Assignment 9: APM and Queueing Analysis

Solution
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Problem 1

a) An international airport has two parallel runways separated 800 meters away form each other. The following parameters are known for this airport. The technical parameters are given in Figure 1. The airport operates segregated operations where one runway is used for arrivals and the second one for departures. The airport does not operate simultaneous departures today.

Technical Parameters (inputs)	Parameter	Values
Dep-Arrival Separation (nm)	δ	2
Common Approach Length (nm)	γ	8
Standard deviation of Position Delivery Error (s)	σ	20
Probability of Violation	Pv	5

Figure 1. Technical parameters

The airport operates under IFR conditions with the separation matrices shown in Figure 2 and 3.

Minimum Separation Matrix (nm)		Arrivals-Arrivals			
	Trailing Aircraft (Header Columns)				
Lead (column 1)	Small	Large	B757	Heavy	Superheavy
Small	3	3	3	3	3
Large	4	3	3	3	3
B757	5	4	3	3	3
Heavy	6	5	4	3	3
Superheavy	8	8	8	8	8

Figure 2. Minimum Arrival-Arrival Separation Matrix

Departure-Departure Separation Matrix (seconds)			
		Trailing	
	Small	Large	Heavy
Small	60	60	60
Large	90	90	90
Heavy	120	120	120

Figure 3. Minimum Departure-Departure Separation Matrix (seconds).

	Small	Large	Heavy
ROT (s)	46	52	60
Percent Mix	30	40	30
Vapproach (knots)	100	140	150

Figure 4. Runway Occupancy Times and Baseline Aircraft Mix.

a) Estimate the IMC conditions Arrival-Departure Capacity diagram when the airport operates in segregated mode.

The Pareto diagram is a rectangle whose sides are determined by the saturation arrival and departure capacities. Using the spreadsheet calculator provided in class we obtain the following results. The arrival saturation capacity using the standard 3/4/6 nautical mile separations is 24 arrivals per hour. The departure saturation capacity is estimated to be 40 departures per hour. The expected headway between successive departures is 90 seconds.

Minimum Separation Matrix (nm)		Arrivals-Arrivals		
	Trailing Aircraft (Header Columns)			
Lead (column 1)	Small	Large	B757	Heavy	Superheavy
Small	3	3	3	3	3
Large	4	3	3	3	3
B757	5	4	3	3	3
Heavy	6	5	4	3	3
Superheavy	8	8	8	8	8

Error Free Separation Matrix					
	Trailing Aircraft (Header Columns)				
Lead (column 1)	Small	Large	B757	Heavy	Superheavy
Small	108	77	76	72	72
Large	226	77	76	72	72
B757	265	106	76	72	72
Heavy	312	142	112	72	72
Superheavy	384	219	214	192	192

Pij Matrix					
	Trailing Aircraft (Header Columns)				
Lead (column 1)	Small	Large	B757	Heavy	Superheavy
Small	0.090	0.120	0.000	0.090	0.000
Large	0.120	0.160	0.000	0.120	0.000
B757	0.000	0.000	0.000	0.000	0.000
Heavy	0.090	0.120	0.000	0.090	0.000
Superheavy	0.000	0.000	0.000	0.000	0.000

Buffer Matrix (Bij)					
	Trailing Aircraft (Header Columns)				
Lead (column 1)	Small	Large	B757	Heavy	Superheavy
Small	33.00	33.00	33.00	33.00	33.00
Large	0.00	33.00	33.00	33.00	33.00
B757	0.00	31.55	33.00	33.00	33.00
Heavy	0.00	24.43	27.59	33.00	33.00
Superheavy	0.00	19.29	22.18	33.00	33.00

Augmented Matrix (Tij + Bij)					
	Trailing Aircraft (Header Columns)				
Lead (column 1)	Small	Large	B757	Heavy	Superheavy
Small	141.00	110.14	109.06	105.00	105.00
Large	226.29	110.14	109.06	105.00	105.00
B757	265.18	137.31	109.06	105.00	105.00
Heavy	312.00	166.71	139.82	105.00	105.00
Superheavy	384.00	238.71	235.82	225.00	225.00
Arrivals Only Capacity (per hour)			24.00		

Figure 4.1 Solution for Arrival Saturation Capacity.

