AIRPORT CONGESTION MAPPED BY CATASTROPHE GEOMETRY

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الخلاصـة :

لقد أصبحت المطارات المزدحمة بالبشر في أنحاء العالم إحدى التحديات الاجتماعية والاقتصادية في هذا العقد وكما يسعى مدراء المطارات والمخططون والباحثون جاهدين للحد منها والسيطرة على فترات ذروة الحركة والتي يعتقد أنها السبب الرئيسي للازدحام ، فإنَّ هذا البحث يبحث في وسيلة بديلة لمجابهة هذه المشكلة . بافتراض أن حدوث فترات الذروة ظاهرة خارجية وبتحديد أكثر العوامل المؤثرة في القدرة الاستيعابية للمطار . فإنَّ البحث يشير إلى أن إحداث تغيير طفيف في تلك العوامل يؤدي في كثير من الأحيان الى تخفيف مشكلة الازدحام . هذا ، وتستخدم الرسومات البيانية المستخرجة من الحاسب الآلي المعتمدة على ما يسمى في علم الرياضيات « هندسة الكوارث » كأدوات إنذار مبكر لإدارة المطار لاتخاذ الاجراءات اللازمة لذلك .

ABSTRACT

Overcrowded and congested airports have emerged as one of the most visible socio-economic disorders of this decade. As the airport managers, planners, and researchers struggle to minimize and/or control the traffic peaks, thought to be the main cause of congestion, we offer an alternative solution. Assuming the incidence of traffic peaks to be an exogenous phenomenon and delineating the most-sensitive-to-airport capacity factors, we shall show that, very often, it takes only marginal change in such factors to alleviate the problem of congestion. Computer-generated graphs, based on catastrophe geometry, then serve as early warning tools to the airport management.

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1. INTRODUCTION AND STATEMENT OF THE PROBLEM

Congestion at airports (see *e.g.* [1]) caused by passenger flows is a function of three elements of the system (see *e.g.* [2]):

{passengers, airport, airlines} (1.1)

and results in serious and complex socio-economic and engineering issues. Revenues derived from transporting people and cargo are eroded by overcrowding, congestion, delays, and stoppages that bring bad publicity and losses to the system in terms of passenger health (due to mental fatigue, anxiety, exhaustion, *etc.*) and direct business impediments. If well-being is defined on the utility scale with the help of suitable transformation tables (see *e.g.* [3]), it can be shown that congestion and oversized queues resemble typical catastrophe geometry graphs. In fact, most catastrophe geometry elements and features can be validated for various socio-economic phenomena of system (1.1) under the above-mentioned conditions. We will show that principles of catastrophe geometry can not only map these unwanted phenomena but that they can also help to avoid them.

2. TOTAL UTILITY FUNCTION FOR ELEMENTS OF THE AIRPORT ENVIRONMENT: THE CATASTROPHE GEOMETRY APPROACH

2.1. Passengers as the Leading Element of the System

From [2] and [4], "passengers" are said to be the most important element of system (1.1) while [5–7] identify three factors of paramount importance to element "passengers":

{timeliness; comfort & well being; physical & mental health}. (2.1)

To evaluate effects of factors (2.1), we use a levels-of-service scale as introduced in [8, pp. 14–15] and [5] to qualitatively display crowding, queuing, and delaying (of passengers) in the airport(s). Conversion of multiattribute and mostly behavioral values into common-denominator quantitative scales is discussed in [3]. Note that from the predominant weight of "passengers" in system (1.1) it can be assumed that passenger benefit (or utility) function and the total utility function of system (1.1) have similar graphical shapes. Hence (see *e.g.* [2, p. 35] or [4, p. 7]), when mapping data are scarce, *passenger benefit function becomes a proxy for total utility function of system (1.1).*

