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A REVIEW OF RESEARCH ON AIRPORT CONGESTION DELAYS

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FOR DISCUSSION PURPOSES ONLY

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Although research on airport congestion was reported in the scientific literature as early as 1958, it was not until the late 1960's that a considerable amount of effort was applied to the problem area. During 1968 and 1969, the increasing popularity of travel by jet airliner had brought about a situation of crisis proportion as airports and air traffic control systems in use at that time did not have the capacity to handle the traffic loads imposed upon them.

This crisis situation stimulated interest in the problems associated with airport congestion. From the late 1960's to the present, research continued at a high level in recognition of the prominence of air travel in the United States and because of the high costs in time and money involved in delays within the airport system.

This article will review the literature of the past two decades to report on the current state of the art for research into airport congestion delays. It will be organized in terms of the following general topics: the airport airside; the airport landside; the overall airport as a set of subsystems; and the airport as an integrated system. Research in each of these categories will be discussed in roughly chronological order.

The Airport Airside

The airport airside is defined as encompassing all activities which take place between the airline gate and the airspace in the vicinity of the airport. In other words, the airport airside includes those portions of the airport for which aircraft movement is of primary concern. Research in this area covers aircraft approach and runway use alternatives as well as investigating the impact such factors as wake turbulence, surface traffic and differential landing fees have on traffic levels.

Approach and Runway Analytic Models

The original source of congestion delays in the airport system was the inability of the runway and air traffic control systems to handle heavy traffic loads. The earliest study noted dealing with this problem is an analytic model of the queueing process for arriving aircraft at an airport developed by Galliher and Wheeler [29]. They used constant arrival rates for their queueing model within time intervals during the day. However, these arrival rates were changed for different time intervals to model the time-varying nature of demand on the airport throughout the twenty-four hour day. This research into congestion delays was done in 1958, ten years before the problem reached the crisis stage. Little was done in the intervening years until the crisis actually occurred in the late 1960's.

In 1969 Carlin and Park used a dummy variable regression analysis to estimate delays to arrival aircraft at New York's Kennedy International Airport [14]. Odoni used an analytic model of runway use to examine the behavior of traffic in using the runway [58]. This was followed a year later by Koopman, who used several analytic models to examine landings and takeoffs on a single runway. While this study was very limited in scope, Koopman followed it two years later with a discussion of the effect of time-varying loads on aircraft approach and runway congestion [50,51]. In 1972, three studies by the Mitre Corporation dealt with the possibilities of increasing the effective capacity of runways either through more efficient utilization of the single runway or through the construction of a dual-lane runway consisting of two parallel runways in close proximity. These studies were done by Harris, who also used an analytic model to calculate the capacity of a single runway under Instrument Flight Rules [36,37,38].

Other Considerations

Approach and runway use has been influenced by several factors. Wake turbulence, which is a function of the physical attributes of the aircraft, serves as a constraint on the efficient use of runways. Difficulty in controlling surface traffic also prevents the optimal use of available airfield facilities. In addition, economic incentives have been proposed to shift demand for use of runways from peak usage periods. These topics will be discussed below.

Wake Turbulence. A limiting factor to the improvement in utilization of airport runways is the problem of wake turbulence. While every aircraft creates turbulence, the wake vortices produced by the wingtips of an aircraft are stronger and longer lasting as the weight of the aircraft increases. The advent of the larger jets, particularly the wide-bodied planes, meant that the vortices generated by these planes could send a following aircraft out of control and cause it to crash. Recognition of this problem led the Federal Aviation Administration to set separation standards for succeeding aircraft on the same flight path. These standards took into account the relative weights of the two aircraft in each pair of planes following the same path. The greatest separations are required for those aircraft following "heavy" jets, which are capable of weighing 300,000 pounds when fully loaded. These planes are classified as "heavy" regardless of their actual weight when loaded [81].

One of the most attractive means of increasing the capacity of present runways would be to reduce the separation between arrival aircraft and between succeeding takeoffs in order to utilize the runway more efficiently. The necessity for imposing wake turbulence separations meant that this approach becomes severely limited as the proportion of heavy jets increases in the mix of planes using any given airport.

Research on the problem is continuing, and it now appears that the best hope for dealing with this problem lies in either dissipating the wake vortices at the source, or in accurately detecting the presence of the vortices near the airport [25,45,84]. This would mean that the separation standards could be safely modified for each individual aircraft according to conditions. This latter approach would be helpful because the vortices tend to dissipate quite rapidly under some atmospheric conditions. If this occurred in a specific instance, the separation between following aircraft could be reduced.

