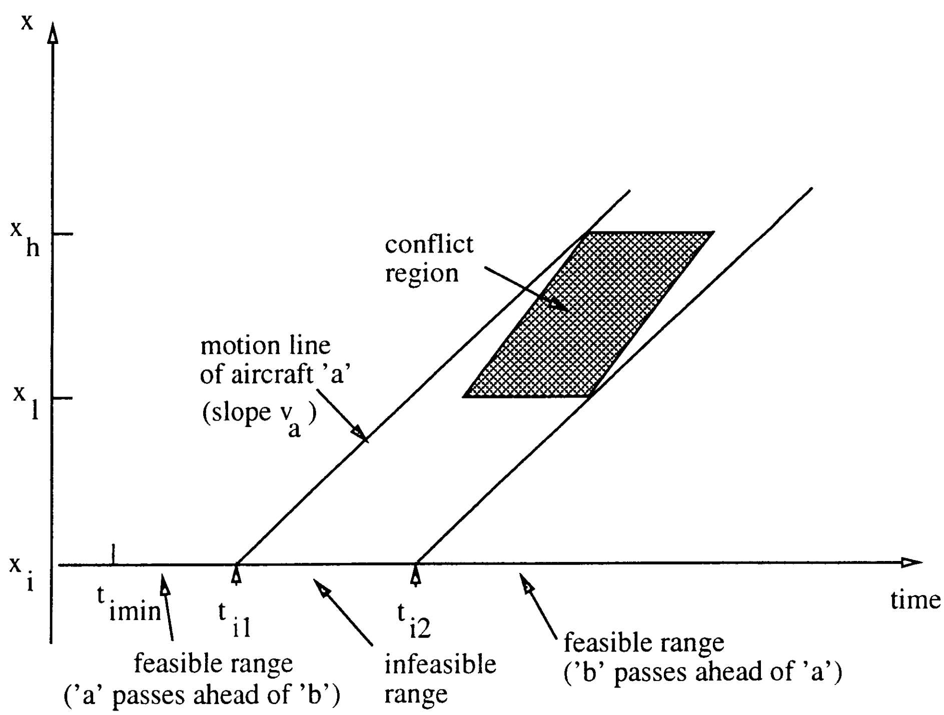
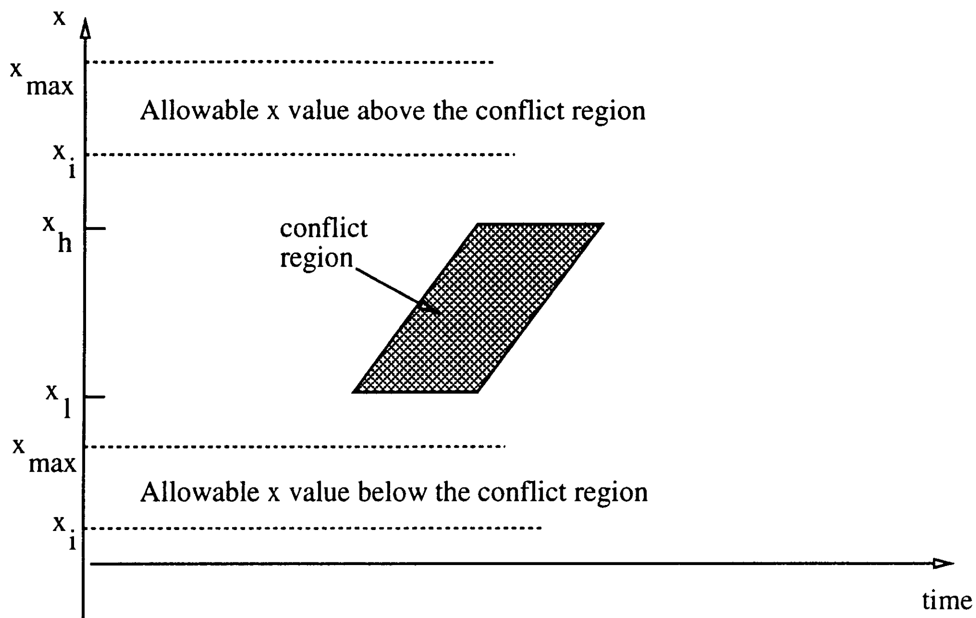


Figure 3b: Conflict resolution, both aircraft with one speed
($v_a < v_b \cos(0)$)



Fgure 4a: Geometrically impossible conflict

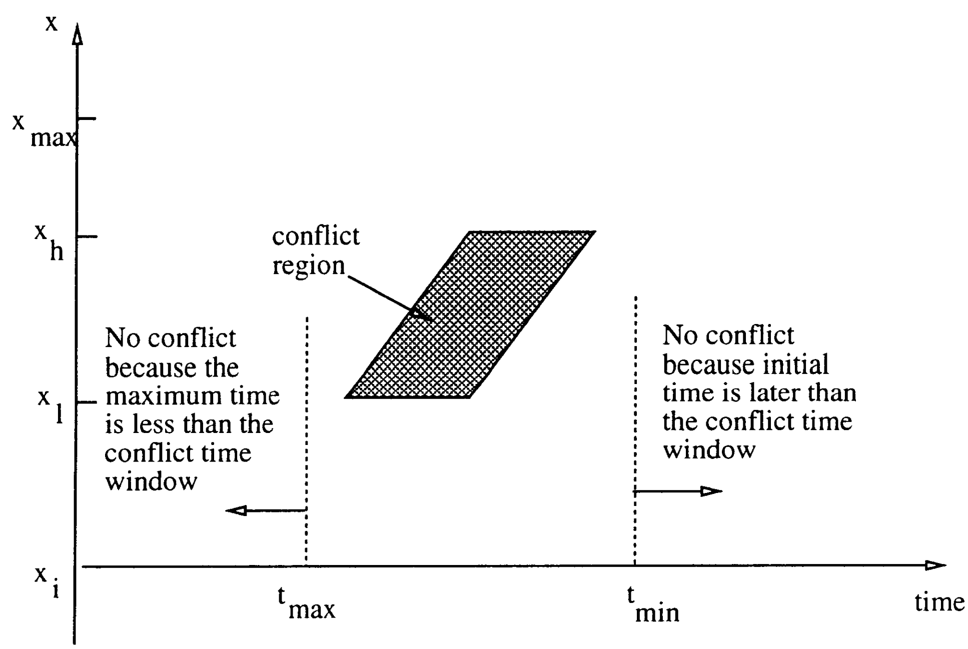


Figure 4b: Temporally impossible conflict

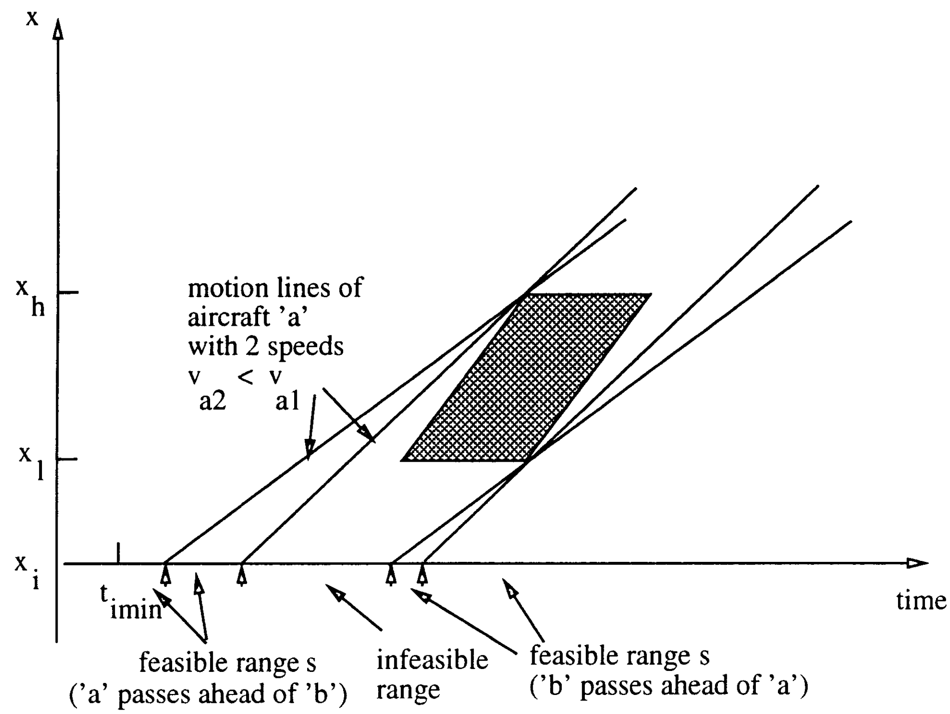


Figure 5b: Conflict resolution, aircraft 'a' with two speeds
$(v_b \cos(0) > v_{a1} > v_{a2})$

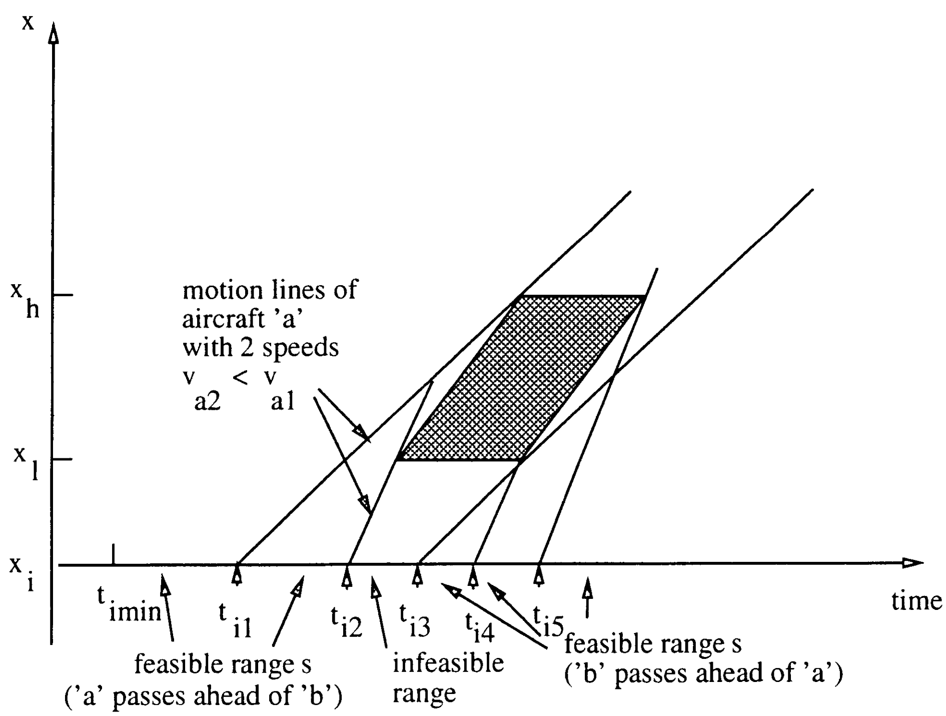


Figure 5c: Conflict resolution, aircraft 'a' with two speeds
$(v_{a1} > v_b \cos(0) > v_{a2})$

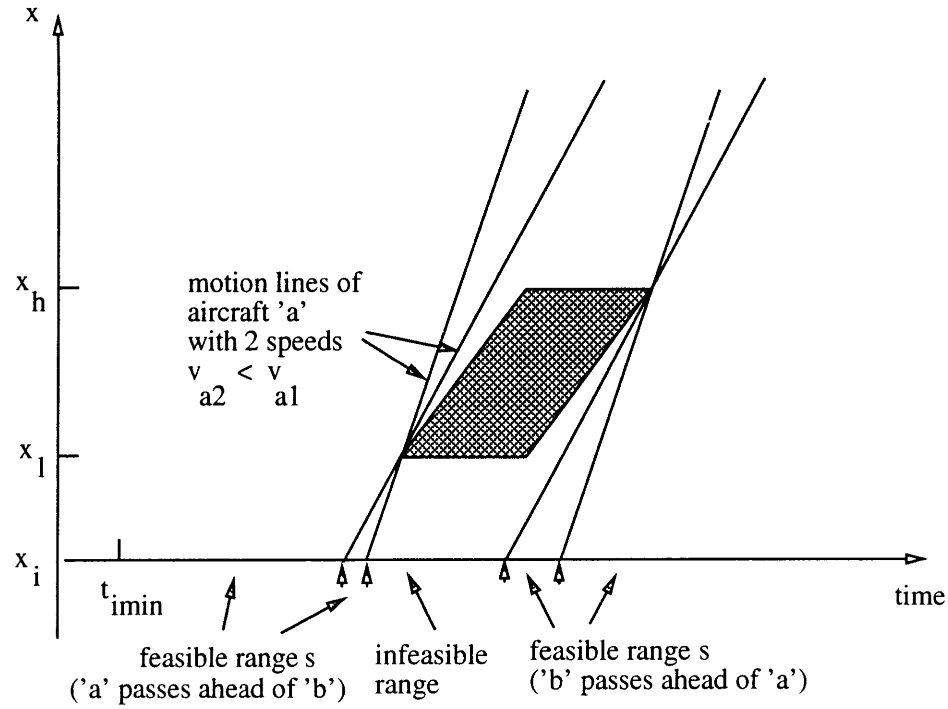


Figure 5a: Conflict resolution, aircraft 'a' with two speeds
$(v_{a1} > v_{a2} > v_b \cos(0))$