2.2. Essentials of Catastrophe Geometry

Classical physics is essentially the theory of various kinds of smooth behavior. Other things, however, jump. Water suddenly boils. Ice melts. Stock markets collapse. These are sudden changes caused by smooth alterations in the environment. For example: an earthquake is caused by forces that gradually build up until friction can no longer hold them. The sudden changes involved were termed catastrophes (see *e.g.* [9, pp. 1–3] to convey the feeling of abrupt, dramatic jumps. The term is an appropriate one, too. In [10] and elsewhere, road traffic congestion is modeled by catastrophe geometry and yet, throughout the "ordeal", you wait sitting in relative comfort of a passenger car or a bus. When it comes to airport passengers, they usually have to endure hours standing, squashed in the airport terminal(s).

Catastrophe geometry recognizes *control variables* and *behavioral (state) variables.* An example from biology explains that the sudden appearance or disappearance of substantial colonies of species has been known to occur, and is to be expected, even with only smooth variations of the environment. Here, the appearance or disappearance (of the colonies of species) represents *a state (behavioral) variable* whereas environmental change is a control variable.

We are immediately interested in two features here (see *e.g.* [9, pp. 84–85]):

{catastrophe jumps occur when a smooth variation of controls causes discontinuous changes in behavioral variables; and, if we reverse the path of the control variables we do not necessarily reverse the path of the behavioral variables}. (2.2)

2.3. Derivation of Passenger Benefit Function and Its Mapping Through the Catastrophe Geometry

To derive a *passenger benefit function* $B(F)$ of system (1.1) assume, again, a two-dimensional space. There is a vertical-axis *behavioral variable* scale on which states of utility- (or benefit-) describing factors (3.1) are transformed into the uniform interval $\langle 0,1 \rangle$ (see *e.g.* [3, pp. 41–69]). If *passenger utility is inversely proportional to passenger density,* where *passenger density* (k) is defined for our purpose (instead of *mass/volume*) as *the number of passengers* (m) *in a certain (constant) terminal space* (q), then *control variable* F on the horizontal axis stems from the formula.

$$q = k.\tilde{\mathbf{v}}$$

(see *e.g.* in [13, p. 78]), where $\tilde{\mathbf{v}}$ is *average passenger velocity,* and from subsequent corollaries:

Passenger density (in a given terminal) is inversely proportional to *average passenger velocity.*

Passenger density is a linear (monotonically increasing) function of *the number of passengers* (in a given terminal).

Average passenger velocity is a more (of an average passenger) through the terminal in *a unit of time.*

Hence, when dealing with a variable (*number of passengers*) m per unit of time t and assuming constant terminal design, we can define F,

$$F = \Delta m / \Delta t, \tag{2.3}$$

as the *number of passengers entering the airport in a certain time interval.*

We say that for small F in $B(F)$, the slope dB/dF is always positive and increasing within $\langle F_{\min}, F' \rangle$, even though for F close to $F_{\min}$ there is only a skeleton staff present at necessary services and thus even a trickle of passengers have to queue up at, say, one server. For large F in $B(F)$, the slope dB/dF eventually becomes a decreasing function of F with

$$\lim_{F \to \infty} dB/dF = 0. \tag{2.4}$$

A graphical rendition of $B(F)$, which for large F draws on the law of diminishing returns (see *e.g.* in [11]), is presented in Figure 2.1.

2.4. Derivation of the Utility Function for an Airport and Airlines

Taking "passengers" out of system (1.1), the "airlines" and the "airport" try to maximize profit by flying as many aircraft (as close to full capacity) as possible. Thus, we can say:

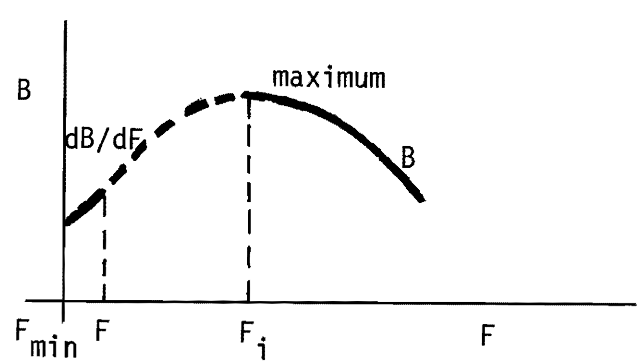

Figure 2.1. Passenger Benefit Function for Small and Large F.