Airfield Surface Traffic. Problems associated with the control of aircraft moving on the airport runways and taxiways were investigated as early as 1966. Dowe described the airfield taxi procedures in use at that time and followed this three years later with a plan for building a computer simulation model of such traffic [22,23]. This model was not built, however. While Dowe was primarily interested in the problems of delay on the airport surface, the latest interest in investigating the movement of aircraft on the airfield arose from safety rather than delay problems. Due to the size and complexity of many major metropolitan airports, the ability to control the movement of aircraft on the surface at many of these airports is severely diminished. This occurs even in good weather because the view of the airfield surface from the control tower is obstructed by tall buildings in some areas of the airport. Control of aircraft surface movement at these airports is extremely difficult in poor weather conditions.

Because of problems with aircraft crashes at Boston's Logan Airport and Chicago's O'Hare Airport, a great deal of renewed interest has been stimulated in improving the ability to detect and control the movement of aircraft on the airfield. Studies by Baran, D'Allessandro, Hagerott, and others have led to the development of innovative systems for improving such control [6,19,35]. It is expected that once these systems are perfected, they will be adopted for those airports where airfield surface traffic is difficult to control. It should be clear that improvement of the ability to detect the movement of aircraft on the airport surface should not only aid in providing increased safety for those aboard the aircraft, but should also lead to decreases in taxiing delays.

Peak Load Pricing for Landing Fees. One solution for airport congestion caused by limited runway capacity seemed natural to several economists. This solution was to charge an increased price for use of the runway at those times of the day when congestion was especially severe. The basic idea is that substantially increased costs for use of the airport runways during peak hours would tend to shift demand to the less congested and therefore less expensive times of the day. This would serve to smooth the congestion peaks and effectively increase the capacity of the airport to handle more traffic during any given day with much lower levels of delay. While Grampp was one of the earliest to suggest this sort of peak-load pricing in 1968, Piper and Keen have separately revived the matter as recently as 1973 and 1974 [32,64,47]. Perhaps the most noted efforts in this regard have been by Carlin and Park, by Kiefer, and by Eckert [15,48,24]. The basic problem with this approach to the solution of airport congestion delays is that it is, in essence, a stopgap measure. Continual increases in demand will require that airport capacity be increased eventually in spite of this approach. Furthermore, the implementation problems connected with this approach are enormous. The traveling public has not shown a willingness to travel at off-peak hours in substantial numbers even to obtain price reductions. Also, while the federal government can set quotas for the number of landings allowed per hour, it cannot set landing fees for individual airports. This comes under the jurisdiction of each individual airport's management.

The solution taken, beginning in 1969, was to impose hourly quotas on the number of arrivals allowed to land at the three New York airports, Chicago's O'Hare Airport, and Washington National Airport. These quotas were imposed under especially heavy load conditions and were known as Flow Control Procedures. These were later supplanted by the Advanced Flow Control Procedures, which were replaced in turn by the Central Flow Control Facility in Kansas City [11]. These flow control procedures have the effect of holding aircraft on the ground at their origin airports if they would incur probable delays of more than one hour at the controlled destination airport. This is in lieu of spending approximately the same length of time circling in a holding pattern near the destination airport. The effect has been to reduce congestion in the airspace near the controlled airports. This procedure may also have contributed somewhat to the safety of airline passengers because of the reductions in flight times.

Approach and Runway Simulation Models

Several studies have been done in which a simulation model was constructed in order to aid in investigating the behavior of the terminal airspace and runway systems. The study by Gilsinn at the National Bureau of Standards in 1971 included the construction of a SIMSCRIPT 1.5 simulation model of the airspace and runway for a large airport [31,30]. This model is called the DELCAP airport simulation and deals with the airport runway configuration and operating modes. The influence of the mix of aircraft types and of separation standards is considered in determining the likely delays to be encountered by aircraft in this part of the airport system. The model does not consider traffic on the airfield surface other than the runway. It was subjected to a validation study in an effort to test the approximation of the model to reality. Rinker constructed a very small GPSS simulation model with a separate FORTRAN data preprocessor program to simulate the use of the approach and runway by arriving STOL (Short Take-Off and Landing) aircraft at an airport [67]. Booth used a somewhat more sophisticated FORTRAN simulation model to analyze runway capacity at an airport [12]. By far the most sophisticated of the simulation models for the terminal airspace and runway is the FORTRAN simulation model constructed by the Research Triangle Institute in 1972 [66]. This model simulates the radar vectoring for arrival and departure aircraft in the terminal airspace as well as the use of the airport runways. The model also provides a graphic CRT (TV-screen) display of the simulated situation.