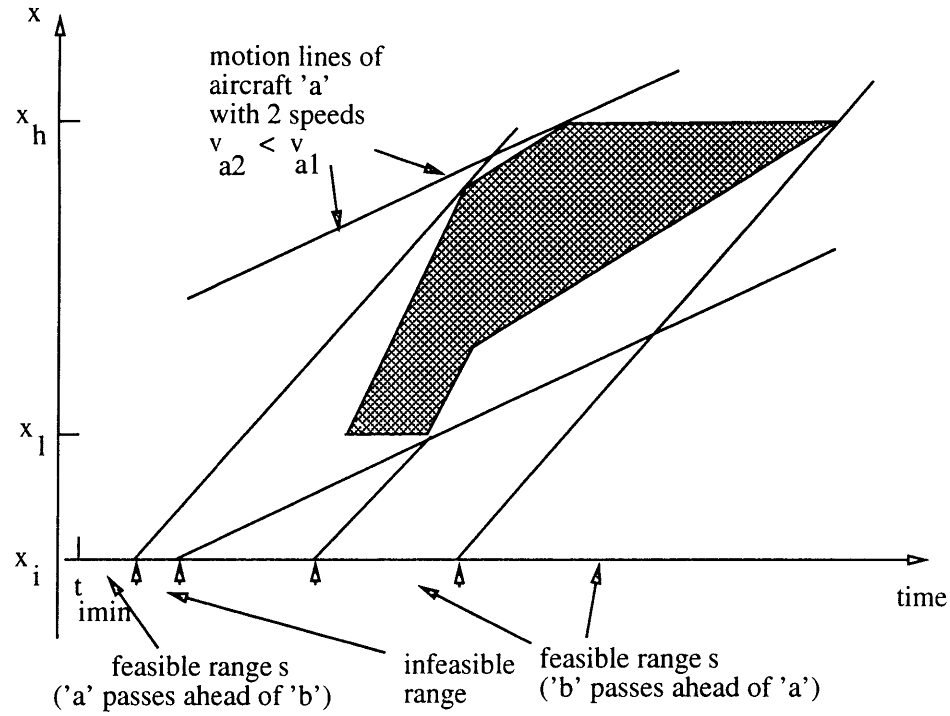


Figure 8e: Conflict resolution, both aircraft with two speeds
($v_{b1} \cos (0) > v_{a1} > v_{b2} \cos (0) > v_{a2}$))

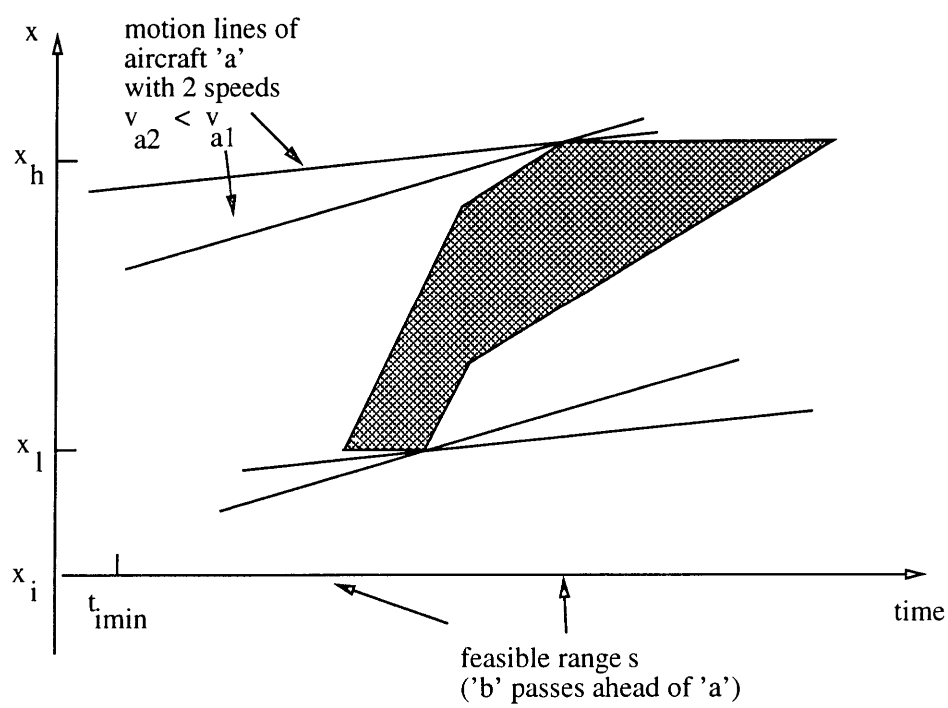


Figure 8f: Conflict resolution, both aircraft with two speeds
($v_{b1} \cos (0) > v_{b2} \cos (0) > v_{a1} > v_{a2}$))

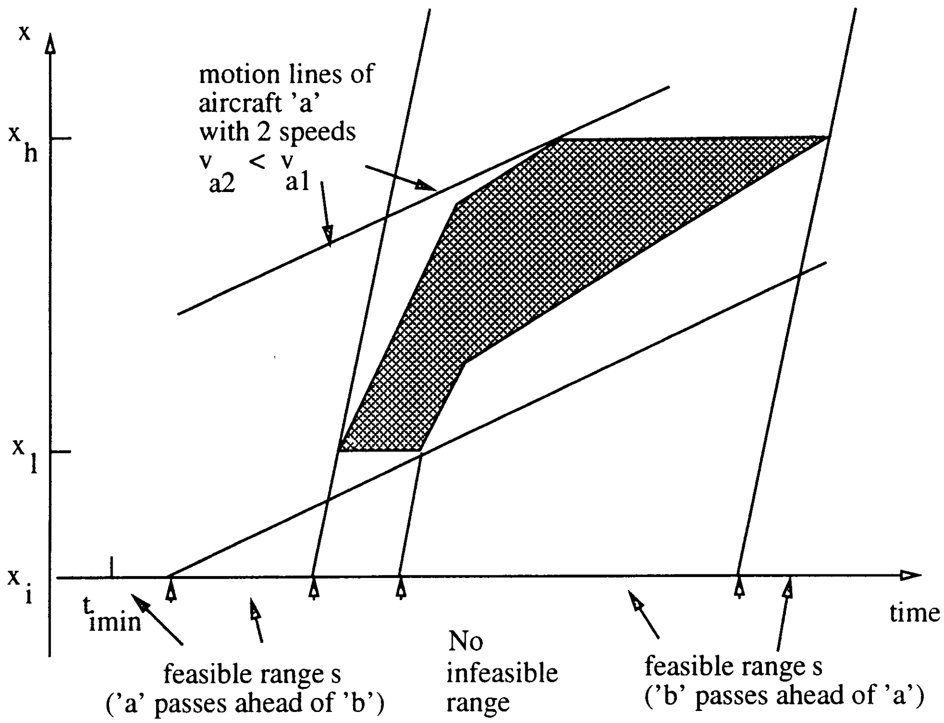


Figure 8c : Conflict resolution, both aircraft with two speeds
($v_{a1} > v_{b1} \cos(0) > v_{b2} \cos(0) > v_{a2}$))

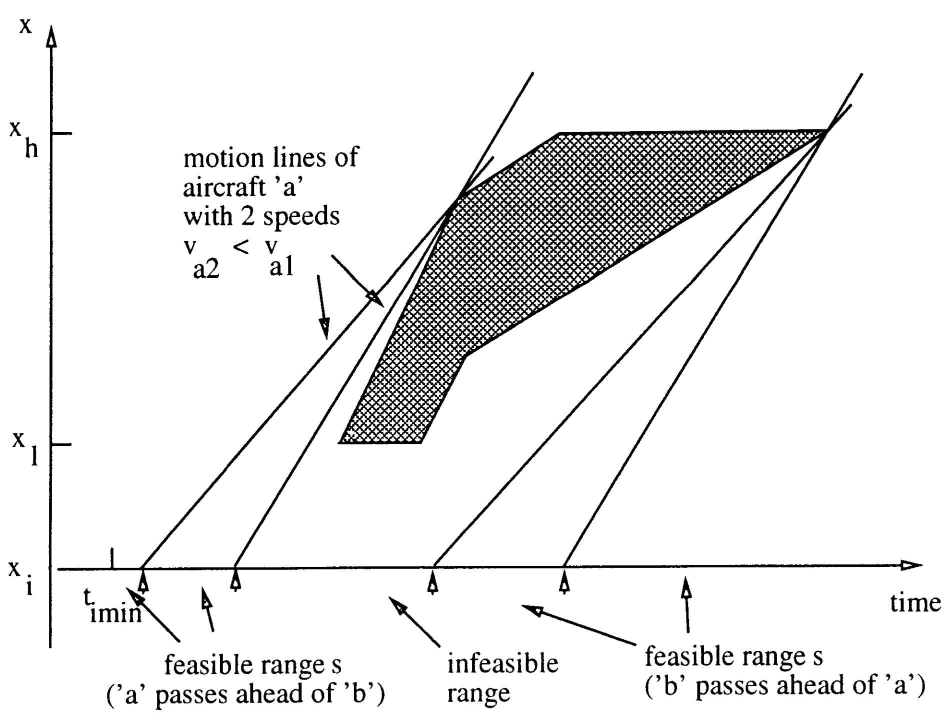


Figure 8d: Conflict resolution, both aircraft with two speeds
($v_{b1} \cos(0) > v_{a1} > v_{a2} > v_{b2} \cos(0)$)

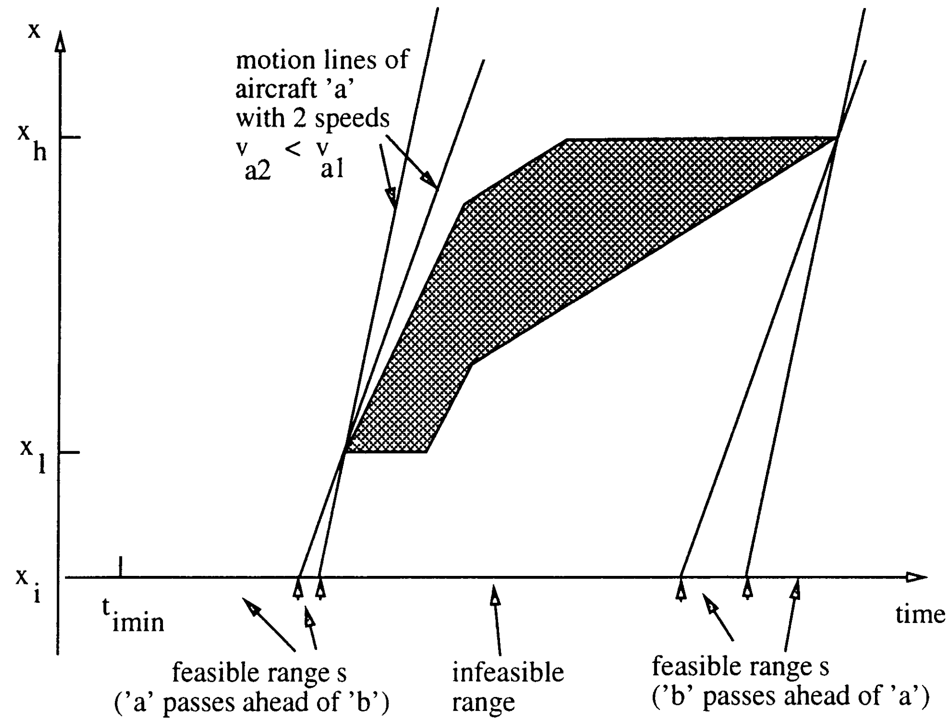


Figure 8a: Conflict resolution, both aircraft with two speeds
($v_{a1} > v_{a2} > v_{b1} \cos(0) > v_{b2} \cos(0)$)

