Lift Traffic Analysis 1890-1960

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Abstract. A survey of recent literature on lift traffic analysis reveals that only one pre-1950 source is referenced in this body of work: "The Probable Number of Stops Made by an Elevator," Bassett Jones, *General Electric Review,* August 1923. Although this investigation included a survey of Elevcon papers from 1986 to 2014, and thus had an international scope, a detailed search for non-English articles was not undertaken as part of this research.

While the number of works that include Jones' 1923 article in their bibliography highlights the significance of this article, the fact that only one source is referenced from the period from 1890 to 1960 prompts the following questions. 1.) What was the intellectual context for Jones' work? And, 2.) Were there others who sought to establish a mathematical basis for determining lift traffic needs?

This paper will examine the history of lift traffic analysis from 1890 to 1960 and will chronicle the initial development and articulation of quantified criteria and mathematical formulas designed for determining the proper number of lifts and required traffic flow. The early history of this subject defines the foundation for contemporary work as well as serving as a reminder that, while many things have changed (often dramatically) since the first half of the 20th century, others appear (perhaps surprisingly) to have remained the same.

1 INTRODUCTION

This investigation uncovered a surprising wealth of material related to this topic. The related subjects of the proper number of lifts for a given building and their associated traffic metrics were common topics of discussion from 1890 to 1960. However, while this subject matter was occasionally the topic of dedicated works, it was more often found imbedded in general works on lift design and engineering. Finding this material required using a variety of searches through various online databases (including Google Books) and surveying lift books from this period. The following paper (in spite of its length) represents an edited view of the material discovered during this investigation. The works discussed below represent an effort to trace the primary ideas developed during this period. However, as with many research efforts, this paper should be considered the foundation upon which a more comprehensive work may be constructed.

2 1890 - 1899

A critical characteristic of the history of lift traffic analysis between 1890 and 1960 is the presence of lift operators and starters. The fact that lift operation, from doors to traffic scheduling, was directly controlled by people – in real time – distinguishes this period from the present day. Thus, the challenge faced by lift engineers included predicting passenger behavior as well as the behavior of lift system operators. The gradual emergence of metrics and formulas that serve as the foundation for modern lift traffic analysis occurred against this human backdrop.

By 1890 architects and engineers, building owners and users, and the lift industry were all well aware of the importance of providing good lift service to commercial buildings. The normative method of operation was to run the lifts on a predetermined schedule or interval of service. The common approach was to have the lifts depart from the ground floor at set intervals, travel to the top of the building – regardless of the need to drop off or acquire passengers at the top floor – and then return to the ground floor. This ensured a consistent flow of lifts throughout the building. Typical intervals in the 1890s ranged from 30 to 45 seconds, depending on the size of the building. Large buildings typically employed “Starters,” who were charged with directing the lift operators’ actions and ensuring that an adequate traffic flow was maintained.

The need for the constant presence of moving lifts was due, in part, to the lack of adequate signaling systems that allowed waiting passengers to summon cars. In the beginning it was not uncommon for passengers to simply stand adjacent to a shaft and call (quite loudly) “up” or “down” to alert the lift operator to the need to stop. The first hall call buttons and in-car indicators alerted the operator of a waiting passenger and their desired direction of travel, however these systems provided this information while the car was moving, such that the alert came – in theory – with just enough warning that the operator could stop their car at the required floor.

While the operation of lifts on a set schedule was believed to offer the best service, it did not constitute a basis for determining how many lifts a given building required. By 1890 the importance of the lift’s “round trip time” was known and was defined as dependent on the “number of stops for receiving and discharging passenger and (the) car speed” [1]. Lift traffic was divided into two categories: local (also referred to as “way” or “accommodation”) and express service. The impact of car size and configuration was also recognized, with a suggested maximum area of 49 sq. ft., with the preferred plan being wide and narrow with the door as wide as possible [1]. Finally, one of the first “rules of thumb” stated that the “number of elevators is proportionate to the cubic contents of a building” [1].