Airlines and an airport profit is, generally speaking, a function of passenger flows F (defined in (2.3)) that can be processed and flown in a certain time interval. This is also the airlines' and the airport's criterion of utility. (2.5).

Despite the self-destructive quality implicitly contained in (2.5), best illustrated by Figure 2.1 for large F, we denote a combined benefit to the airport and airlines segment of (1.1) by $U_A(F)$ and call it a *combined utility*.

Figure 2.1 shows implicitly that for large F the combined utility $U_A(F)$ is decreasing and can, eventually, fall into disutility (as discussion at the end of paragraph 2.5 points out). This happens when the airport system becomes so congested that revenue-generating passengers (and hence aircraft) cannot be processed and extra help, overtime, and remedial actions have to be paid for by the airport authority. At that point everybody loses.

Assumption 2.1.

In the two-dimensional space $U_A(F)$ and F, there is a point F_0 on the F-axis in which the utility curve $U_A(F)$, being a tail of the similarly shaped $B(F)$ curve (to be easily derived from dB/dF graph in Figure 2.1; see *e.g.* [9, pp. 386–387]), intersects the F-axis. For every flow greater than F_0, $U_A(F)$ becomes disutility (of negative value).

Assumption 2.2.

A rational decision-making $f(C)$ of an airport management, contesting utility constraints U_C, where C is the physical capacity of the airport, tries to move point F_0 as far to the right on the F-axis as possible. It has three possible courses of action: (1) for U_C that cannot be stretched, an improved efficiency of passenger processing yield point $F_0{}^*$; (2) stretching the utility constraints U_C to $U_C{}'$ without efficiency improvement gives us some improvement, F_0', too; (3) combination of (1) and (2) yields, however, the most promising improvement at $F_0{}^{*\prime}$.

Both assumptions can be represented by the graph in Figure 2.2.

A very simple model of combined utility for the airport and airlines, $U_A(F)$, follows from Assumptions 2.1 and 2.2 and Figure 2.2, where

$$U_A(F) = U_C - [f(C)]F. \tag{2.6}$$

The term $f(C)$ in Equation (2.6) can be interpreted as follows: for an airport with large capacity or of flexible enough design that its capacity can be easily stretched, the management action (through its decision-making and operational expertise) amounts to very little; we can say that it converges to zero. For inadequate-capacity and/or fixed-capacity airports that cannot meet the smooth throughput demand, no matter how hard the management tries, the term $f(C)$ represents a sizeable stumbling block with its negative sign.

2.5. Derivation of the Total Utility Function and Its Limit Cases

Combining $B(F)$ with $U_A(F)$, we obtain the total utility function $U(F)$, where