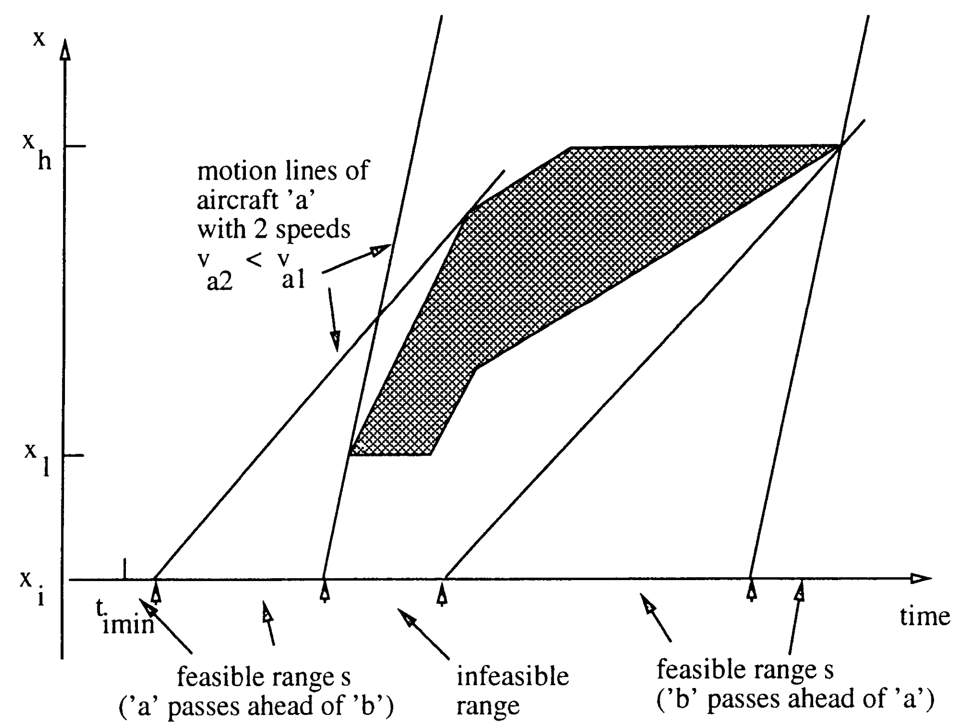


Figure 8b : Conflict resolution, both aircraf with two speeds
($v_{a1} > v_{b1} \cos(0) > v_{a2} > v_{b2} \cos(0)$)