Departure-Departure Separation Matrix (seconds)							
	Trailing Aircraft (Header Columns)						
Lead (column 1)	Small	Large	B757	Heavy	Superheavy		Expected Value
Small	60	60	60	60	60		E(Td)
Large	90	90	60	90	60		
B757	120	120	60	60	60		90
Heavy	120	120	120	120	90		
Superheavy	150	120	120	120	120		
Departures Only Capacity (per hour)			40.00				

Figure 4.2 Solution for Departure Saturation Capacity.

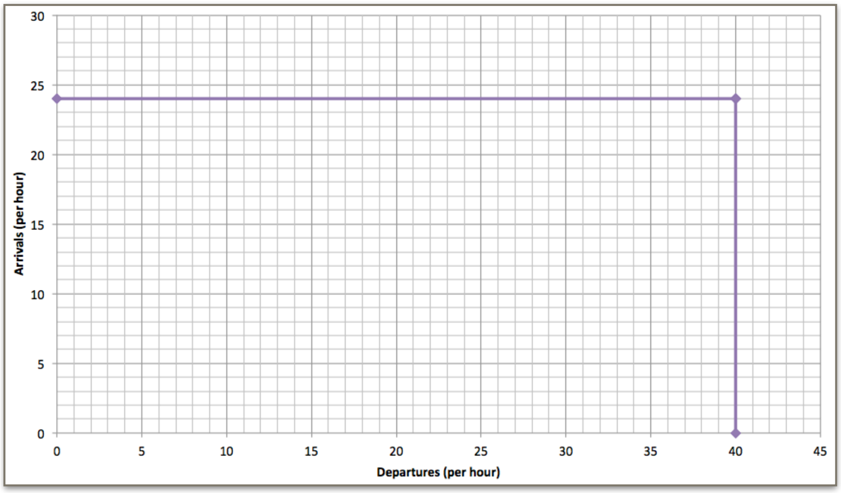


Figure 4.3 Pareto Diagram for Segregated Runway Operations.

b) During a busy period in a typical day of the airport has a surge of 60 aircraft departures are scheduled in a 60-minute period. The demand decreases to 35 /hr after the surge. During the same 60 minute period, 40 arrivals are scheduled by the airlines.

a) Calculate the resulting departure delays during the surge of traffic. How many aircraft are affected?

Use the deterministic queueing model to estimate the delays to departure operations. Setup the problem with a demand function so that:

$$\lambda(t) = \begin{cases} 60 \text{ if } t \leq \ 1.0 \text{ hour} \\ 35 \text{ if } t > 1.0 \text{ hour} \end{cases}$$

$$\mu(t) = \{40 \ \forall t$$

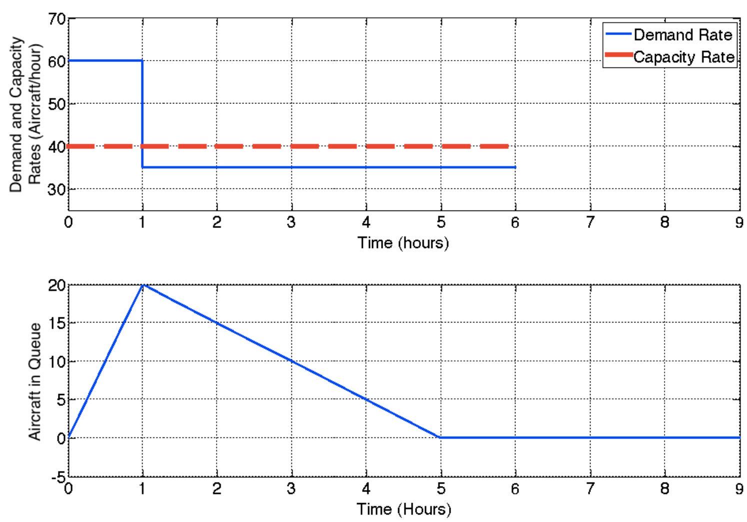


Figure 4.4 Demand and Capacity Rate Functions for Airport Problem. Aircraft Queue Length is also Shown in the Second Plot of the Figure. Area under the queue length triangular area is 50 aircraft-hours.

The number of departing aircraft affected by the queue is known to be 200 aircraft (60 aircraft in the first hour and 35 in the next 4 hours). Therefore, the average delay per aircraft is:

$$\bar{W} = \frac{50 \text{ acft-hr}}{200 \text{ acft}} = 0.25 \text{ hours}$$

b) Average passenger values time at $20.00/hr. Airlines value their operating cost at $2,800/hr per aircraft. Find the cost of the lack of departure capacity per day.