Overall Airside Simulation Models

The models discussed in the previous section provided a sophisticated look at the problems of congestion delays in the terminal airspace and on the airport runways. The scope of the simulation models to be discussed in this section includes not only the terminal airspace and runway but also the use of the airport taxiways. This allows the interaction between taxiing procedures and the use of the airport runways to be examined.

Willis constructed a GPSS/360 simulation model to examine the use of the runways and taxiways at Moissant International Airport in New Orleans for 1970, 1975, and 1980 projected loads [86]. Hosford and Lovitt went one step further with a FORTRAN IV simulation model of the airside of a STOL airport [44]. Their model included the runways and taxiways as well as the simulated use of airline gates. In a parallel effort, Adarkar constructed a FORTRAN IV simulation model of the approach airspace, runways, and taxiways for the airport system [1,2]. The distinguishing feature of this model is that it may be run in either fast time or "real time" and has a CRT graphic output capability to display the workings of the model as they proceed.

In 1971, Englander constructed a FORTRAN simulation model of the overall airspace and airside systems of the airport. A sketchy description of the model is given in his report [28]. In 1971, Higgins and Mpontsikaris did a well-written evaluation of the current state of the art in airside traffic control models, but did not include landside operations in their survey [41]. In 1973, a study was done at the Douglas Aircraft Company to determine new procedures to be used in evaluating airport airside capacity [21]. This is a very comprehensive study of the activities of air traffic controllers, and of the actual use of runways, taxiways and airline gates.

It seems clear that the emphasis in these studies remains on the airport airside as the major focus of airport congestion delays. As will be discussed in the section dealing with the airport landside, this is not necessarily the only factor to be considered in assessing airport congestion delays. However, as late as 1974 Hockaday and Maddison stated that:

> Airport congestion is manifested in many ways, but it is most apparent in, and is characterized primarily by, delay to aircraft resulting from insufficient capacity of the airfield system [42].

This comment indicates the authors' extensive background and experience with the problems of airport airside congestion but does not indicate that there may be an equally important part of the airport which they do not mention but which does cause congestion delays.

The Airport Landside

The airport landside is defined to mean those portions of the airport system for which the movement of passengers is most important, whether on foot or in vehicles. The landside includes both the ground access and terminal building sections of the airport system when considered in an overall sense. It should be clear that congestion delays in the airport landside could be as important to the passengers experiencing them as those which they encounter while inside an aircraft. Research into these problems will be discussed in terms of the ground access and terminal building sections of the airport system and in terms of the overall airport landside when considered as a unit.

Ground Access Research

Studies have been done on the problems of ground access at several major U.S. airports. These studies were intended to examine currently severe congestion delays in the ground access for these airports and to suggest improvements which would have an immediate impact in relieving these delays. Such studies were done at Washington National Airport and Dulles International Airport, both in Washington, D.C., Los Angeles International Airport, San Francisco International Airport, and at Logan International Airport in Boston [63,10,20,61,53,18]. In an effort to examine the problem further, a study was done using factor analysis and regression analysis to arrive at the relationships between the volume of ground access traffic and the modal split of that traffic for major U.S. airports in the future [27].

Terminal Building Research

Most studies of the activities in the airport terminal building concentrated on a small part of the overall structure. An example is the study by Reese in which a simulation model was constructed for studying passenger flows in a concourse at Chicago's O'Hare Airport [65]. A similar example is Robinson's study of baggage handling systems for airport arrival passengers using a GPSS III simulation model [68]. Other such studies were reported by Barbo, Horonjeff, Kaneko, Paullin, and by Smith and Murphy [7,43,46,62,71].

The studies by Chamberlain and Micka went somewhat further in that a SIMSCRIPT simulation of the United Airlines terminal at Kennedy International Airport was constructed [16,17]. This simulation of a separate, self-contained terminal building considered staffing levels for the lobby, gate, ramp, and baggage operations in that terminal. The studies were done in order to assess the impact of the introduction of wide-bodied airliners on the operations at that terminal. This model captures the interaction effects which take place between activities in different parts of the terminal building.

In 1970, Whorf at Ford Motor Company studied the potential effects of the introduction of a people-mover system at the Salt Lake City Airport through the use of a GPSS/360 simulation model [85]. This model considered the mutual use of gates between airlines and also included the use of the people-mover system to move passengers between a common departure lounge and the parked aircraft. The study also included an origin-destination passenger survey at the Salt Lake City Airport.

A somewhat different study was done by Nanda, Browne, and Lui in which they constructed a GPSS II simulation model for the baggage claim and U.S. Customs processing areas used for international arrival passengers at Kennedy Airport's International Arrivals Building [57]. This well-constructed model is used to examine congestion delays encountered by passengers in this section of the airport.