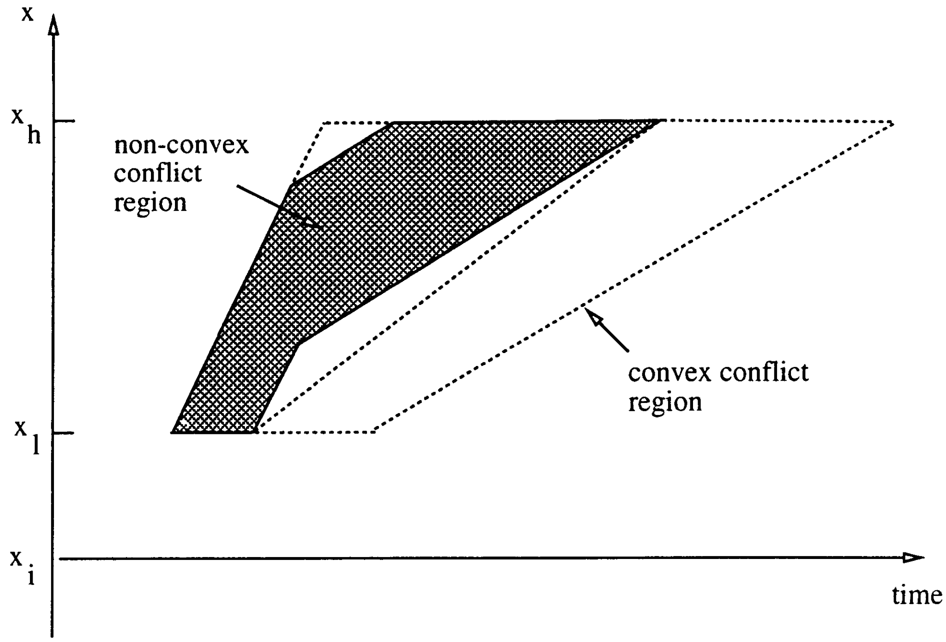


Figure 9: Reducing a two speed conflict region
to a one speed conflict region

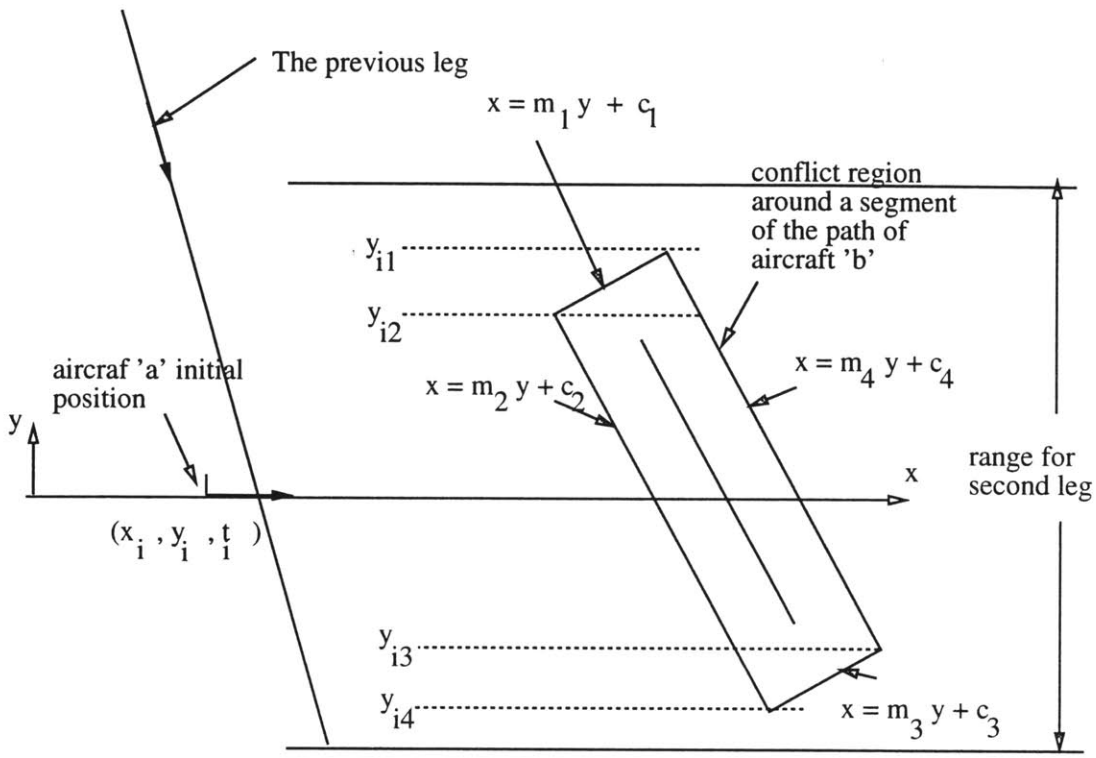


Figure 6: Conflict resolution for a generic leg

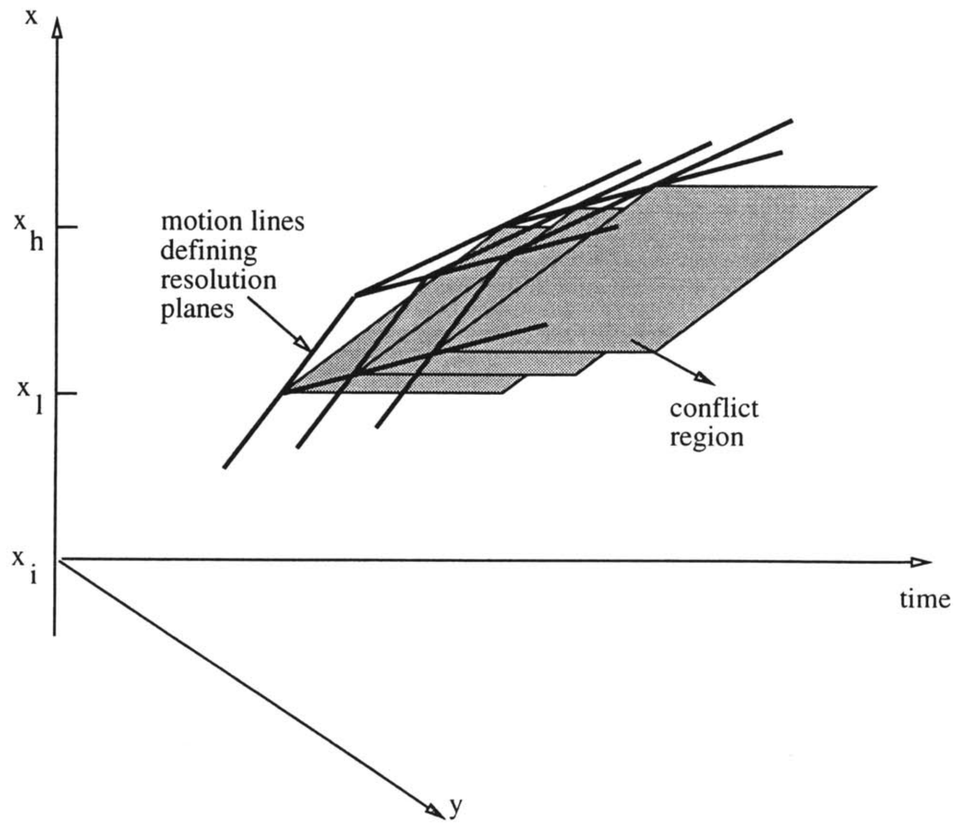


Figure 7: The conflict region and resolution in 3D

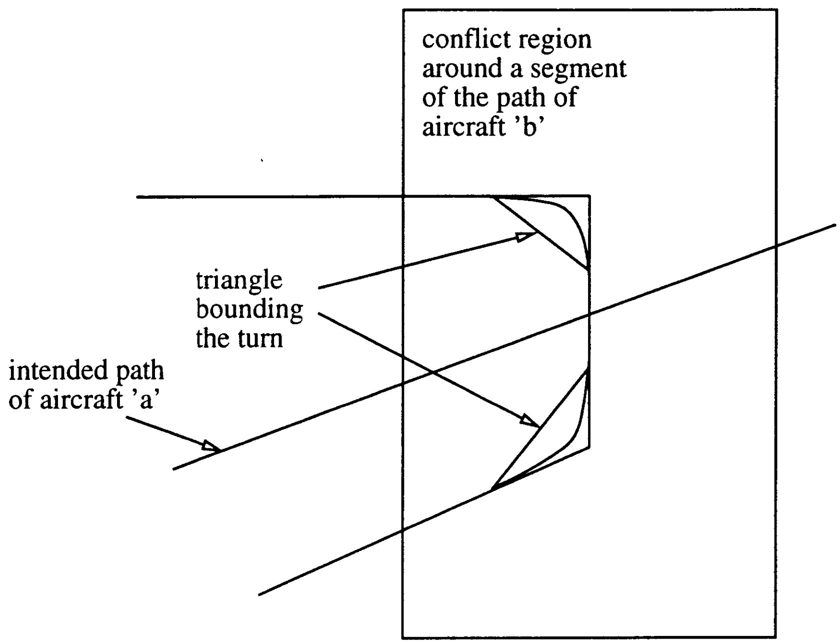


Figure 10: Dealing with turns

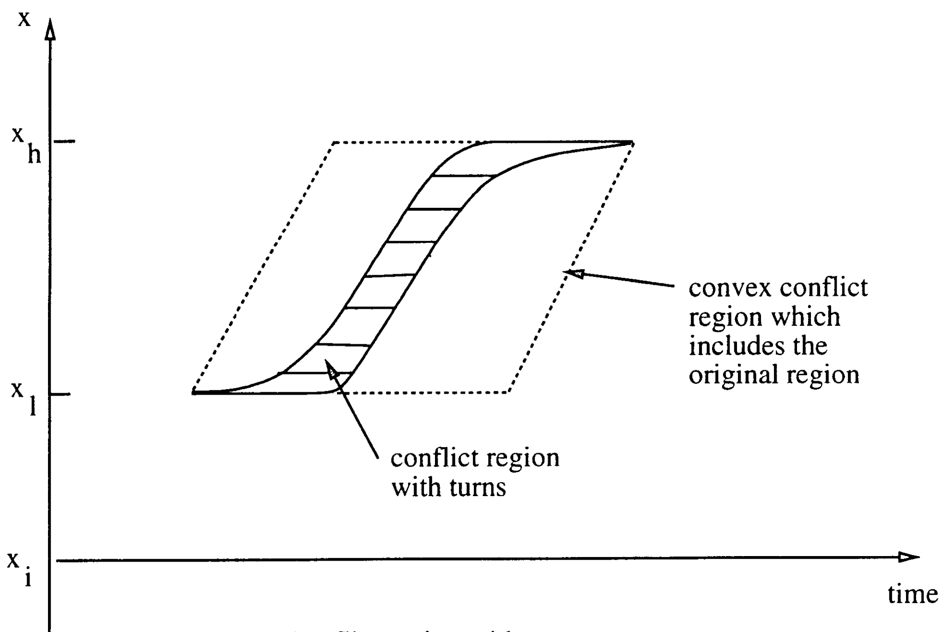


Figure 11: Conflict region with turns

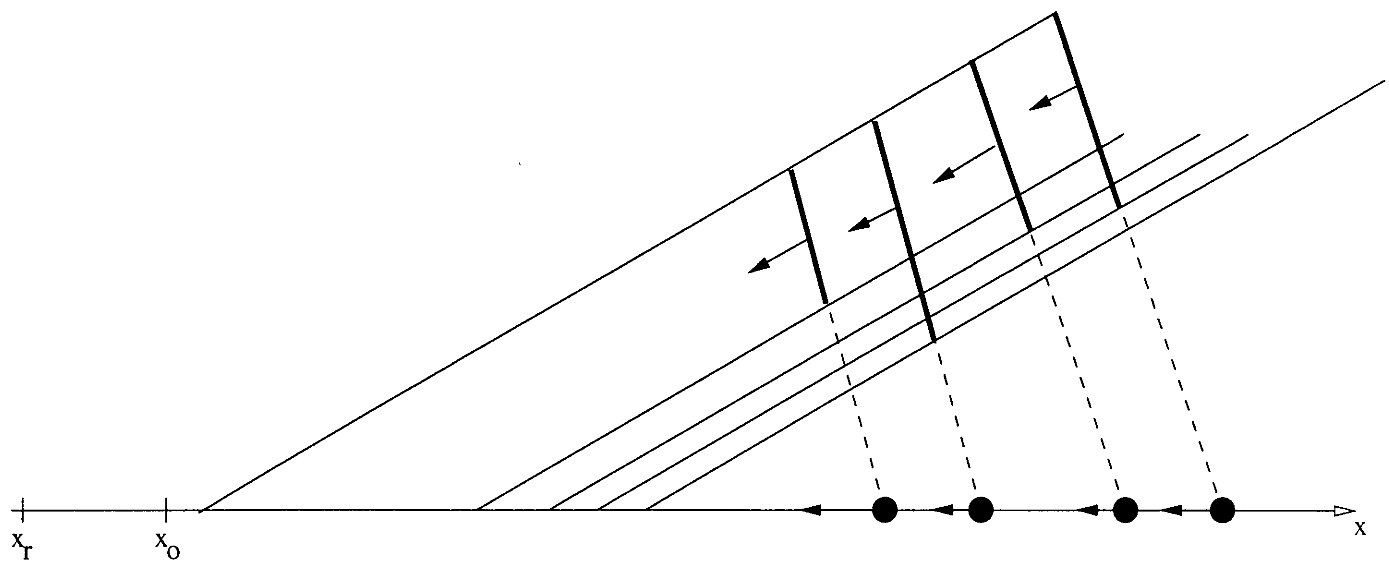
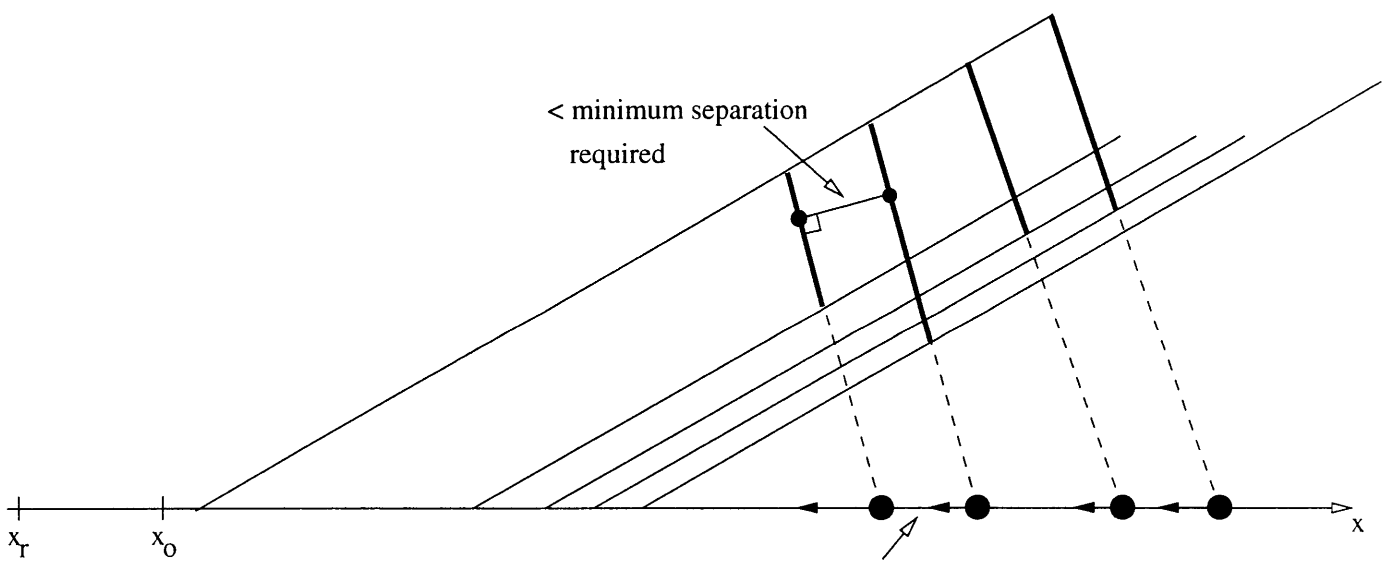


Figure 2: Multiple slot markers on the intercept leg



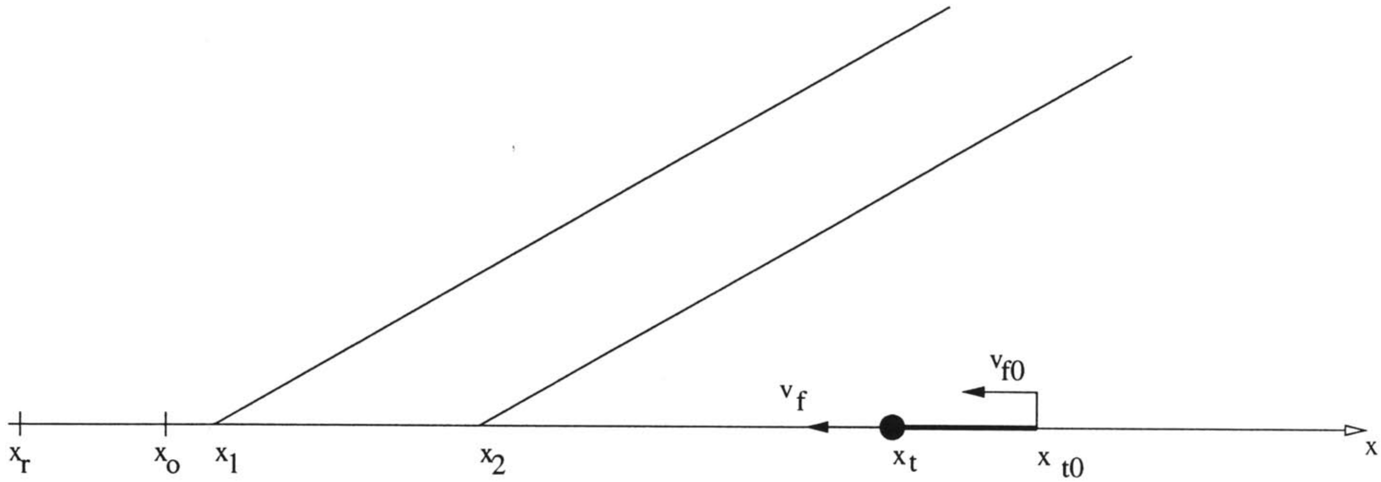


Figure 3: The slot marker on the centerline with centerline speed change

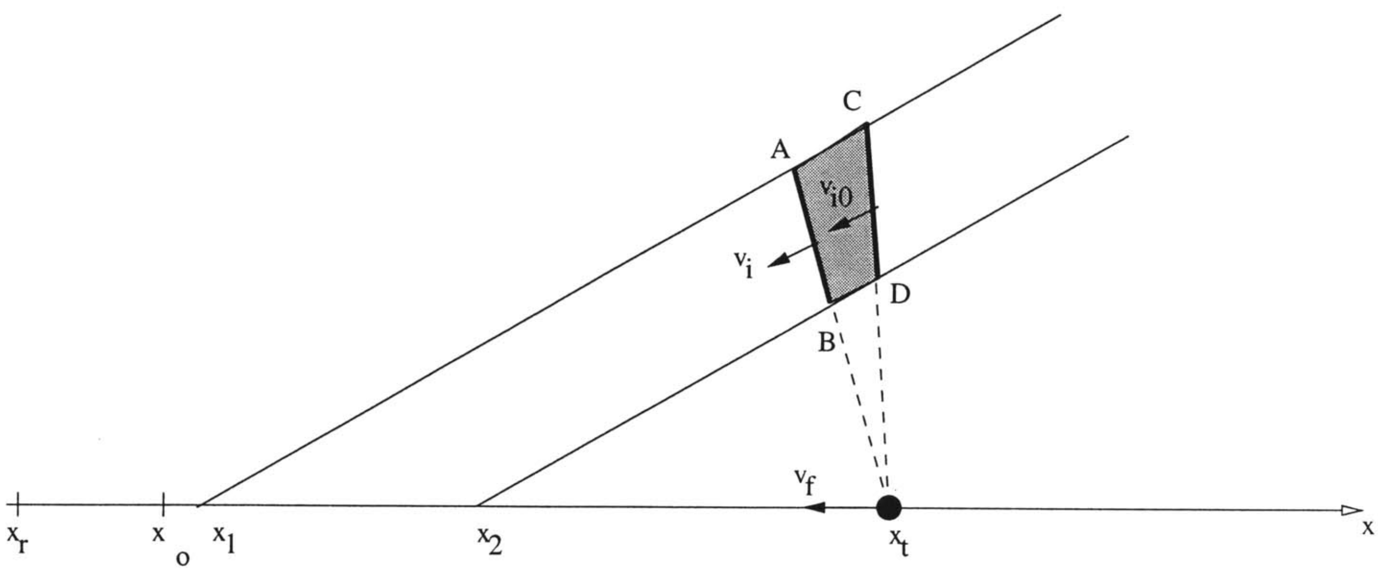


Figure 4: The slot marker on the intercept leg with intercept leg speed change

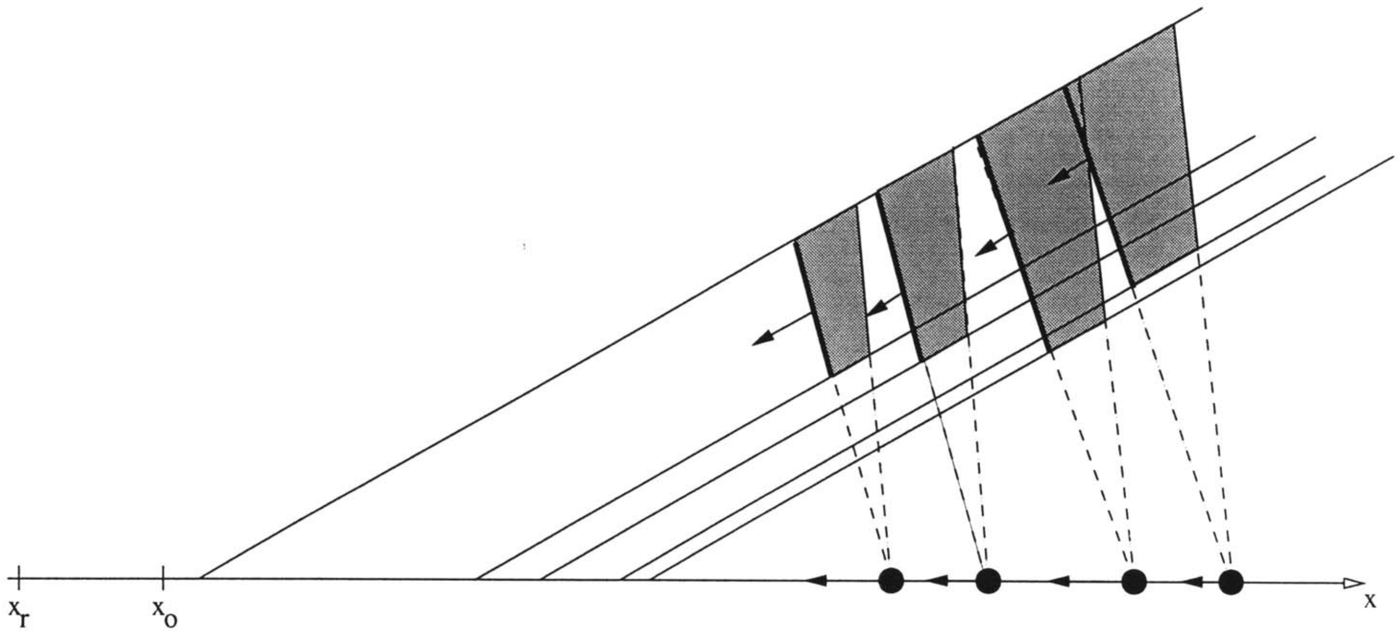


Figure 5: Multiple slot markers on the intercept leg with intercept leg speed change