We do not know the aircraft size for the problem. However, we know that in the US NAS system, the average aircraft size is 132 seats seats per aircraft (per course notes). The average load factor in the NAS today is 82% (per course notes). The delay costs to passengers is:

$$C_{delays-pax} = (50 \text{ acft-hr})(132 \text{ pax/acft})(0.82)(\$20/\text{hr-pax})$$
$$C_{delays-pax} = \$108{,}240 \text{ per day}$$

The delay costs to the airlines is:

$$C_{delays-airline} = (50 \text{ acft-hr})(\$2800/\text{acft-hr})$$
$$C_{delays-airline} = \$140{,}000 \text{ per day}$$

This problem clearly illustrates the costly alternatives facing airports when demand exceeds capacity even for short periods of time. If the problem is re-current over one year, the annual costs to airlines and passengers will be 51 and 20 million dollars.

Problem 2

A TSA security area at a small airport receives passengers in a random fashion at a rate of 120 passengers per hour during the busy period of time in the morning. The security area has 2 x-ray stations to check carry-on luggage. The x-ray procedure can handle 63 passengers per hour.

This problem is solved using stochastic queueing equations. The word random in the statement of the problem implies random passenger arrivals. Lets assume time between arrivals conforms to a negative exponential distribution.

a) Estimate the average delay expected per passenger for this setup.

Running the stochastic queueing model equations we obtain:

System utilization (%) = 95.2381

Idle probability (dim) = 0.02439

Expected No. of passengers in queue (Lq) = 18.583

Expected No. of passengers in system (L) = 20.4878

Average Waiting Time in Queue (hours) = 0.15486

Average Waiting Time in System (includes service) (hours) = 0.17073

The average waiting time in the physical queue is 9.3 minutes.

b) Find the number of passengers that would queue on the typical busy period at the TSA station.

The number would be 18.6 passengers on average.

c) Find the probability that exactly 10 passengers wait for service at the TSA security station.

This is found by estimating Pn=10. A plot of the probabilities for the system states is presented below.

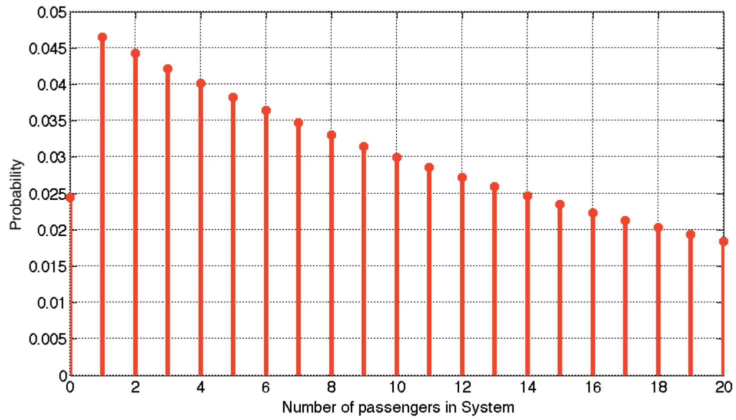


Figure 4.5 Plot of the Probabilities that the System is in State n.

The probability that exactly 10 passengers wait for service is equivalent to estimate the probability that 12 passengers are in the system because the system has two servers (2 passengers in service and 10 passengers waiting). The plot above shows that Pn=12 is 0.027 or 2.7%.

d) Find the probability that more than 20 passengers queue at the TSA security area.

This is found estimating the probabilities from 0-22 and then subtracting from 1. The operation is shown below with 33.4% chance that more than 22 passengers are in the system (or more than 20 with in line).

$$P(x>22) = 1 - \sum_{x=0}^{22} P_n$$

$$P(x>22) = 1 - 0.666$$

$$P(x>22) = 0.334$$

Problem 3

During the busy morning periods, Atlanta International Airport has a peak demand flow of 9,500 passengers per hour (one-way) traveling from various concourses to the main terminal (see Figure 2). The Bombardier Innovia APM 100 system consists of Transit Units (TU) with 4 cars holding up to 70 passengers each (at maximum capacity).