$$U(F) = U_A(F) + B(F) = U_C - [f(C)]F + B(F). \tag{2.7}$$

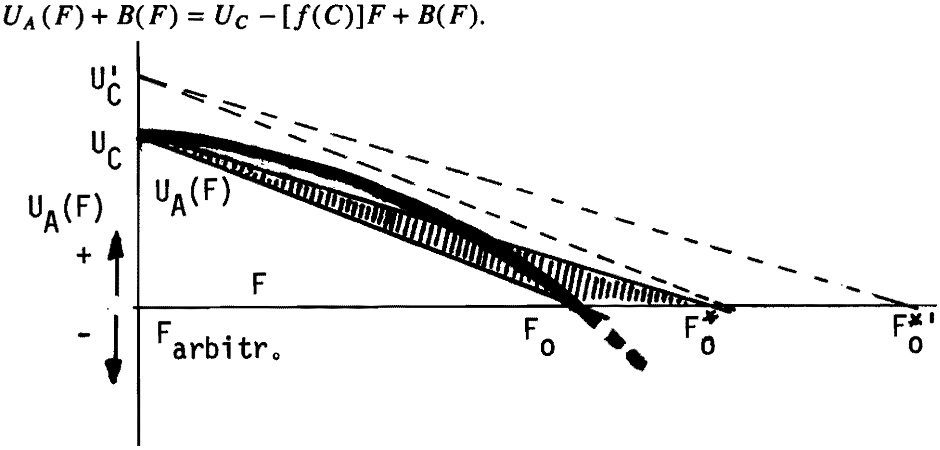

Figure 2.2. Ways of Improving the Combined Utility $U_A(F)$ *for Large* F.

Applying the catastrophe manifold criterion (see [9, p. 78]) to (3.7), we have

$$dU/dF = dB/dF - f(C). \tag{2.8}$$

Equation(2.8) demonstrates two things: (*a*) importance of the passenger benefit function for the mapping of the system's utility function and (*b*) importance of easily stretchable capacity of an airport. Absence of flexible and easy-to-stretch capacity, as follows from the definition of $f(C)$, causes the value of $f(C)$ to become large. Thus, in system (2.1) everybody suffers because the graph dB/dF (and hence dU/dF) is pushed into disutility below F-axis and, consequently, in the two-dimensional space (U, F) the graph of total utility U dips fast into disutility even for relatively small increment of "passenger tidal wave F" (defined in (2.3)).

Note: Discussion and examples of similar graphs for ecological and biological applications appear in [9, pp. 386–387].

2.6. Mapping of the Total Utility Function

For practical mapping and, ultimately, improvement of accommodating capability of total utility function (2.7), when unexpected large flows F appear, we start with a two-dimensional traffic problem analogous to our case. In a speed-flow graph of traffic congestion in [8], [12], and particularly in [10], which we reprint in Figure 2.3, the author asserts that as volume (or volume-capacity ratio) increases, speed decreases *until a fold catastrophe occurs*.

As it follows from (2.8) and subsequent discussion (including reference to [9, pp. 386–387], we shall henceforth assume that the total utility function can be mapped by the shape of the "speed-volume" curve in Figure 2.3, that we present in Figure 2.4 with the following characteristics (some of them to be discussed later):

Practical capacity is such that, under most conditions, flow of passengers F_P can be processed with at least a 'tolerable' level of utility U_T (see *e.g.* [5], [12]).

Increased practical capacity (achieved by the management action $f(C)$ is seen in Figure 2.5, where F_P is increased to F_{P*} in a response to expected "tidal wave" flow greater than F_P.

Maximum achievable capacity is such that flow-densities up to F_{MAXP*} can be processed without the effects of fold catastrophe.

2.7. Airport Overcrowding: A Behavioral Example of Catastrophe Geometry

Assuming that at some point overcrowding at an airport leads to a fold catastrophe of the total utility function, as demonstrated in Figures 2.3 – 2.4, then from (2.2) it follows that such overcrowding shows *non-reversibility* of its effects. An example of such effects, and managerial activity trying to cope with them, may be illustrated by what happened at Gatwick Airport during the Spanish controllers' strike in August 23–24, 1987. The BAA attempted to manage the situation by erecting huge marquees around Gatwick with electronic destination screens, light