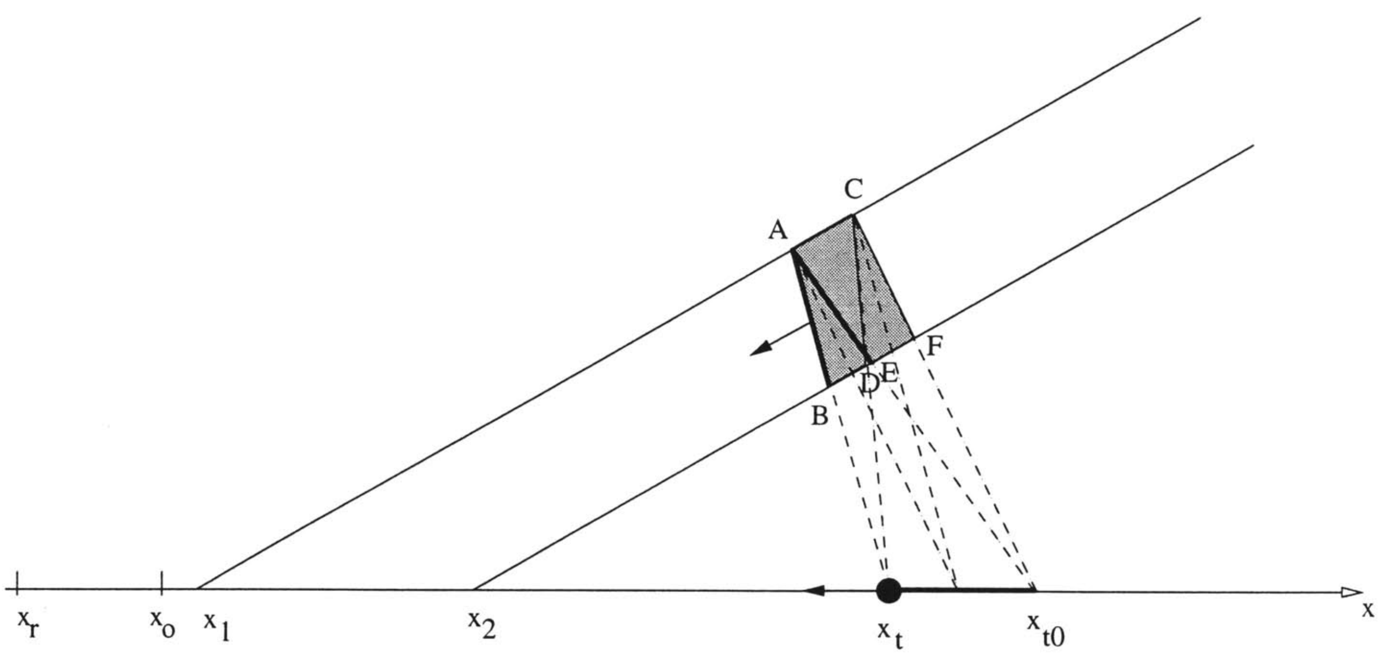


Figure 6: The slot marker on the intercept leg with centerline and intercept leg speed changes

