ACRP Report 40
Airport Curbside and Terminal Area Roadway Operations

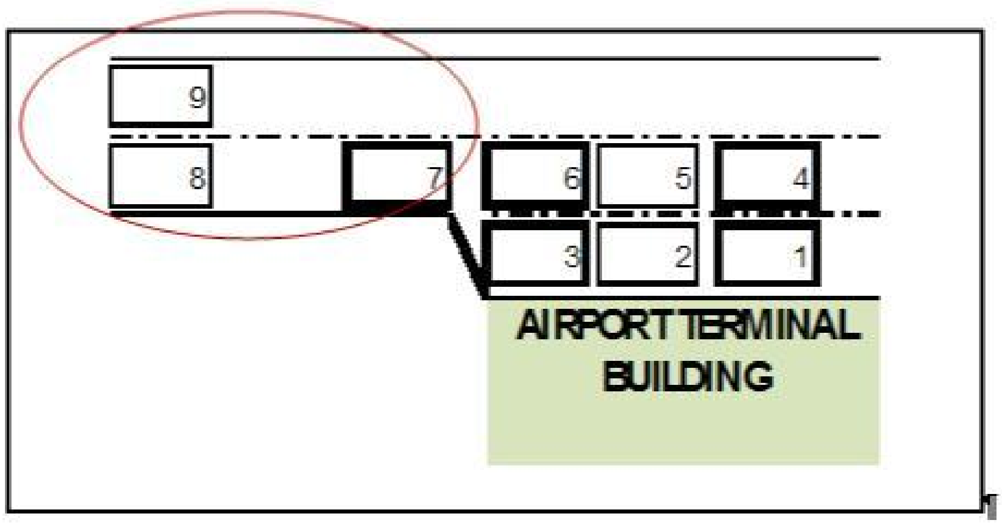
Appendix G

OVERVIEW OF THE CURBSIDE ANALYSIS METHODOLOGY IN THE QUICK ANALYSIS TOOL FOR AIRPORT ROADWAYS (QATAR)

Vehicles queuing to drop off passengers at airport terminal buildings are a good example of a queuing system in general. The vehicles arrive at the terminal area at a certain rate, wait to secure a desired drop off slot (if other vehicles occupy those spaces), drop off passengers, and then leave. Queuing theory provides mathematical approximations of such a process to predict the length of queues formed and the time the vehicles (or other entities) spend in the system.

Figure G-1

EXAMPLE OF A QUEUING SYSTEM AT AN AIRPORT TERMINAL BUILDING



A queuing system is usually divided into three components: (1) the arriving entities or vehicles in this application (sometimes referred to as the "calling population"), (2) the service facility or server, and (3) the queue. In Figure G-1, the curbside spaces in front of the terminal represent the service facility (server), vehicles 1 through 6 are vehicles stopped at the curbside and vehicles 7, 8, and 9 (approaching the terminal) represent the queue.

The capacity of such a system is influenced by the rate at which vehicles arrive, the order in which they are served, and how quickly they are served. In formal queuing theory, the arrival rate is modeled by assuming the vehicles' arrival pattern follows a specified probability distribution. The order in which the vehicles are served is referred to as the queue discipline. For example, if drivers secure slots strictly in the order in which they arrive, the queue discipline is referred to as first-in-first-out. The service rate is a function of the capability of the server. In the example above, the curbside space is the server. The service rate is the average time it takes passengers to disembark, their baggage to be offloaded from the vehicle, and the vehicle to depart from the curbside space. The time spent by motorists waiting to secure a drop-off space is not included. The service rate can be modeled either as a constant value or based on an assumed probability distribution.

The performance of the whole system is measured in terms of the length of queues formed and the time spent in the queue. In the example above, the level of service of the system will be influenced by the number of vehicles dropping off passengers in the lanes adjacent to the curbside lane, and how long the queues in those lanes last. Systems with shorter queues and queues that last for short durations represent a better level of performance and thus are desirable.

Mathematical equations of queuing systems can be solved either analytically or by developing simulation models. Solutions to analytical models are limited by the assumptions made about the arrival rate, service rate, probability distributions, nature of the calling population, and the assumption of steady-state conditions. Analytical models can provide a fairly accurate representation of a queuing system, especially for planning purposes. However, for detailed and complex systems (e.g., where movements of individual vehicles at the curbside need to be captured), simulation models can provide a more accurate representation. The downside of most simulation models is the large amount of input data and extensive run times required compared to analytical models. The QATAR model presented below is a simple analytical queuing model with carefully selected assumptions of arrival and service rates of vehicles at airport curbsides.