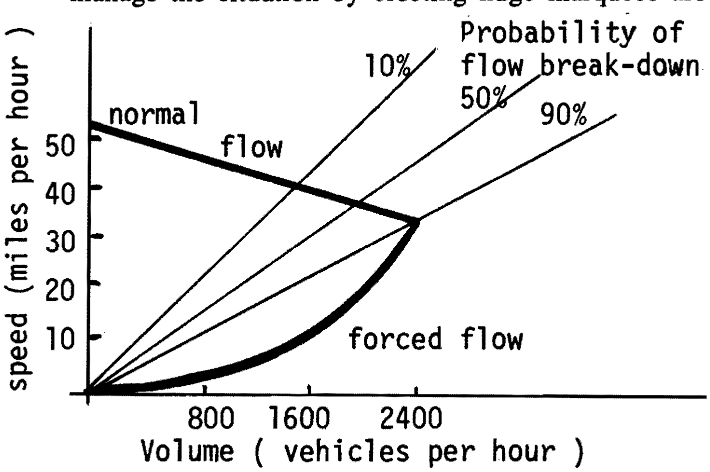

Figure 2.3. Underwood's Speed-Flow Model.

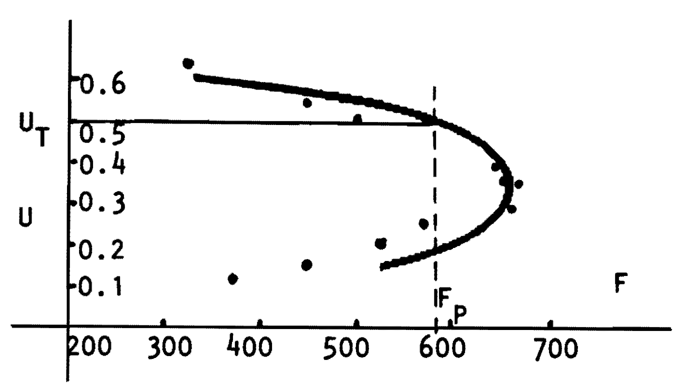

Figure 2.4. "Speed-Volume" Shape of the Total Utility Curve.

refreshments, and amusement for children. It is, of course, possible to remove some of the more desperate people (usually families with children) to nearby shelters but even then their utility (or benefit) function, in terms of factors (2.1), will improve only marginally. In this case, passengers' vacations were ruined by, at the very least, prolonged anxiety.

3. CALIBRATION OF THE 'CATASTROPHE' CURVE WITH REAL-LIFE AIRPORT DATA

Before any meaningful management action can be initiated, the mapping and calibrating of possible passenger benefit (catastrophe) curve should be done. In a real-life example, a sample of processing times, staffing at immigration desks, and passenger flows F were obtained for a certain airport with average staffing of 3 officers and processing times ranging from 1.2 to 1.5 minutes per passenger. It was established that to achieve minimum acceptable utility level at 0.5, on the scale $\langle 0,1 \rangle$, the practical capacity F_P (eventually its extension F_{P*}) would need a total utility curve (as in Figure 2.4) that folds well to the right of 600 passenger flow density.

For mapping of the passenger benefit (or utility) curve we have used a GPSS-based simulator with two variates: *a number of servers* and *length of processing time per passenger*.

The following numerical characteristics were used in the simulation runs:

Flows of passengers arriving at immigration counters, denoted by a. (3.1)

Average value of overflow, denoted by b. (3.2)

'Average contents' queue characteristic, denoted by c, stems (see [13]) from the formula

c = sum of waiting times/length of simulation. (3.3)

Flow of passengers from immigration to next destination is denoted by d, where $d = a - (b + c)$. (3.4)

State of passengers' benefit (on the importance scale) is denoted by e, where $e = d/a$. (3.5)

Reasoning. In conversion tables, 1 is the highest score for the quality benefit (or well-being). Thus, e should converge to 1 when there is an uninterrupted flow of passengers through immigration. This can happen only when $d = a$. The greater the queue lengths and overall waiting times, the lower the level of passenger well-being should be reflected. Thus, for a very small exiting flow a, should be small too.

Using Figure 2.4 as a parable, d then becomes our horizontal-axis variable, *i.e.*

$$F = d, \tag{3.6}$$

and for the vertical axis (represented by the passenger-benefit characteristic), the behavior of e in (3.5) comes very close to our purpose. Thus, we postulate:

$$U = e. \tag{3.7}$$

Simulation runs for the above conditions are summarized in Tables 3.1 and 3.2.