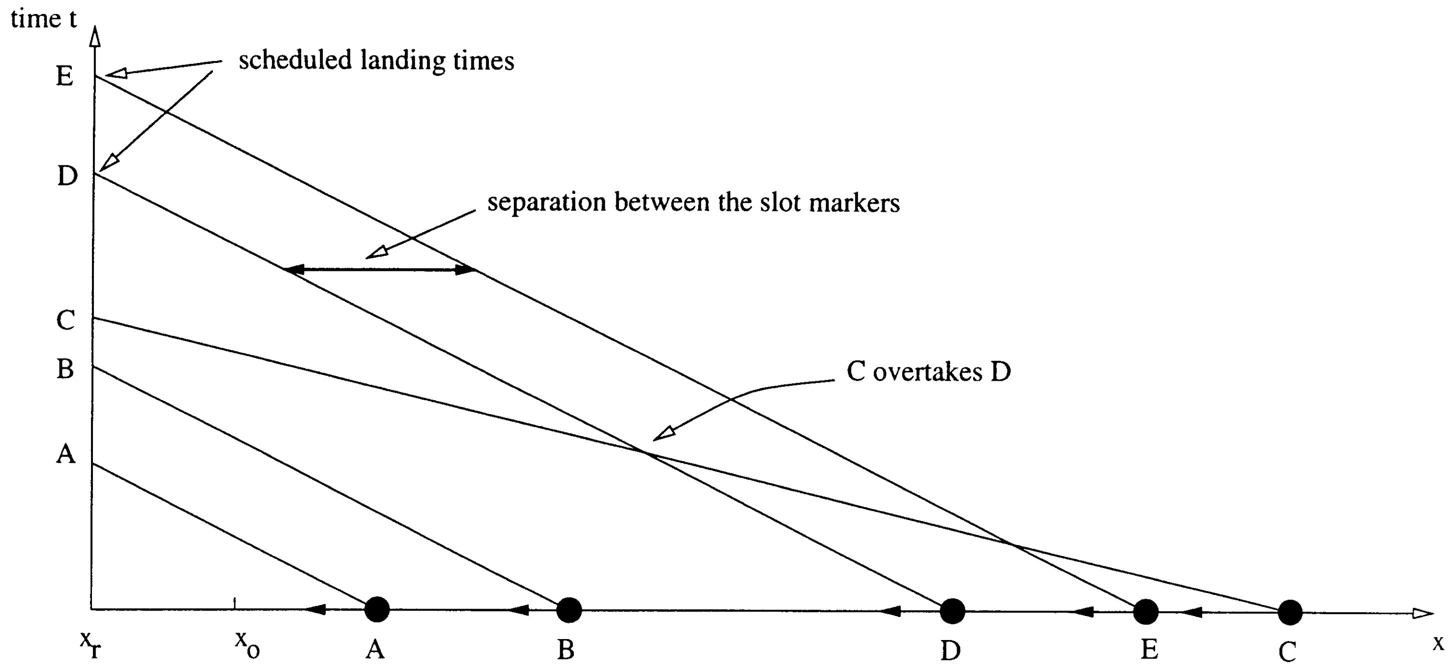


Figure 7: The motion lines of the slot markers on the centerline

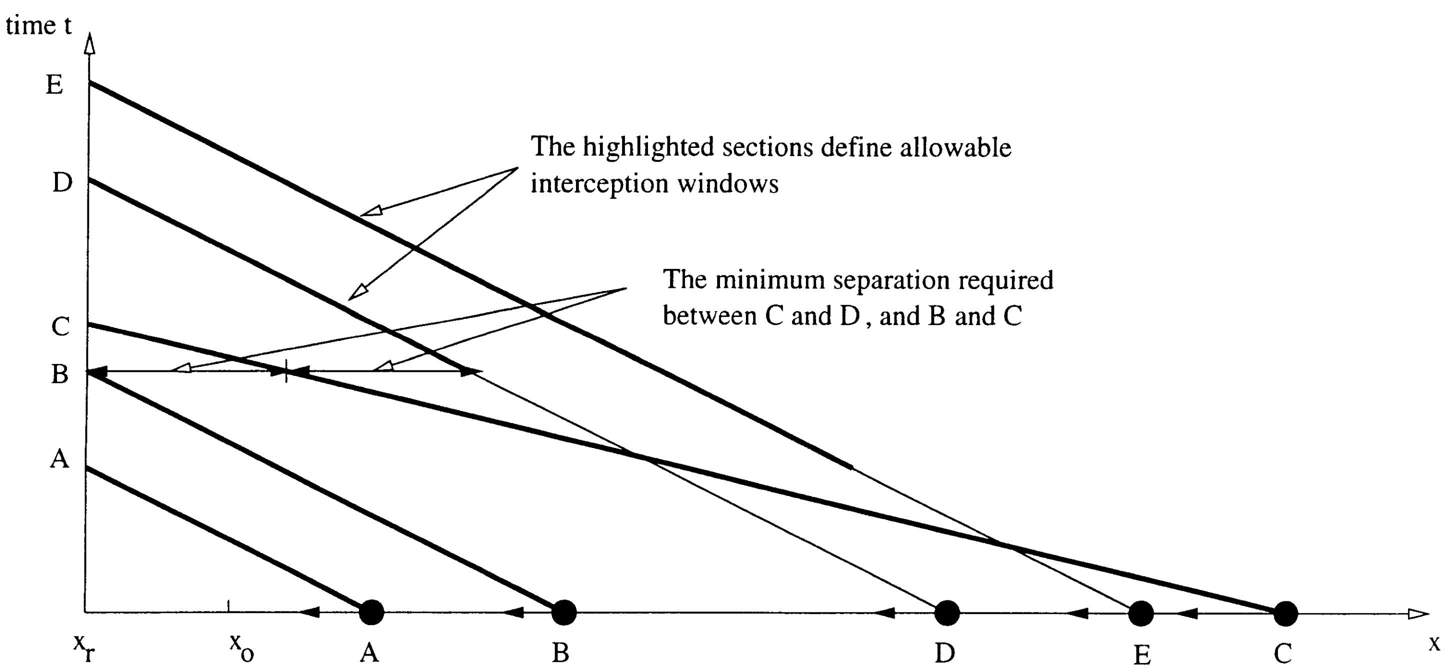


Figure 8: The allowable interception regions on the slot markers motion lines

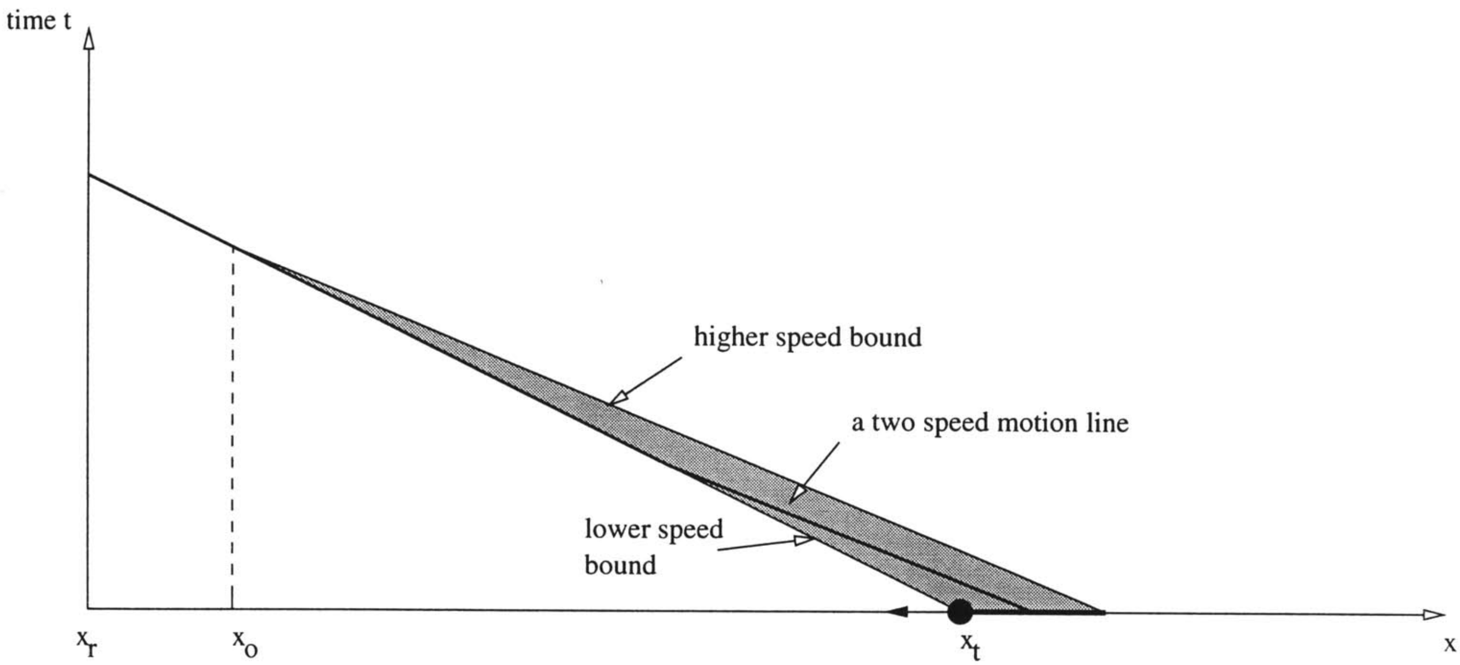


Figure 9: The motion locus of a centerline slot marker with speed change

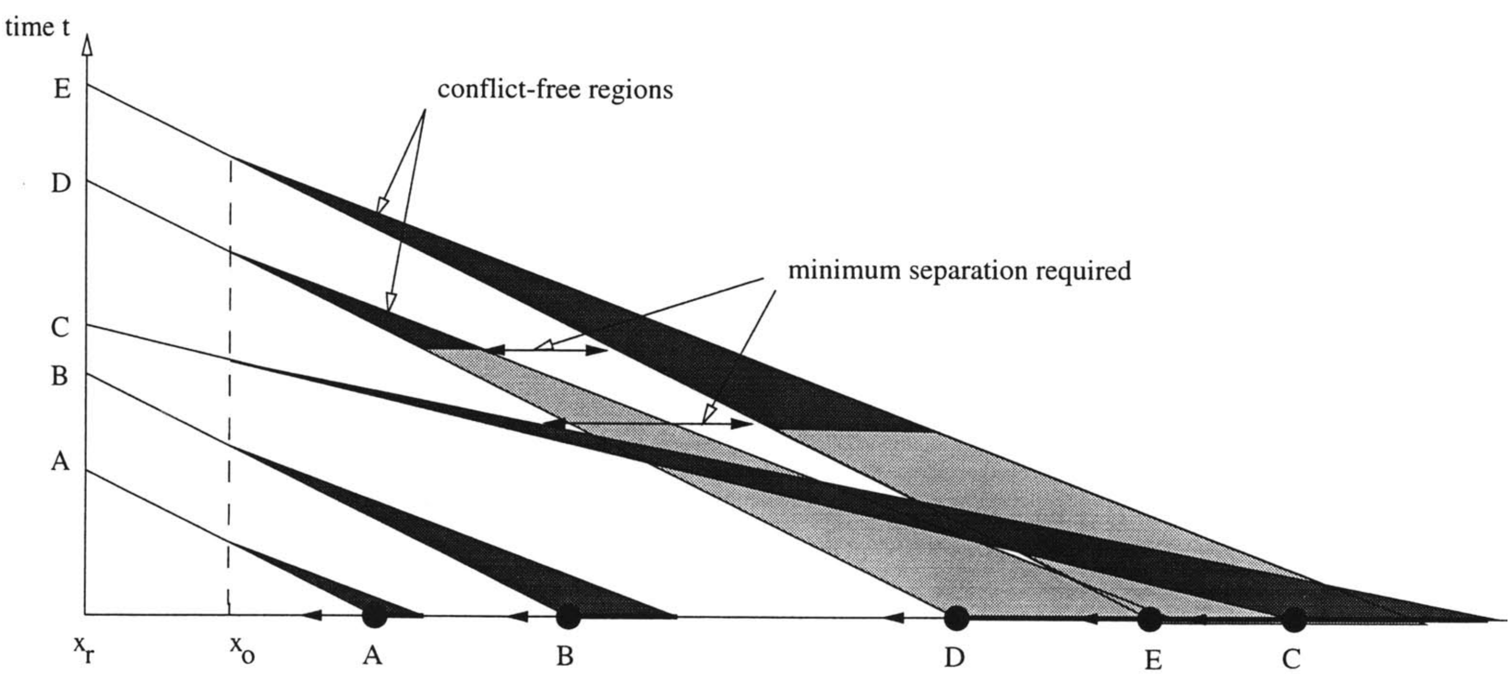


Figure 10: The allowable interception regions on the motion loci of the slot markers with speed change

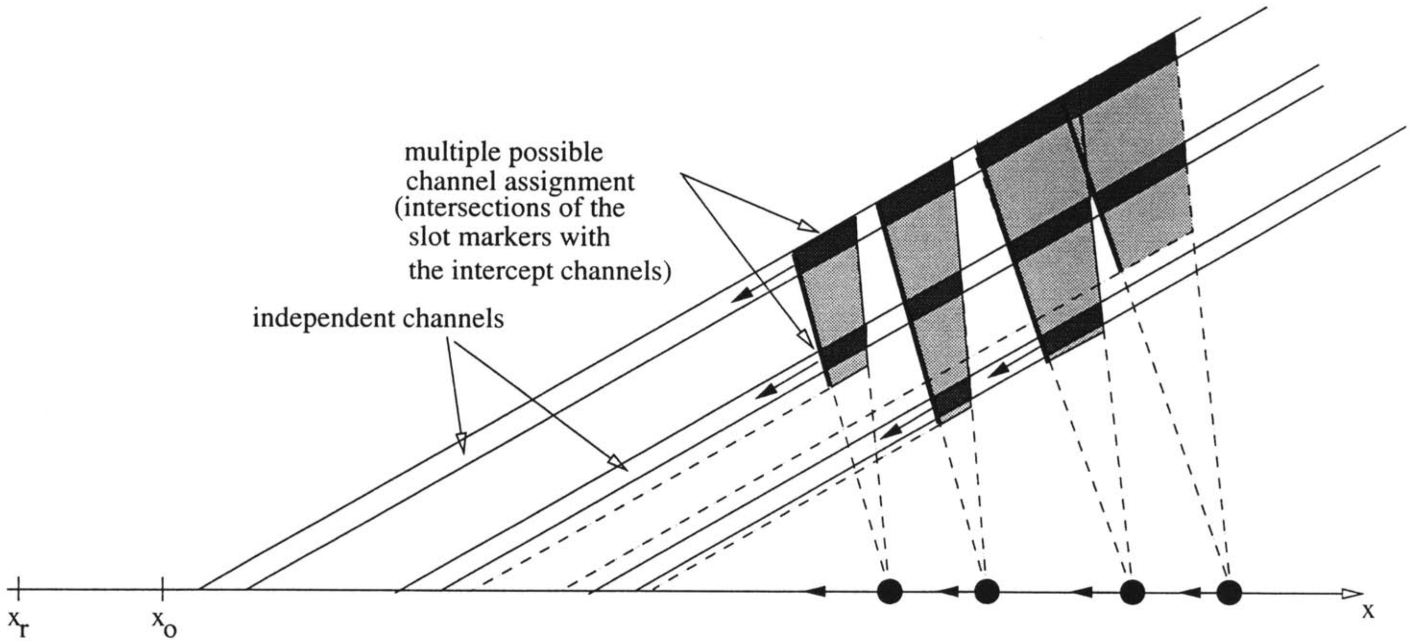


Figure 11: Channel grid superimposed on the slot markers on the intercept leg

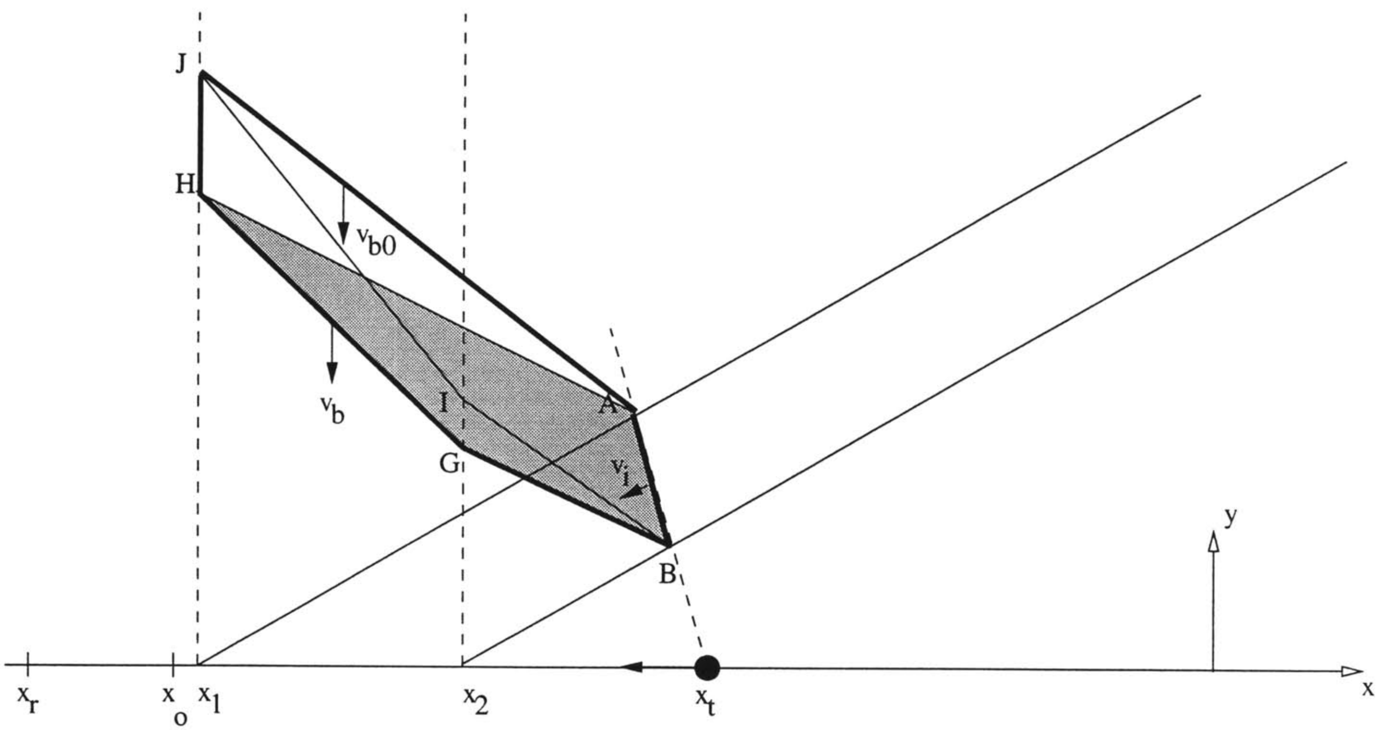


Figure 12: The slot marker on the base leg corresponding to AB, with base leg speed change

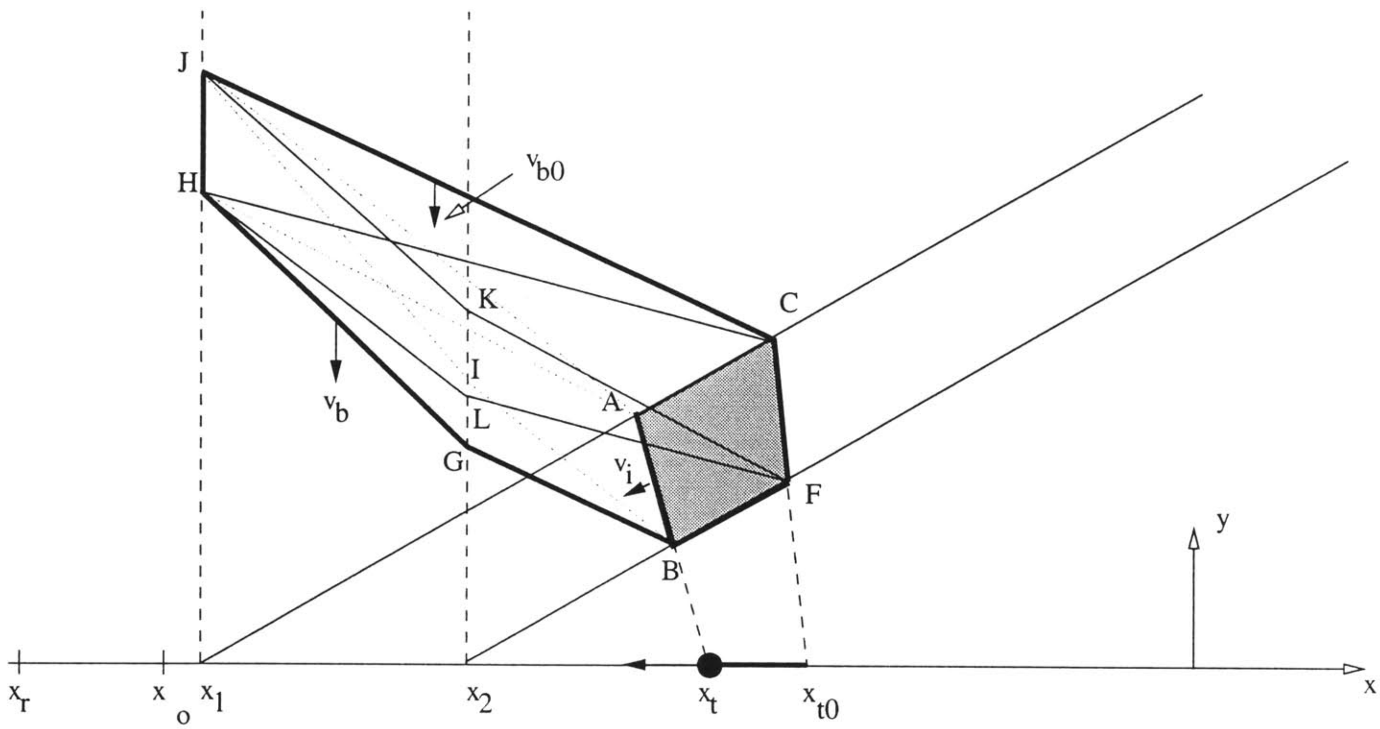


Figure 13: The slot marker on the base leg with speed change on the centerline, the intercept leg and the base leg