In 1893 engineer George Hill gathered one of the first data sets on lift operation. He surveyed twenty buildings in New York City and collected information on: 1.) the number of stories served, 2.) the number of lifts, 3.) the number of offices, 4.) the interval between trips, 5.) the working speed (recognized as distinct from contract speed), and 6.) the car size and the number of passengers carried [2]. Hill’s examination of the data led him to a series of “independent observations”: 1) that an elevator car travels from one-third to one-eighth of the time, 2.) the time spent in traveling increases with the number of stories served, 3.) the time spent in traveling decreases with the increase in the number of offices on a floor, and 4.) the time that the elevators are not running will thus be seen to fix the number, as well as the size and the speed [2]. Hill claimed that he had attempted to “reduce the results” of his investigation “to some uniform law,” however this proved to be “very difficult, as the service in each building depends upon the class of tenants” [2].

3 1900 - 1909

The first decade of the twentieth century saw the first attempts to derive Hill’s hoped for uniform law for determining lift needs. In 1901 consulting engineer Charles G. Darrach (1846-1927) proposed the first formula to determine lift service where a = car area in sq. ft., A = office area in sq. ft., and T = total trips per hour (Eq. 1) [3]. Darrach had also gathered information from existing

$$a = \frac{A}{T \times 22} \qquad (1)$$

buildings and, in addition to his formula, he published the first lift data tables for existing buildings. These tables included the number of stories, office area above the first floor, number of lift cars, building sq. ft. served per car, car area, trips per hour and average operating speed. Table 1 represents one of Darrach's tables. His formula and data tables were reprinted in two editions of

Table 1 Darrach, Lift Data (1901)

	Stories	Office area above first floor	No. of cars	Building sq. ft. served per car	Area of car sq. ft.
St. Paul Building, New York	25	83,200	6	13,900	23.6
Empire Building, New York	21	150,000	10	15,000	42
North American Building, Philadelphia	18	90,500	5	18,100	27.6
Real Estate Trust Building, Philadelphia	17	155,650	10	15,560	23.7
Bowling Green Building, New York	16	222,000	9	24,700	…
Land Title Trust Building, Philadelphia	15	66,400	5	13,300	29.6
Stephen Girard Building, Philadelphia	13	67,000	4	16,750	29
Drexel Building, Philadelphia	10	180,000	6	21,700	21.4

Frank E. Kidder's *The Architect's and Builder's Pocket* (1904 and 1908) [4]. Interestingly, both editions also included an additional data set provided by Otis engineer Charles H. Kloman (Table 2). Kloman apparently also provided insights into Otis' approach to lift traffic, as Kidder reported

Table 2 Kloman, Lift Data (1904)

Building	No. of Elevators	No. of Floors	Total Floor Area	Floor area per Elevator
Broad Exchange Building	18	20	465,540	25,864
Empire Building	10	20	170,000	17,000
Park Row Building	10	25	315,000	31,500
Bank of Commerce Building	7	19	172,000	24,571
Atlantic Mutual Building	6	18	162,000	27,000
S.E. Cor. Broadway & Maiden Lane	6	18	129,000	21,500
American Exchange Bank Building	3	16	72,000	24,000

that: "the officers of the Otis Elevator Co. have come to the conclusion that the best service is obtained with a large number of small cars having a capacity of not over 15 passengers, rather than with fewer large cars" [4].