Consideration of the overall terminal building from a very different viewpoint is provided in Braaksma's Ph.D. thesis in which he constructed a computer program to aid in the physical planning phase of designing new terminal buildings [13]. Two excellent studies have been done by the Ralph M. Parsons Company in which they construct a planning manual for the apron and terminal building complex at a major metropolitan airport. This very detailed analysis would be useful for designing or modernizing nearly any kind of terminal building at a major airport [59,60].

Overall Airport Landside Research

Although the studies previously cited have concentrated on the terminal building as such, the major research focus for airport congestion delays has shifted to the examination of the airport landside as an overall system. This emphasis is especially evident in the Proceedings of the Transportation Research Board's Conference on Airport Landside Capacity, held in May, 1975 [77]. The papers presented at this conference stressed that the airport landside must be considered as a system, interfacing with the airport airside system.

It was further stated that the emphasis on solutions for airport congestion delays should now be on the landside because of the previous improvements made to the airside of the airport. In other words, most of the research on airport congestion delays had been done on problems in the airport airside so that conditions on the airside have been improved. This has resulted in the capacity bottleneck for the airport system being shifted to the landside [77]. Further emphasis is given to this point by McCabe and Carberry's review of airport landside simulation models [54]. This report discusses the requirements for effective simulation models of the airport landside as well as providing reviews of seven existing models. McCabe and Carberry rate the Bechtel Corporation and Tippets-Abbett-McCarthy-Stratton (TAMS) simulation models as the most effective. Both of these models use the GPSS simulation language and appear to be proprietary company property. Because of this restriction, complete details regarding the nature of each of these models are not available.

Both the Transportation Research Board and the McCabe and Carberry reports consider the airport landside to be an integrated system for that section of the airport. However, the airport airside and terminal airspace sections of the airport are not covered except in passing. The authors believe that these parts of the airport system can be as important as the landside in examining congestion delays, and that all of these sections of the airport should be included on an overall integrated system basis.

The Overall Airport as a Set of Subsystems

Treatment of the airport in total, but not on an integrated system basis, is shown by the Civil Aeronautics Board and Federal Aviation Administration airport studies, which were done in 1970 at the direction of the U.S. Congress [78,26]. These studies were a response to the crisis situation which existed in 1968 and 1969 and were designed specifically to investigate the causes and effects of airport congestion.

An excellent study dealing with all phases of airport operations as well as all other aspects of air transportation was done by the Aviation Advisory Commission in January, 1973. This report on the long-range needs of aviation considers the percentage annual rate of growth in passenger enplanements in terms of the relationship between forecasts of traffic growth and expected high, moderate, or low growth in the Gross National Product [5]. Although all aspects of airport and aviation interests are covered in this report, the airport is not considered as an integrated system. The same is true of the report by Rogers on short-haul air transportation and its impact on the airport system [69].

Continuing interest in the problem of airport congestion delays is shown by the two bibliographies published by the National Technical Information Service in 1974 and 1975 [33,34]. These studies provide an overview of all federally funded research in this field up to the date of compilation. The coverage of these bibliographies is somewhat more comprehensive than their titles would suggest, since they cover many of the aspects of airport congestion delays discussed here.

The Airport as an Integrated System

While none of the research cited to this point has treated the metropolitan airport as an integrated system, a small amount of work in that direction has been done. Treatment of the airport as an integrated system includes the ground access, landside, airside, and terminal airspace as interfacing parts of the total metropolitan airport system. In a pioneering effort, the McDonnell Douglas Corporation performed a feasibility study in 1967 for a simulation model which would consider the airport as an integrated system [55]. This report, which was done before the serious congestion delays of the 1968-1969 period occurred, lays out the requirements for a simulation model of the entire airport system. However, the model was not actually built.

The authors of the McDonnell Douglas study stated that the process of constructing such a model would provide the model builders with a wealth of insights into the operation of the metropolitan airport as a system, and could also be used to analyze changes to the system in terms of their impact on the traffic through it [55, pp. 1, 58]. It was obvious from the nature of the report that a simulation model capable of adequately representing the entire airport system would have been very large and very complicated. In fact, that task was apparently viewed as so large and so complex that the undertaking was not begun.

The next attempt at modeling the airport as an integrated system appears to have been made by Bechtel Corporation and by Tippets-Abbett-McCarthy-Stratton (TAMS) in their construction of large-scale GPSS simulation models of the landside section of the metropolitan airport as an integrated system. The only published reference to the Bechtel and TAMS models appears to be the study by McCabe and Carberry [54]. This report evaluates simulation models applied to airport landside problems. The TAMS model coverage includes the passenger and vehicular traffic between the airport boundary and the airline gates. In other words, it treats the overall airport landside as an integrated system but does not include the airport airside in any fashion.