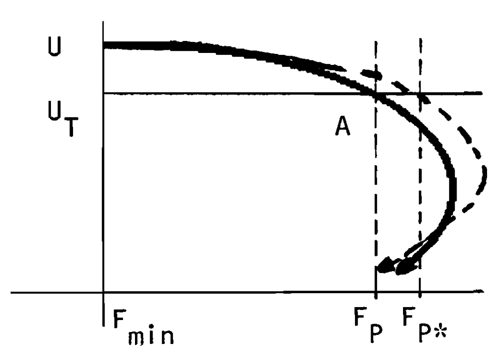

Figure 2.5. Increased Practical Capacity in Figure 2.4.

Table 3.1. Results for 3 Officers and 1.5-Minute Processing Time.

a	*b*	*c*	*d*	*e*
156	71	0.18	85.0	0.55
468	234	6.50	228.0	0.49
647	391	15.00	241.0	0.38
828	502	26.60	299.0	0.37
981	622	39.90	320.0	0.33
1088	730	52.10	305.9	0.29
1150	796	59.80	294.2	0.26
1244	919	74.60	250.4	0.21
1319	970	84.00	265.0	0.21
1420	1117	100.50	202.5	0.15
1546	1316	120.10	109.9	0.08
1690	1515	140.90	34.1	0.03
1798	1679	162.00	−43.0	−0.03

Table 3.2. Results for 3 Officers and 1.2-Minute Processing Time.

a	*b*	*c*	*d*	*e*
503	184	5.4	313	0.63
667	305	12.7	349	0.53
884	394	20.7	419	0.48
1006	488	31.4	486	0.48
1313	683	58.9	571	0.44
1463	749	77.6	586	0.41
1570	935	98.1	536	0.35
1628	981	107.1	539	0.34
1992	1408	157.8	426	0.22
2154	1622	184.1	346	0.17
2314	1766	212.3	335	0.15
2615	2144	275.1	225	0.09

Table 3.3. Results for 4 Officers and 1.5-Minute Processing Time.

a	*b*	*c*	*d*	*e*
498	173	4.8	320.0	0.65
812	344	17.2	450.0	0.56
1012	482	30.6	499.0	0.56
1651	912	98.6	640.0	0.39
1731	964	109.5	657.5	0.38
1771	981	113.8	676.2	0.38
1900	1114	134.0	652.0	0.35
2063	1329	159.9	575.0	0.28
2148	1465	175.4	507.6	0.24
2341	1692	207.0	442.0	0.19
2482	1872	231.0	380.0	0.16

Table 3.4. Results for 4 Officers and 1.2-Minute Processing Time.

a	b	c	d	e
481	111	2.7	367.3	0.77
833	262	13.2	557.8	0.67
1011	350	22.2	638.8	0.64
1243	448	35.6	759.4	0.62
1400	521	47.0	832.0	0.60
1461	548	51.3	861.7	0.59
1720	680	76.5	963.5	0.57
1918	806	102.3	1009.7	0.53
1994	863	111.2	1046.8	0.53
2221	993	147.4	1080.6	0.49

Using (3.4), (3.6) for horizontal- and (3.5), (3.7) for vertical-axis scales, we map two different-efficiency passenger benefit (or utility) curves in Figures 3.1 and 3.2. The difference $F_{P*} - F_P$ (*i.e.* 500−300 = 200 passengers) is the result of improved efficiency and management action $f(C)$.

Neither F_P in Figure 3.1 nor F_{P*} in Figure 3.2 is sufficient to meet our objective (*i.e.* $F_{P*} > 600$). The problem and possible solution reverts now to one of utility limit increase U_c', presented as strategy (2) or, better still, strategy (3) in Assumption 2.2 and depicted by point F_0' (or F_0*') in Figure 2.2. The solution, *i.e.* to obtain F_{MAXP*}, lies in increasing the number of immigration officers (working more effectively). The appropriate runs are seen in Tables 3.3 and 3.4 with the passenger benefit curves mapped in Figures 3.3 and 3.4.