The key figure in this decade was engineer Reginald P. Bolton (1856-1942). In addition to publishing numerous articles on lift engineering and traffic design, in 1908 he published the first book devoted to this subject: *Elevator Service: Operating Conditions and Proportions, with diagrams, formulas, and tables for passenger travel, schedule and express operation, with the relation of the elevators to the building, and proportions and loads of cars*. Bolton divided his subject into nine chapters: "The Problem of Vertical Transportation," "Operating Conditions," "Passengers and Operators," "Rating the Work of the Elevator," "Computing the Average Work," "Express Service," "The Shape and Size of the Car," "Load and Speed Combinations," and "The Building and its Proportionate Service." He also provided a glossary of 36 lift terms as well as a variety of charts, tables and diagrams that illustrated his topic. Like his predecessors, Bolton's work was based on an analysis of data collected from existing buildings (Table 3).

Table 3 Reginald P. Bolton, Lift Data (1908)

SCHEDULE INTERVALS			
In existing buildings in New York City			
Expresses			
Floors	Net Area per Floor	Number of Cars	Schedule (seconds)
10 - 19	17,000	9	17
11 - 20	12,000	6	25
10 - 19	8,750	5	30
13 - 25	5,000	4	34
11 - 18	6,800	3	45
Locals Combined With Express			
10	17,000	9	17
10	10,900	6	15
10	8,750	5	24
10	6,850	5	24
13	5,300	4	22.5
14	6,700	3	40
Locals Only			
25	7,600	10	18
24	4,375	6	26.5
19	3,500	5	27.6

The unique aspects of his efforts included a diagram depicting the normative lift traffic pattern found in a typical office building (Fig. 1) and a series of formulas intended for use in traffic analysis. The formulas used a series of variables that addressed a wide range of lift operation attributes (Table 3). His formulas were predicated on a decidedly idiosyncratic constant derived from his observations of lift traffic, which he labeled the "Bolton Rating." This term defined a lift's "mean work," or the typical number passengers carried per trip, as 0.4 of the number floors served by a lift [5]. He also derived a series of constants from his observations of lift traffic (Tables 4 & 5).

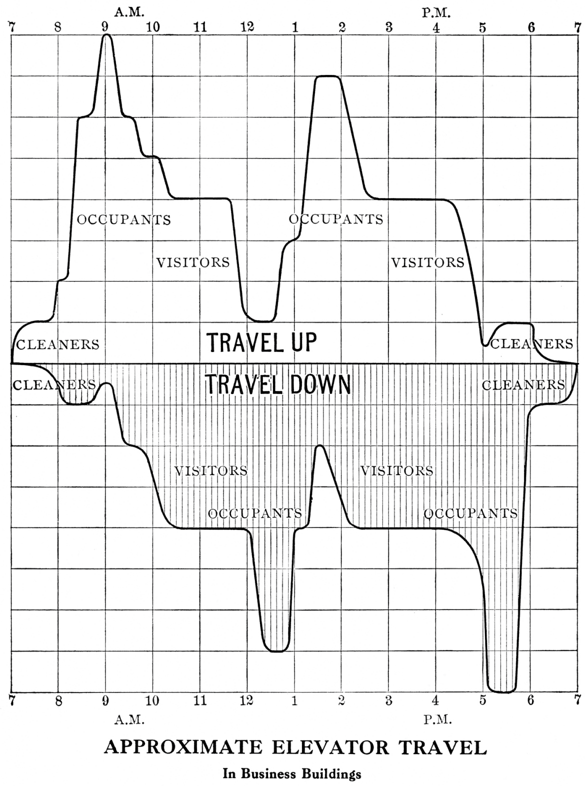

Figure 1 Bolton, Typical Office Building Lift Traffic Pattern (1908)

Table 3 Reginald P. Bolton, Formula Variables (1908)

A	Occupied area per floor of the building in square feet.
a	Occupied area per elevator, in square feet.
c	Occupied area per car per floor in square feet.
o	Occupied area per passenger or occupant in square feet.
n	Number of elevators.
f	Floors served by the elevator, always above the ground floor.
t	Traveling time, or time occupied by the motion of the car, in minutes.
l	Loading and unloading time in minutes.
s	Mean speed between average landings in feet per second.
i	Schedule or interval between starts of the elevator.
r	Round-trip time of a local elevator in minutes.
e	Floors run past by an express elevator.
d	Time of the express distance in minutes.
R	Total round-trip time of an express elevator, in minutes.
p	Passengers per hour, in each direction.
h	Total height of the local floors served, in feet.