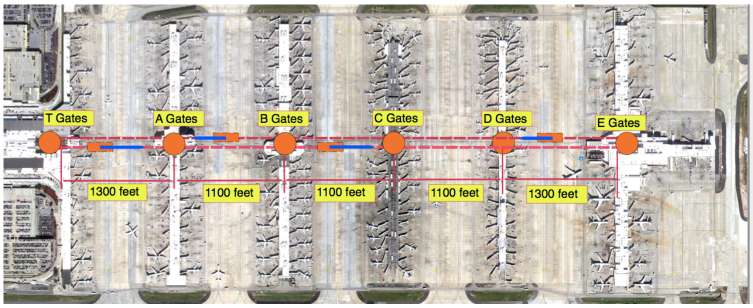


Figure 2. Atlanta APM System Layout.

a) Estimate the capacity of system if the minimum headway os 1.5 minutes. Is the system able to handle the peak load?

$$C_{APM} = \frac{3600 C_V n_{TU}}{h_{\min}}$$

where:

C_{APM} = APM capacity (passengers/hr)

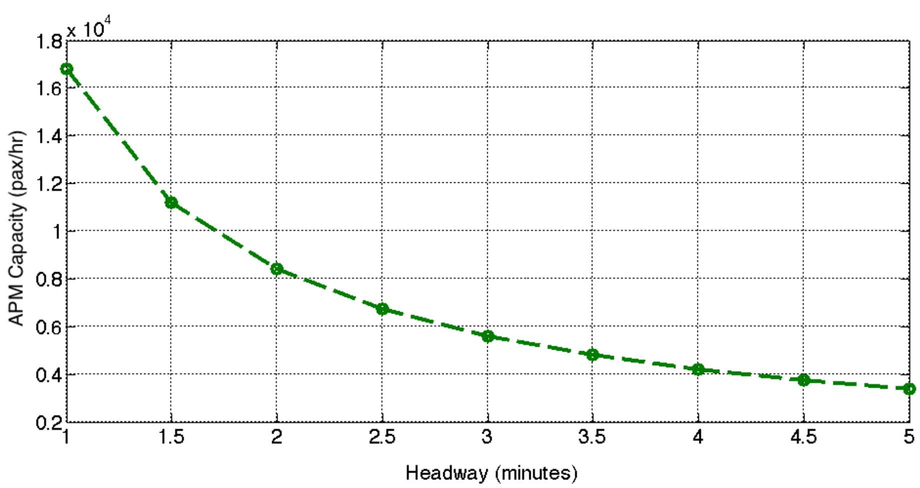
C_V = Individual car capacity (passengers)

n_{TU} = Number of cars per transit unit (cars)

$h_{\min}$ = Minimum headway (seconds)

$$C_{APM} = \frac{3600(70)(4)}{(90)} = 11{,}200 \text{ passengers/hr}$$

b) Plot the APM system capacity as a function of headway. Use a range of headways from 5 minutes down to 1 minute (the minimum safe headway).

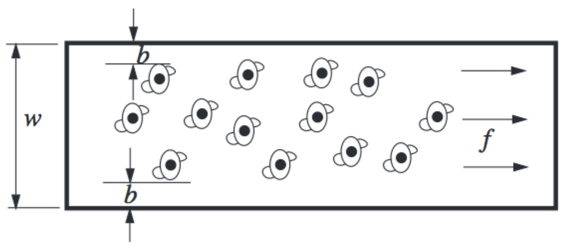


c) If the airport demand increases by 50% in the next 20 years, make recommendations.

The system will be pushing the limits of capacity running at 1 minute headways. This is technically feasible with current technology. However, if the Level of Service is to improve, run Transit Units with 5 cars per TU and 75 second headways. This provides with a capacity of more than 17,000 passengers per hour.

d) If the APM fails, estimate the width of the underground corridor needed to move all passengers without APM. In this solution assume the traffic flows are symmetrical with 9500 passengers traveling each directions between the two busiest satellite terminals. Show your work.

The volume of traffic is 9,500 passengers per hour per direction (since passengers can transit the underground corridor in both directions). This translates into 19,000 passengers per hour or 317 passengers per minute. Assume Level of Service for design (B) with 7 pedestrians/minute per foot of width design standard (see Table in notes - page 50).



To satisfy 317 pedestrians per minute, the corridor should be **45 feet wide** (317/7). Add 2 x 2 feet boundary layers and we have a 50 foot wide corridor. This provides good LOS (B). If LOS C would have been used, the corridor width with boundary layers would have been 36 feet.