Management action in Figure 3.4 should then be able to accommodate most, if not all, possible contingencies.

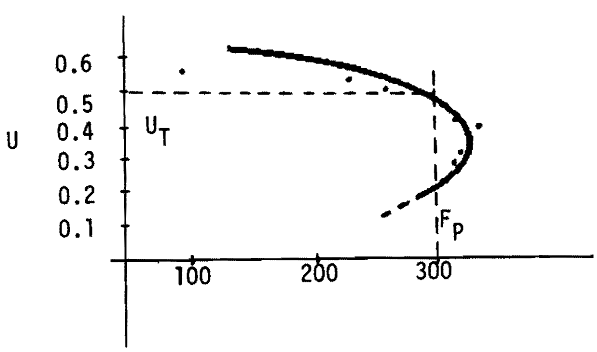

Figure 3.1. Passenger Benefit Curve for the Data in Table 3.1.

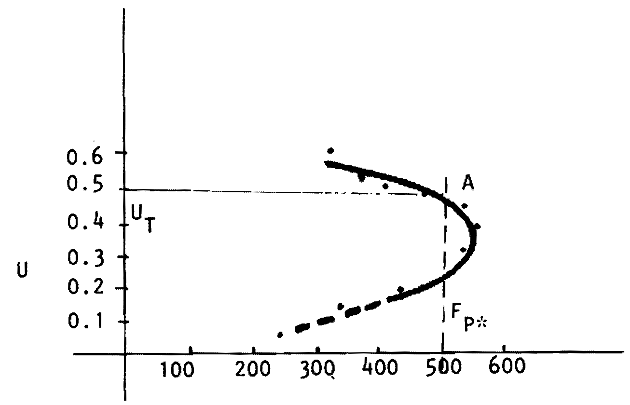

Figure 3.2. Passenger Benefit Curve for the Data in Table 3.2.

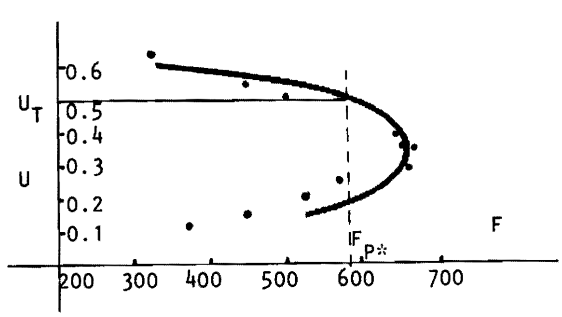

Figure 3.3. Passenger Benefit Curve for the Data in Table 3.3.

4. TECHNIQUES TO AVOID AIRPORT CONGESTION

4.1. Most Effective Use of Existing Capacities

The goal is to maximize available practical capacity, denoted by point $F_{\mathrm{MAXP}^{*}}$, on F-axis, where $F_{\mathrm{MAXP}^{*}}$ also includes point $F_0{}^{*\prime}$. From Assumption 2.2 and Figure 3.3 it means:

$$F_{\min} F_{\mathrm{MAXP}^{*}} = \max[F_{\min} F_{\mathrm{P}}] + F_{\mathrm{P}} F_{\mathrm{MAXP}^{*}} \ . \tag{4.1}$$

The first element on the right-hand side of (4.1) calls for maximum effective use of existing practical capacity; essentially alternative (1) in Assumption 2.2. From computer simulations (see *e.g.* [16]) we obtain clear indications of bottlenecks and of what can be done to stretch existing capacities.