Table 4 Bolton, Lift Formula Constants (1908)

Average distance between landings	24 feet
Number of landings	.4(total number of floors up and down)
Time per landing (door handling, etc.)	5 seconds
Time per passenger to enter and exit	2 seconds
Time per visit to top floor & gate handling at ground floor	9 seconds

Table 5 Bolton, Lift Formula Constants (1908)

Nominal Speed (feet/minute)	600	500	400	300
Mean Speed (feet/minute)	440	380	320	260
Mean Speed (feet/second)	7.33	6.33	5.33	4.33

His equation to determine round trip time (calculated for a number of different operating speeds) reveals his general approach to deriving his formulas (Eq. 2). Bolton, however, did not explain the

600 ft./min. $r = (f \text{ x } .1345) + .15$ (2)

500 ft./min. $r = (f \text{ x } .1432) + .15$ (2)

400 ft./min. $r = (f \text{ x } .1550) + .15$ (2)

300 ft./min. $r = (f \text{ x } .1723) + .15$ (2)

origin of the constants used in these formulas. An analysis of Bolton's approach reveals that the constant used in the bracket with *f* (the floors served by the elevator) was derived as follows: (Average distance between landings ÷ Mean Speed in feet/second) + .4(Time per landing + Time per passenger to enter and exit) + (Time per passenger to enter and exit at ground floor). This formula, when applied to the various lift speeds produced a constant that expressed the speed per floor in terms of feet per minute (Eq. 3).

$$600 \text{ ft./min.} \qquad (24 \div 7.33) + .4(5 + 2) + 2 = 8.07 \text{ ft./sec. or } 0.1345 \text{ ft./min.} \qquad (3)$$

The .15 added to the end Eq. 2 was the 9 seconds, expressed in terms of minutes, allotted for the car's visit to the top floor and gate handling at ground floor. Thus, his formula attempted to account for the fact that most lifts did not operate at their contract speed, that they did not stop at every floor, and that the passengers' and elevator operators' actions were factors in determining the total lift operating speed. The summation of his work was a massive fold-out chart (placed at the back of his book) that allowed users to determine the number of express and local elevators needed for a given building to meet a desired interval of service.[1]

Although Bolton's book was the subject of numerous reviews, it is difficult to gauge its actual influence, particularly because it was self-published and thus it is impossible to determine its distribution or marketing.

4 1910 - 1919

The drive to gather data on lift use and develop formulas to calculate required lift service continued into the next decade. In 1912, commercial engineer Edmund F. Tweedy and electrical engineer Arthur Williams co-authored a book titled *Commercial Engineering for Central Stations*, which included a series of "papers," many of which had been previously published in *Power* and the *Electrical World*. The papers addressed a wide range of topics including coal heating systems, generating electricity, electrical power use, refrigeration and cooling systems, and "The Passenger Elevator in Office Buildings" [6]. Tweedy (1876-1949) authored the chapter of lifts, a fact that was revealed the following year when he published a revised version of his paper titled "Operating Characteristics of the Modern Passenger Elevator" [7].

Tweedy collected an impressive data set on lifts in 26 buildings in New York City that included: 1.) the net rentable area above the ground floor, 2.) the number of floors above the ground floor, 3.) the number of elevators (local and express) and the floors served, 4.) the car dimensions, 5.) the sq. ft. of rentable floor area per sq. ft. of car area, the lift rated capacity in lbs., 5.) the lift type (hydraulic, electric drum or electric traction), 6.) the electric lift motor rating, 7.) the average miles traveled per day (excluding Saturdays, Sundays and Holidays), 8.) the average round trip time in minutes, 9.) the average time interval in seconds, and 10.) the average speed (including stops) in ft. per minute). Tweedy also discovered that, in some cases, the lift system had been predicated on "furnishing transportation for all of the building occupants within a certain specified time of arrival, say within a period of 20 minutes or 30 minutes" [6].