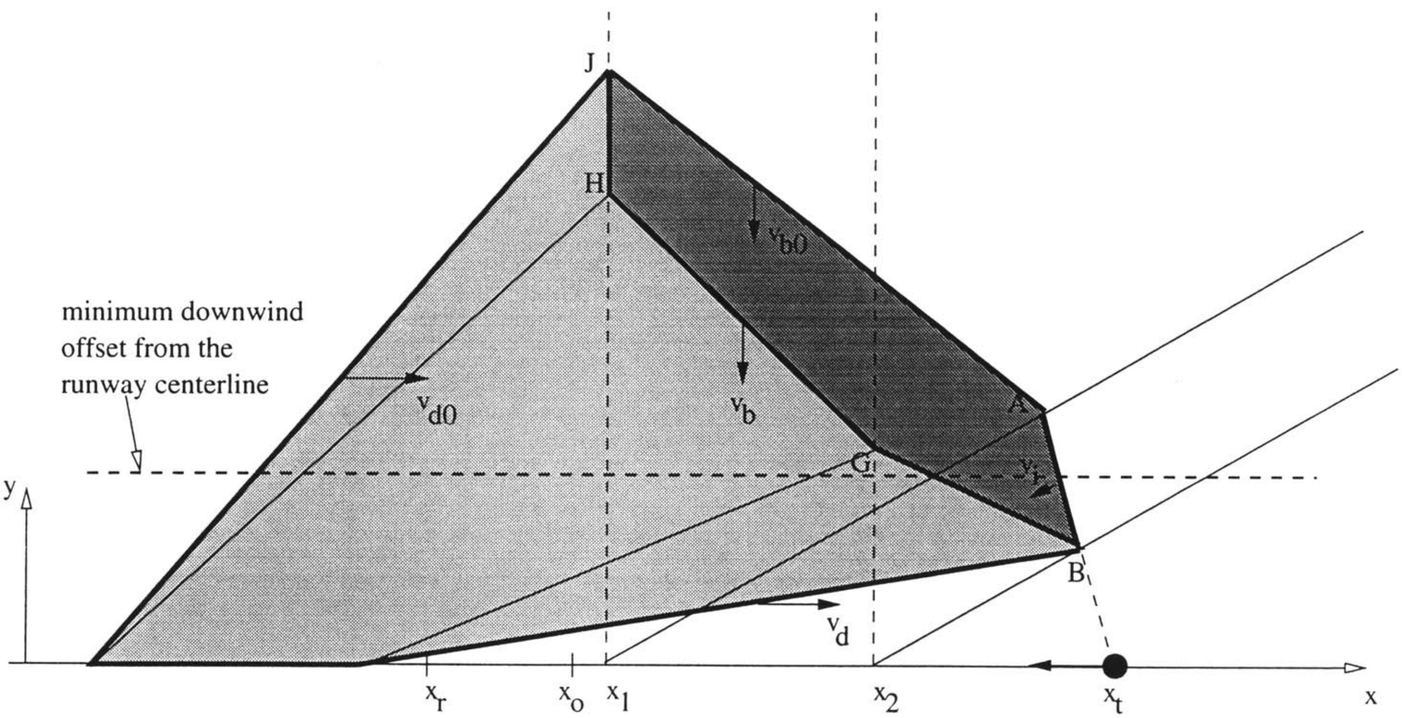


Figure 14: The slot marker on the downwind leg corresponding to ABGHJ on the base leg

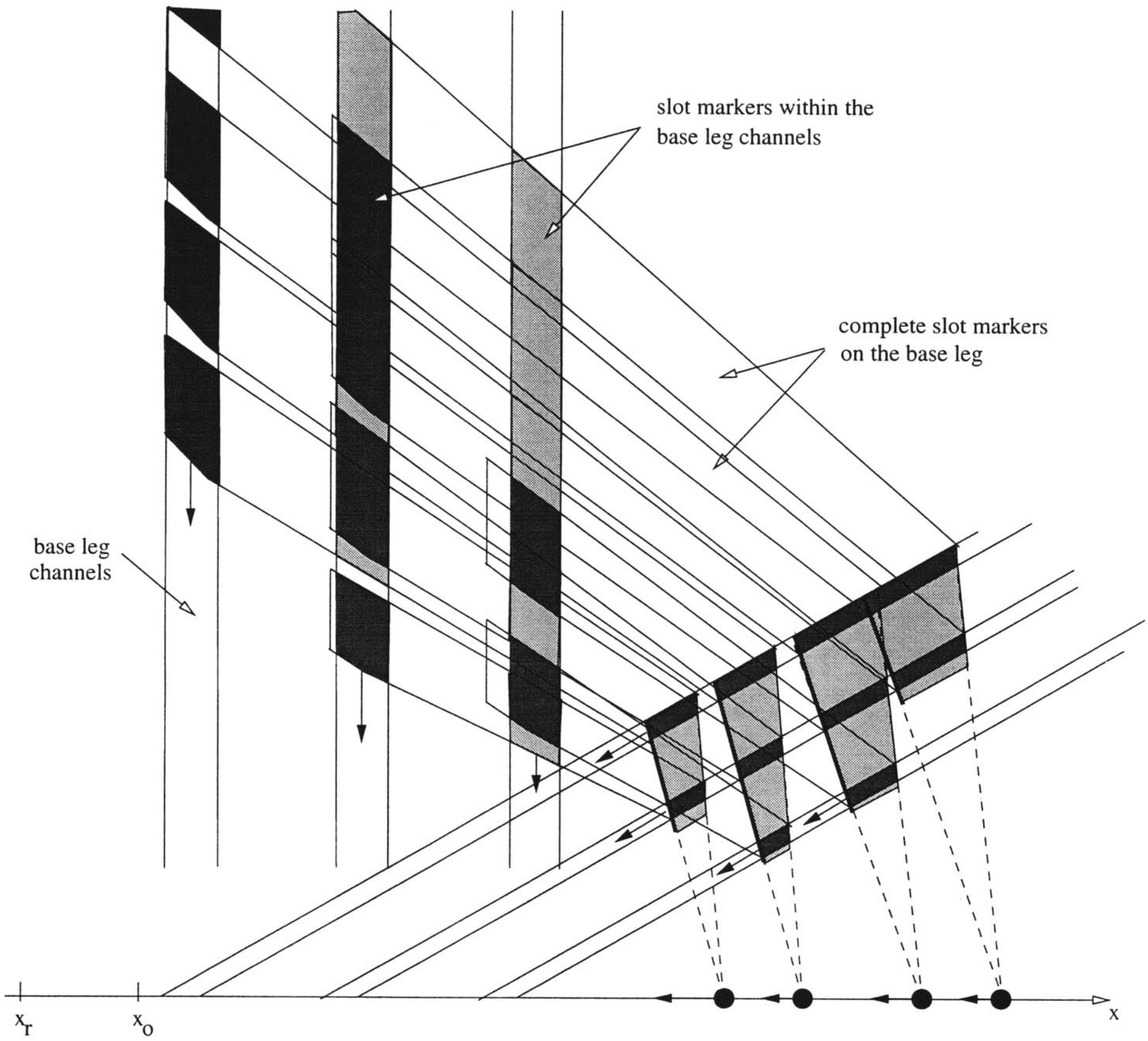


Figure 15: Channel grid superimposed on the slot markers on the base leg

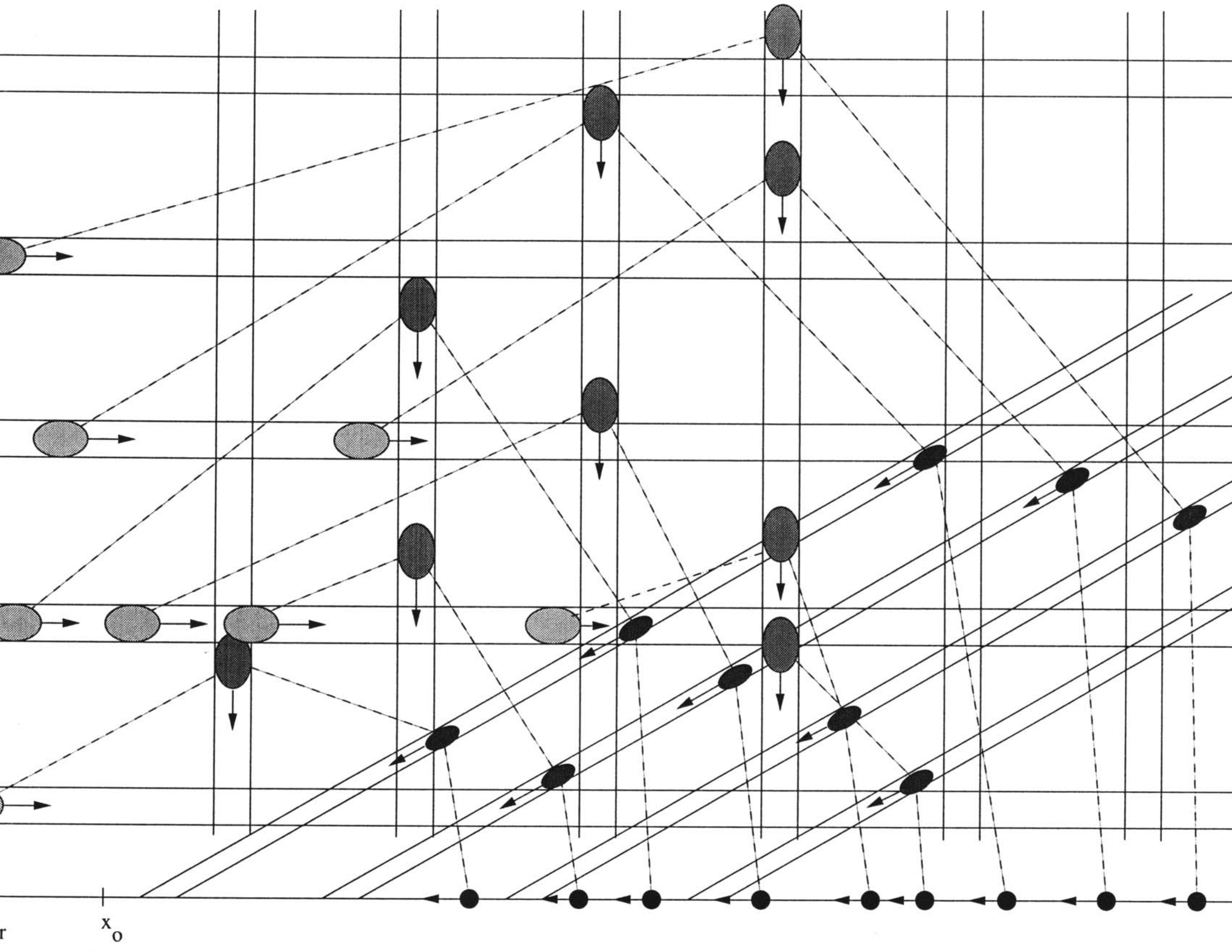


Figure 16: The concept of the intermediate slot markers on a grid of channels alligned with the pattern legs: slot markers on the centerline, intercept leg, base leg, and downwind leg are shown