QATAR CURBSIDE QUEUING MODEL

Queuing Model Structure

The basic assumptions used in developing the QATAR curbside queuing model are presented below. Several excellent texts exist on queuing theory. For a primer, readers can refer to ***Operations Research*** (Hillier and Lieberman) and ***Applications of Queue Theory*** (Newell). (Please refer to the references at the end of this appendix for full citations.) The field of queuing theory is well developed with standardized terminology. The following paragraphs introduce the standard queuing theory terminology and the assumptions used in constructing the model.

A queuing system consists of a facility providing some form of service to a defined population. The key values used to define a queuing system are the arrival rate, service time, number of servers, system capacity, calling population, and queue discipline. The time between arrivals (inter-arrival time or arrival rate) of members into the queuing system is modeled as a probability distribution.

The roadway in front of the airport terminal represents the service facility. It is modeled as a multiserver facility, with each curbside space considered a server. The system capacity is assumed to be infinite. The size of the population can be either ***finite*** or ***infinite***, but for analytical models, it is usually defined as infinite because of the difficulty of deriving analytical solutions for ***finite*** systems. The queue discipline is specified as first-in-first-out.

Model Equations

The variables below are the key inputs into any basic queuing model (Hillier and Lieberman)

s - Number of servers in the service facility
λ - Mean arrival rate of customers
μ - Mean service rate of the overall system

The output variables of interest from the model are:

L_q - Number of customers in the queue
L - Number of customers in the queuing system (customers in the queue and the customers being served)
W_q - Expected waiting time in the queue
W - Expected waiting time in the queuing system
P_n - Probability that exactly "n" customers are in the queuing system

It should be noted that queuing models are derived assuming ***steady-state*** conditions. For example, at some airports, there are relatively few early morning flights and, consequently, few vehicles driving through the terminal curbside area. The system is in a ***transient state*** and queues form and disappear quickly or sporadically. As more flights begin to depart (or arrive), there is a more steady flow of vehicles in and out of the terminal area and the condition during those times is more analogous to a ***steady-state*** condition.

Another restriction for queuing models is that the utilization factor (ρ) is less than 1. Rho is defined as $\rho=\lambda/(s*\mu)$. The terms λ, s, and μ have the same meaning as defined above – subscripts have been dropped for convenience. In addition, it should be noted that, for any model, if the mean arrival rate (λ) is greater than the mean service rate (μ), the queue would grow indefinitely.

It is well documented in operations research literature, and commonly assumed in transportation applications that customers randomly arriving at a service facility have an arrival pattern similar to a Poisson distribution process. The assumption of a Poisson arrival process yields an exponential inter-arrival time distribution.

Detailed derivations are provided on pages 386 through 391 of Hillier and Lieberman's text. Assuming an exponential service rate for an airport terminal curbside is realistic because, although drop-off and pickup times vary close to a mean, in some instances passengers take a long time to disembark, either because of a large party size, large amount of luggage, or other reasons.

Based on the above, a multiserver queuing system with a Poisson arrival process, a mean service rate that follows an exponential probability distribution, and an infinite calling population are assumed. If the queue discipline is 'first-in-first-out,' the following analytical results for the basic outputs can be derived. Please refer to Hillier and Lieberman's ***Operations Research*** text for a step-by-step derivation of the results.

$$\boldsymbol{L_q} = [P_0(\lambda/\mu)^s * \rho] / [s!(1-\rho)^2]$$
$$\boldsymbol{L} = \boldsymbol{L_q} + (\lambda/\mu)$$
$$\boldsymbol{W_q} = \boldsymbol{L_q} / \lambda$$
$$\mathbf{W} = \boldsymbol{W_q} + (1/\mu)$$
$$\boldsymbol{P_n} = [(\lambda/\mu)^n * P_0/n!] \qquad \text{if } 0 \le n \le s$$
$$\boldsymbol{P_n} = [(\lambda/\mu)^n * P_0]/s!s^{(n-s)} \qquad \text{if } n \ge s$$

QATAR Model Inputs

The model is set up as a series of 10 zones. Each zone represents a designated area at the airport terminal curbside. To analyze each zone, the model requires inputs to estimate the equivalent number of servers, information on the characteristics of approaching traffic, and the curbside behavior of drivers. The inputs to the model are:

- Length of the zone
- Number of lanes in the zone
- Dimensions of each vehicle type
- Number of vehicles approaching the zone in an hour (arrival rate)
- Vehicle mix of approaching vehicles (taxicabs, buses, etc)
- Estimate of the propensity of drivers to double park (the input in the model is 'number of vehicles in first lane when next car uses second lane', and 'number of vehicles in second lane when next car uses third lane').