While Tweedy did not use this data to develop lift design formulas, he followed Bolton's lead and developed a chart intended to meet this need: "Chart for determining the number and size of elevators required for office buildings of a given total occupied floor area" (Fig. 2) [6]. The chart allowed the user to select the time period in which to "move all building occupants in one direction" (20 or 30 minutes), the maximum round trip time, and car size. Interestingly, building size was given in terms of occupied floor area (20,000 to 180,00 sq. ft.) rather than building height. The chart could be used to determine local and express lift service, with each considered separately relative to the portion of the building served.

[1] The chart, due to its size, does not lend itself to reproduction at a small scale. A large reproduction will be available at the symposium.

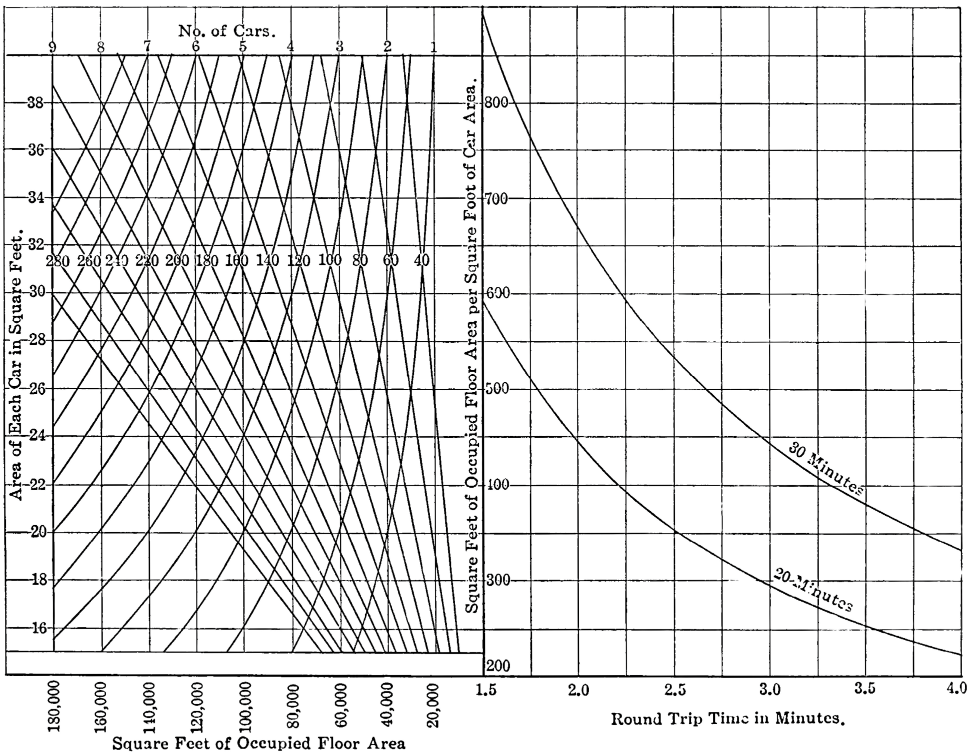

Fig. 2 Tweedy, Chart for determining the number and size of lifts (1913)

In 1914 M. William Ehrlich published a three-part article on lift systems. Although Ehrlich made no mention of Bolton's work, he was either aware of his work or, perhaps, had read a review of the book written by William H. Bryan. Bryan had suggested that the "Bolton Rating" – the mean work or typical passengers carried per trip was 0.4 of the number floors served by a given lift – would be more accurately expressed as 0.5 [8]. Ehrlich used the higher number in his formulas and also assumed that one lift should be allocated per 24,000 gross sq. ft. and, like Bolton, he employed numerous variables (Table 6).