From the description provided by McCabe and Carberry, it appears that the Bechtel Corporation Model is somewhat more comprehensive, since it treats the movement of passengers and vehicles between the airport boundary and the airline gates in a more detailed fashion. This model is programmed in GPSS-V, which is an advanced dialect of the GPSS language. Similar to the TAMS model, the Bechtel model appears to treat the airport landside as an integrated system but does not appear to include the airport airside. Every indication in the McCabe and Carberry report points in this direction, with one exception. That exception is a diagram which indicates that Bechtel may have intended to eventually include the movement of aircraft from the airport outer marker to the gate. This appears to be no more than a clue to the intended direction for future research with the Bechtel model, rather than an accomplished fact.

A simulation model has been developed which does appear to treat the airport as an integrated system for both the airside and landside. The model constructed by Hiatt, Gordon, and Oisen is a FORTRAN simulation model of the entire airport system on an integrated basis [40].

In 1977 Low reported on a GPSS/360 and FORTRAN model of a large metropolitan airport as an integrated system [52]. This model encompasses both the airside and landside sections of the system. In contrast with the Hiatt, Gordon, and Oisen model which is a continuous flow simulation, the Low model is a discrete-event simulation.

Although modeling the airport as a flow simulation allows a more simplified treatment and does not require as complex a simulation model as the discrete approach, it does not allow the measurement of delays for individual passengers along the individual paths they choose. The Low model can be used to study situations in which interactive effects between separate parts of the airport system have a bearing on the operation of the system as a whole. It also permits the examination of interactive effects which are encountered by passengers following a particular path but which do not appear for other passengers. The use of a discrete-event, time-oriented simulation model to represent the operation of the entire metropolitan airport system on an integrated basis has several important advantages. This method facilitates the examination of the capability of each part of the system to handle the loads imposed upon it. The discrete simulation approach also provides a means of examining interactive effects between different parts of the system. These interactive effects are likely to appear only under heavy load conditions, but a failure to take them into account properly could be costly. In the worst possible case, congestion relief measures might be applied which would be very expensive and would be very difficult to undo, but which made the problems worse instead of solving them.

Conclusion

Review of the literature of the past twenty years pertaining to the problem of airport congestion delays has indicated several trends. First, researchers concentrated their efforts on those specific parts of the total system which were actual or anticipated bottlenecks. Because of congestion problems, the aircraft approach and runway usage were investigated. At nearly the same time, the ground access section of the airport system was the subject of several studies because of delay problems. This research was carried out in attempts to ascertain the best means of relieving congestion in those locations. Almost at the same time, research was conducted for specific parts of the terminal building. While most of these studies were done in order to aid in analyzing existing congestion problems, at least one study was done in order to assess the probable future impact on terminal building congestion of the introduction of wide-bodied aircraft.

Second, this narrow focus on congestion delays in specific parts of the airport system gradually gave way to an expansion of the scope of such studies. More and more of the airport system tended to be included within the limits of such studies. Researchers apparently realized that the parts of the system which they had been investigating did not operate in isolation, but interacted with other parts of the system as well.

Third, a shift took place from the original emphasis on the airport airside as the major source of congestion delays. Since so much improvement had been made in the handling of aircraft on the airside, the expected source of congestion delays then became the handling of passengers and ground vehicles on the landside.

Fourth, the development of a total-system approach to the problem of airport congestion delays meant that delays could be investigated on a system-wide basis. While previous efforts to study the airport airside and landside had been expanded to include those sections of the airport on a system basis, the airline gate usually represented a boundary point. In other words, the scope of those studies included the airside or the landside on a system basis, but not both.

The research by Hiatt, Gordon and Oisen, and by Low represents a step forward in that the airport is analyzed in a total-system context. In this manner, the congestion delay effects for the airport as a whole can be evaluated. The effects of changes in load conditions and in facilities and operating procedures can be evaluated in terms of their impact on the overall system rather than in a sub-optimizing fashion.

The future path of research in this area is, of course, only conjectural. The authors suspect, however, that researchers will continue to model separate components of the airport system in considerable detail. They will, however, be able to utilize the total system models such as those developed by Hiatt, Gordon and Oisen and by Low to investigate the effects of changes in component design or level of operations on total system performance. The interactive effects which occur under heavy load conditions would be of special interest in this context. The authors also believe that attempts will be made to increase the abstraction of the total system models to such an extent that they become easier and less costly to use but still retain a suitable degree of sensitivity to interactive effects in the airport system.

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