Technology plays an even greater role in maximizing existing capacities, to wit: magnetic encoded tags, automated customs and federal inspection procedures, automated assignment of manned service desks according to prescanned incoming passenger flows, *etc.*

4.2. Improving Practical Capacities

The second element on the right-hand side of (4.1) maximizes feasible capacity improvement (*i.e.* alternative (2) or, better still, alternative (3) in Assumption 2.2), for example, increasing the capacity of airport buildings, which is much more difficult to achieve. We can conceive the use of basement, or ground floor space to extend immigration service space at the expense of unused space or marginal services or the development of auxiliary (collapsible/mobile) counters equipped with computer, telephone and power plug-in capabilities. All the while, however, remember that huge, very costly, and untested management activities that try to contest utility (*i.e.* capacities) constraints U_C, usually lead to drop in total utility. For details, see discussion of Equation (2.6) and Equations (2.7)–(2.8).

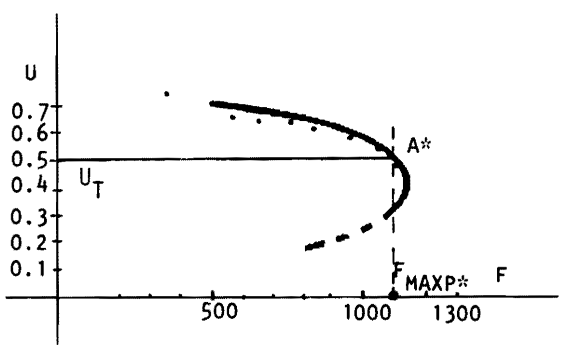

Figure 3.4. Passenger Benefit Curve for the Data in Table 3.4.

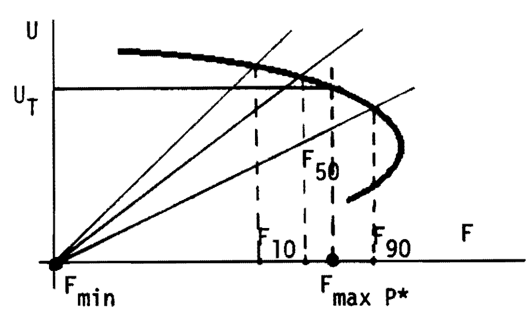

Figure 4.1. Real-Life Utility (Benefit) Curve with Fold Catastrophe Probabilities.

4.3. Early Warning Algorithm

To be able to cope with unexpected "human wave" greater than F_{P*} without catastrophic effects, briefly discussed in paragraph 2.7, some sort of early warning system would be nice to have.

Let us assume that a combination of management actions achieves

$$\{f(C)\} = F_{\min} F_{\text{MAXP}*} \tag{4.2}$$

as, for example, in [17, pp. 27–28].

Assume also an operable computer system to be at our disposal. To design an early warning algorithm, we introduce the graph from [10] seen here in Figure 4.1 and store it in the computer memory.

Next, we require the system to scan a certain daily passenger traffic profile that occurred a week (or its multiples) ago (for week is the basic period in the air traffic scheduling) and project this daily profile flow (with all available updated and upgraded information) into the immediate future. This daily profile forecast is based on incoming scheduled and nonscheduled traffic data, known delays based on weather conditions and specific routes, present state of how individual services are named (under what conditions), and a host of other relevant factors. Then, based on current operational conditions automatically entered into an algorithm (see *e.g.* [18]), the computer invokes the closest-to-reality scenario, runs the terminal flow simulation, and, indicates the position of the (upcoming) flow-point F on the total utility curve in Figure 4.1 (stored in the memory). Finally, it should list all known managerial actions available at this point to that particular airport to that using them we can stem further congestion degeneration (into a full-fledge catastrophe).

The urgency of acquiring a management tool to detect, evaluate, map and cope with giant congestions is underscored by the fact that even now, let alone in the near future, most of the world's airports already experiencing conditions that can easily trigger (and occasionally have) a sort of social catastrophe which can be viewed as the disease of the nineties and, indeed, of the next century.

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