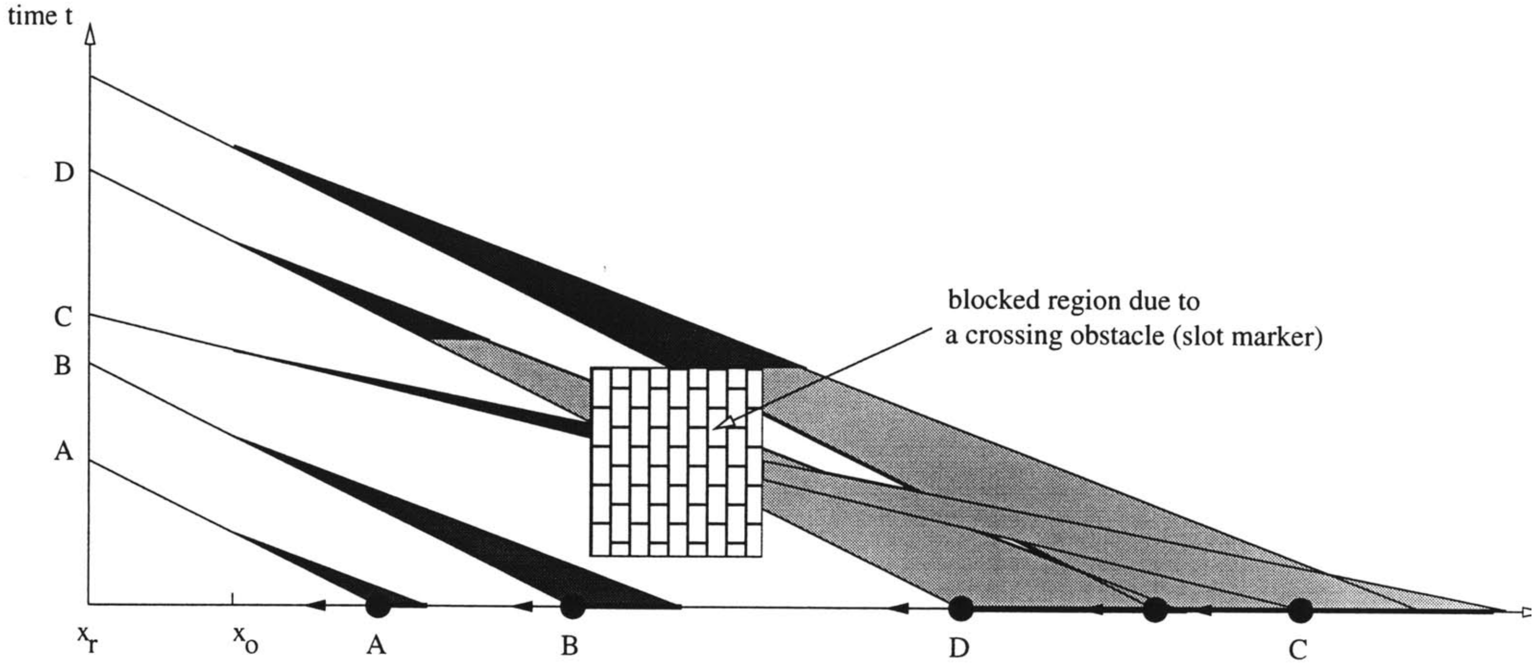


Figure 17: Conflict avoidance with crossing slot markers

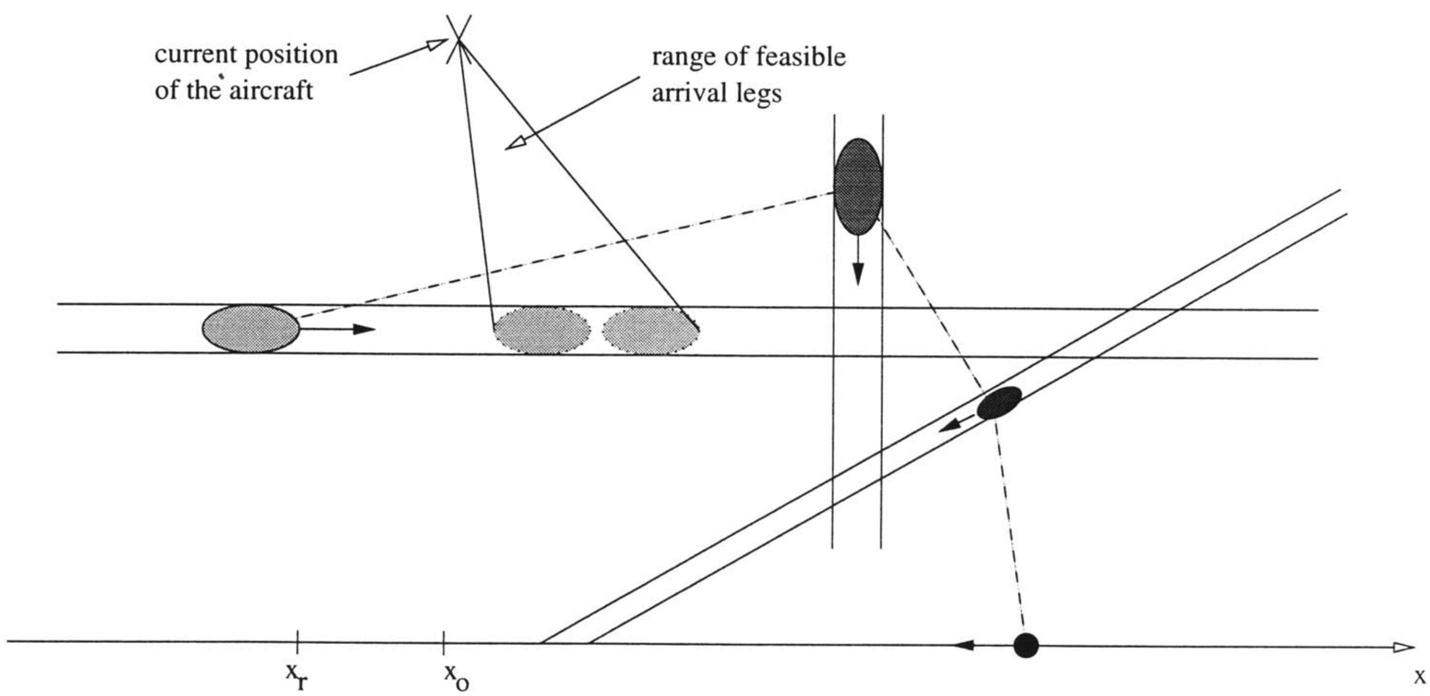


Figure 18: The feasible range of arrival legs that meet the slot marker on the downwind leg

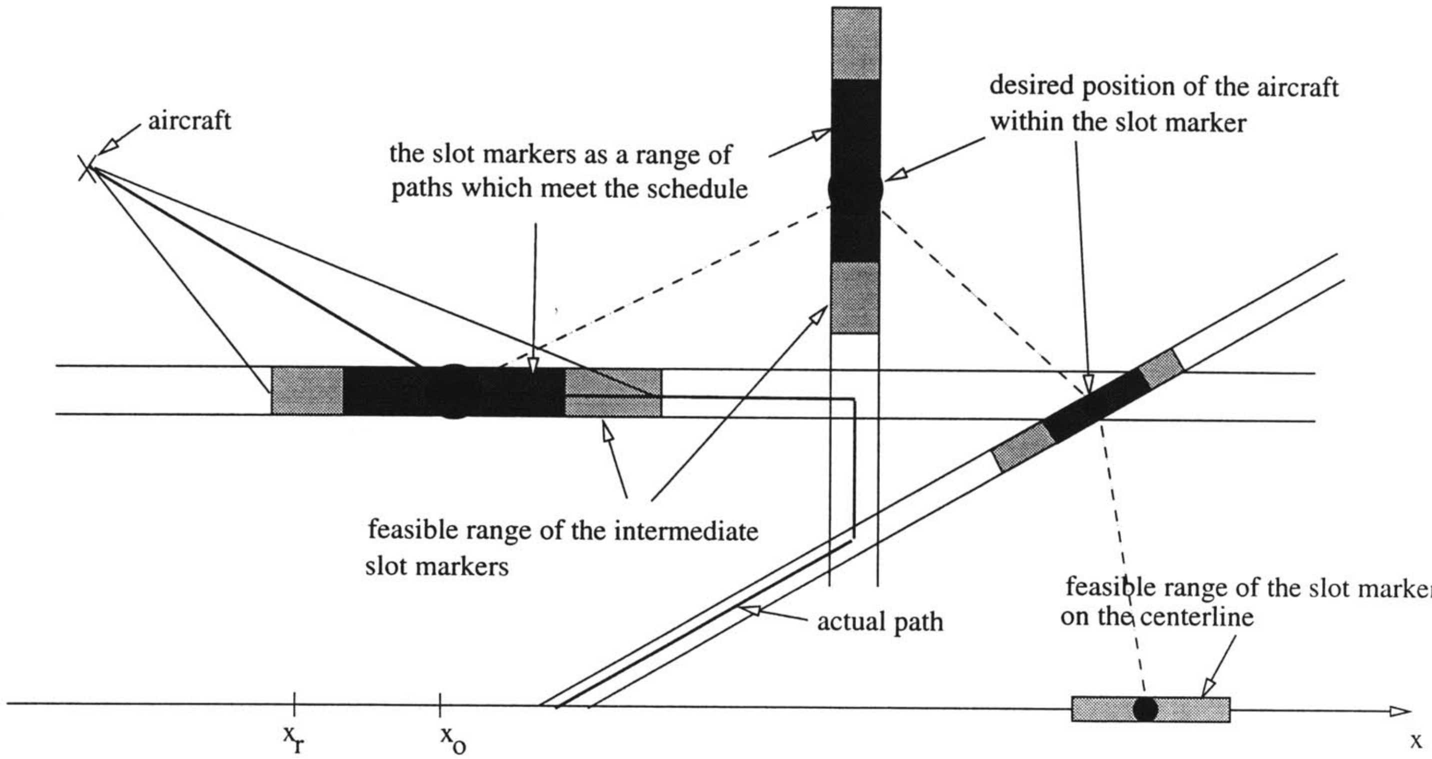


Figure 19: The feasible ranges of the intermediate slot markers

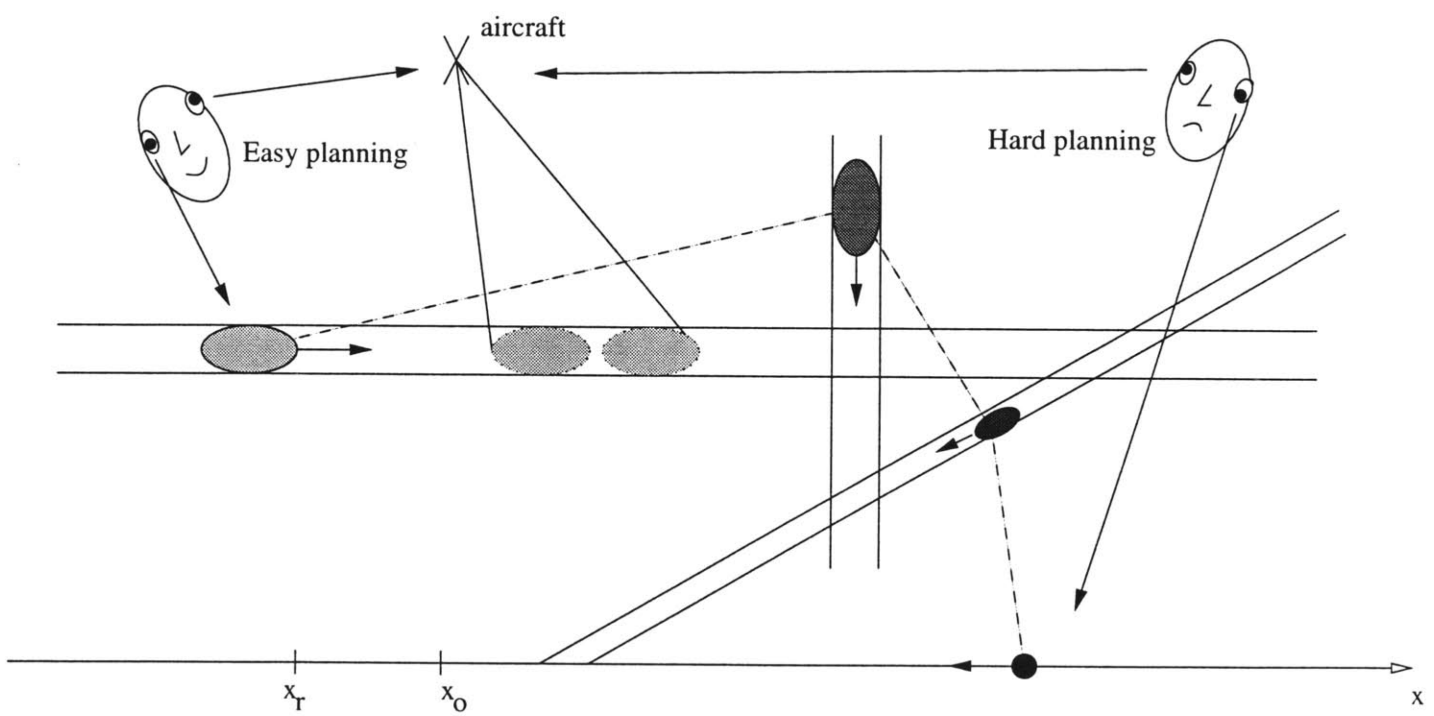


Figure 20: Simplifying path planning by providing the intermediate slot markers decomposing the problem into steps involving less degrees of freedom