Table 6 Ehrlich, Lift Formula Variables (1914)

E	Number of elevators required
A	Square feet of gross building area served
f	Story at which express run terminates
n	Total number of stories served
s	Speed of elevator in feet per minute
Tl	Local round trip time in minutes
Te	Express round trip time in minutes
Ml	Miles traveled per hour by local
Me	Miles traveled per hour by express
CI	Current consumed per hour by local in kilowatt hours
Ce	Current consumed per hour by express in kilowatt
pl	Passengers carried per hour by local one way up or
pe	Passengers carried per hour by express one way up or

Ehrlich's key formulas addressed round trip times for express and local lifts as well as the number of lifts required (Eq. 4 -6).

$$\mathrm{Te} = \left(\frac{25}{s} + \frac{5}{100}\right)n \tag{4}$$

$$\mathrm{Tl} = \left(\frac{25}{s} + \frac{1}{10}\right)n \tag{5}$$

$$E = \frac{A}{24,000} \tag{6}$$

He described Eq. 6 has having been "well substantiated" and "based on existing systems in the larger cities of the United States" [9]. He also noted that "the unit area of the elevator car and its traffic limitations have been included in the computation" [9]. Ehrlich offered no explanation for his various constants, however, he did provide a table that "embodied" their "computations" and that facilitated "the ready understanding of the various formulas" (Table 6) [9]. Ehrlich's formulas replaced Charles Darrach's in the 16th edition of Frank Kidder's *Architect's and Builder's Pocket-Book* [10]. However, two new formulas were added that were not included in his original article (Eq. 7 & 8). These were designed to find the number passengers carried one way, per hour by local (*pl*) or express (*pe*) lifts. Interestingly, Ehrlich's formulas were also featured in another general reference book, Gillette and Dana's *Handbook of Mechanical and Electrical Cost Data*, however in this work the passenger formulas were not included [11]. Kidder noted that information on lifts had been "furnished" by the Otis Elevator Company, the H.J. Reedy Company, Reginald P. Bolton, Charles E. Knox, M. William Ehrlich, and "others" [10]. The absence of the additional formulas in

Table 6 Ehrlich, Lift Data (1914)

1	2	3	4	5	6	7	8	9	10	11	12
Building		Number of Elevators Required					Round Trip Time in Minutes				*f*, or express run, in stories
Number of stories	Gross area, sq. ft.	Total car area, sq. ft.	Cars at 25 sq. ft.	Cars at 30 sq. ft.	Cars at 40 sq. ft.	By formula (1)	Tl at 350 ft. per min.	Tl at 500 ft. per min.	Te at 500 ft. per min.	Te at 600 ft. per min.	
8	80000	89	4	…	…	4	1.3	…	…	…	…
10	100000	111	4	…	…	4	1.7	…	…	…	…
12	120000	133	5	…	…	5	2	…	…	…	…
14	210000	262	11	9	…	9	2.4	2.1	…	…	…
16	240000	300	12	10	…	10	2.7	2.4	1.6	…	10
18	270000	337	14	11	…	11	…	2.7	1.8	…	11
20	300000	365	15	13	10	13	…	3	2	1.8	12
25	375000	577	…	19	15	16	…	…	2.5	2.3	15
30	800000	1221	…	40	30	33	…	…	3	2.7	17

$$\mathrm{pe} = \frac{300}{\mathrm{Te}} \tag{7}$$

$$\mathrm{pl} = \frac{300}{\mathrm{Te}} \tag{8}$$

Gillette and Dana's book, which was published two years after Kidder, suggests that they were, perhaps, devised by someone other than Ehlich. In spite of the presence of Erhlich's formula, Kidder cautioned readers that: "No iron clad rules can be given for all types of buildings, but the larger office buildings, loft buildings or light manufacturing buildings have been sufficiently regular in design to warrant some general rules, based upon experience; even in these cases, however, the governing conditions vary with the size of the building" [10].