HOW THE INPUTS ARE PROCESSED TO PREDICT QUEUING BEHAVIOR

Number of Equivalent Servers per Zone

The available curbside length divided by the average vehicle stall length provides an estimate of the number of equivalent servers in each lane within a zone. The number of equivalent servers multiplied by the number of available lanes provides an estimate of the total number of equivalent servers per zone. Because drivers may choose to park in lanes not intended for loading or unloading, the calculation of equivalent servers uses the total number of lanes on the roadway. The formulas are shown in Equations 1 and 2 below.

(1)

$$\text{Equivalent Parking Spaces} = \frac{(\text{Number of Lanes} * \text{Length of zone})}{\text{Weighted Vehicle Length}}$$

(2)

$$\text{Weighted Vehicle Length} = \frac{(\text{Parking Length of Vehicle Type}_i * \text{Volume of Vehicle Type}_i)}{\sum_i \text{Volume of Vehicle Type}_i}$$

HOURLY VEHICLE ARRIVAL RATE

The number of vehicles arriving at the zone per hour is the sum of the volume of all vehicle types approaching the zone, as shown in Equation 3 below.

(3)

$$\text{Vehicle Arrival Rate} = \sum_i \text{Volume of Vehicle Type}_i$$

SERVICE RATE

The service rate is computed as the weighted dwell time, as shown in Equation 4 below. QATAR does allow the modeling of individual vehicle types. In such a situation, the service rate is equal to the dwell time assumed for the specific vehicle type.

(4)

$$\text{Service Rate} = \frac{\sum_i (\text{Dwell Time of Vehicle Type}_i * \text{Volume of Vehicle Type}_i)}{\sum_i \text{Volume of Vehicle Type}_i}$$

UTILIZATION FACTOR AND RATIO

The utilization factor is determined by the formula shown in Equation 5 below.

(5)

$$\text{Utilization Factor} = \frac{\text{Arrival Rate}}{\text{Service Rate} * \text{Number of Servers}}$$

The utilization ratio is determined by the formula shown in Equation 6 below.

(6)

$$\text{Utilization Ratio} = \frac{\text{Arrival Rate}}{\text{Service Rate}}$$

It should be noted that a utilization factor greater than 1 will result in an error message. In such a situation the number of vehicle attempting to load and/or unload exceeds the number of servers in a zone (i.e., every lane is fully occupied by vehicles attempting to load and/or unload).

NUMBER OF VEHICLES IN THE SYSTEM

Using the results from the above equations, it is possible to then estimate the probability of having N vehicles in the system. In this model, probabilities are computed for N going from 0 vehicles to 170 vehicles. The formula for computing the probabilities is shown in the Model Equations section above. A cumulative sum of the probabilities from zero generates a cumulative density function (CDF). The 95th percentile from the CDF is an estimate of the maximum number of vehicles in the system 95% of the time. The number of vehicles at the 95th percentile is the value used when determining the level-of-service on a curbside. The number of vehicles in the queue is the difference between the number of vehicles in the system and the number of equivalent servers.

MODEL OUTPUTS

The outputs from the model provide estimates of the level of parking congestion at the curbside and the effects of congestion on the outer through lane (the lane(s) farthest from the terminal building).

DOUBLE AND TRIPLE PARKING

Parking activity in each lane is estimated based on the curbside utilization ratio. The utilization ratio is calculated by comparing the total length of vehicles assumed to be parked within a zone simultaneously (based on the 95th percentile from the CDF for that zone) with the curbside length available for parking in that zone. The model then uses two inputs to determine the tendency of drivers to double and triple park (if the zone has only three total lanes, the model assumes that parking only occurs in the first and second lanes).

The user inputs are defined as T_{Lane2}, the proportion of the first lane that is filled before drivers start to park in the second lane, and T_{Lane3}, the proportion of the second lane that is filled before drivers start to park in the third lane. The suggested default value for both inputs is 80%, which means that drivers park in the first lane until 80% of the first lane is occupied and that drivers will park in the third lane once 80% of the second lane is occupied. These values are based on observations at multiple airports with multiple attraction points (e.g., doors, skycap positions) within one curbside zone.

For curbside zones with three parking lanes (i.e., zones with four or more total lanes), the proportion of lanes 1, 2, and 3 used for parking (P_1, P_2, and P_3) is calculated as follows:

- For $v/c \le \mathbf{T_{Lane2}}$,
  $P_1 = v/c$
- For $\mathbf{T_{Lane2}} < v/c \le (1 + \mathbf{T_{Lane3}})$, and while $P_1 \le 1.0$,
  $P_1 = \mathbf{T_{Lane2}} + (v/c - \mathbf{T_{Lane2}})/2$
  $P_2 = (v/c - \mathbf{T_{Lane2}})/2$
- For $\mathbf{T_{Lane2}} < v/c \le (1 + \mathbf{T_{Lane3}})$, and while $P_1 > 1.0$,
  $P_1 = 1$
  $P_2 = (v/c – 1)$
- For $v/c > 1 + \mathbf{T_{Lane3}}$, and while $P_2 \le 1.0$,
  $P_1 = 1$
  $P_2 = (v/c – 1) + (v/c – (1 + \mathbf{T_{Lane3}}))/2$
  $P_3 = (v/c – (1 + \mathbf{T_{Lane3}}))/2$
- For $v/c > 1 + \mathbf{T_{Lane3}}$, and while $P_2 > 1.0$,
  $P_1 = 1$
  $P_2 = 1$
  $P_3 = v/c - 2$

For curbside zones with two parking lanes (i.e., zones with three total lanes), P_1 and P_2 are calculated as follows:

- For $v/c \le \mathbf{T_{Lane2}}$,
  $P_1 = v/c$
- For $v/c > \mathbf{T_{Lane2}}$, and while $P_1 \le 1.0$,
  $P_1 = \mathbf{T_{Lane2}} + (v/c - \mathbf{T_{Lane2}})/2$
  $P_2 = (v/c - \mathbf{T_{Lane2}})/2$
- For $v/c > \mathbf{T_{Lane2}}$, and while $P_1 > 1.0$,
  $P_1 = 1$
  $P_2 = (v/c – 1)$

THROUGH-LANE CAPACITY

The through-lane capacity of an airport curbside roadway is affected by curbside activity (vehicles stopping to load or unload passengers). As the curbside lanes become more congested, double and potentially triple parking will block the roadway through lanes. These complex, nonlinear interactions can be described by the curves shown on Figure 5-2. It should be noted that roadway capacity decreases continuously as curbside utilization increases. The decrease is more prominent when curbside activity reaches a level at which additional lanes are blocked, which justifies the nonuniform slope of the curves.

The curves shown in Figure 5-2 were developed using a combination of microsimulation testing of hypothetical airport curbsides and actual field observation. A VISSIM model was developed to determine the curbside volume stopping in the pickup and dropoff lanes, which corresponds to various curbside utilization levels. By holding that level of curbside activity constant and increasing through-traffic volumes during multiple simulation tests, a progressive collapse of traffic flow was observed, and a queue formed upstream of the curbside section. When the queue became persistent or continuously increasing, the roadway section was said to have reached capacity.

The curves were validated using field data collected at Washington Dulles, San Francisco, and Oakland international airports. The data were difficult to obtain as the only observable time when the roadway reaches capacity is when a persistent queue exists upstream of the curbside section. However, in such situations, the roadway capacity was assumed to be the throughput on the roadway, measurable by standard industry traffic counting techniques.

References:

Hillier, F. S. and Lieberman, G. J. ***Operations Research***. Holden-Day Inc, San Francisco, 1974.

Newell, G. F. ***Applications of Queue Theory***, Chapman and Hall Ltd., London, 1971.

Trani, A. A., ***Class Notes: Principles of Queuing Theory***, Civil Engineering Department, Virginia Polytechnic Institute and State University, http://128.173.204.63/courses/cee3604/cee3604_pub/queueing_theory.pdf, 1999.