Perhaps the most interesting attempt to devise lift formulas during this decade is found in Hermann Gumpel's 1916 article: "Mathematical Laws Governing Elevator Floor Capacity in Office Buildings From the View Points of Efficiency and Safety" [12]. Gumpel (1876-1929) was born in Lübeck and very likely received his engineering education in Germany. He immigrated to the United States in the early1900s, worked as a consulting mechanical engineer in Philadelphia and Chicago, and patented a double-deck elevator system in 1916. He authored a series of articles on lift traffic design in which he offered several lift formulas, which employed a number of variables, including the first that sought account for the impact of visitor traffic (Table 7).

His work paralleled earlier efforts in that he also failed to explain how he derived numerous constants, such as the allowance for visitors using elevators during rush hour (*b*). Gumpel proposed two primary formulas: the first was designed to estimate the number of lifts required – predicated on the desired interval of service (Eq. 9). He claimed that: "To arrive at satisfactory results in elevator traffic problems we have to consider maximum conditions only, as they occur during rush time in the early morning hours, before and after lunch time and late in the afternoon" [12]. Thus, his second formula (Eq. 10) was used to estimate the number lifts needed to meet a 20 to 30 minute period in which all building occupants could be moved in one direction. He assumed two sq. ft. per passenger, thus the car capacity was $F \div 2$.

Table 7 Gumpel, Lift Formula Variables, 1913

N	Number of cars in a battery of elevators
a	Interval of travel (30 to 50 seconds)
t	Round trip time in seconds during periods of maximum traffic, including time for landing and loading at the main floor
A	Rentable floor area to be served by the elevator battery
o	Rental area occupied by one person in a building expressed in sq. ft. (about 80 to 140 sq. ft.)
b	Allowance for visitors using elevators during rush hours (10 to 40)
F	Ground space of one car expressed in sq. ft.
T	Time in seconds during which all occupants of a building have to be moved either direction to or from their place of business (about 20 to 30 minutes).

$$N = \frac{t}{a} \tag{9}$$

$$T = \frac{F \times T}{2 \times t} \tag{10}$$

He then determined the total number of passengers (including visitors) to be served (Eq. 11), which allowed him to arrive at a formula that gave the number of cars required to move a building's occupants in a set time period (Eq. 12). Gumpel was equally interested in the use of lifts during

$$\frac{A}{o - b} \tag{11}$$

$$N = 2\frac{t \times A}{(o-b) \times T \times F} \tag{12}$$

emergencies, and imagined an evacuation plan whereby lifts would "ascend to a certain floor without stop, accept there as many passengers as possible, descend to the main floor and discharge there their human load. This will repeat, till all occupants of the building are removed" [12]. He devised a series of formulas, based on his primary formulas, to determine the number of lifts required to empty a building in a set time period. The various formulas addressed the number of occupants per floor (Eq. 13), the number passengers per car (in an emergency situation he assumed 1.75 sq. ft. per person) (Eq. 14), the number of trips required (Eq. 15), and the time required to remove all occupants from a given floor (Eq. 16). From these he derived a formula that allowed him to determine the total time required to empty all the floors served by a group of lifts (Eq. 17).

$$\text{Occupants per floor} = \frac{A_n}{o-b} \tag{13}$$

$$\text{Number of passengers per car in one trip} = \frac{F \times N}{1.75} \tag{14}$$

$$\text{Number of trips to remove all occupants from one floor} = \frac{A_n}{o-b} \div \frac{F \times N}{1.75} = \frac{1.75A_n}{(o-b) \times F \times N} \tag{15}$$

$$\text{Time required to remove all occupants from one floor} = \frac{1.75A_n}{(o-b) \times F \times N} \times t_n \tag{16}$$

Time required to empty all the floors served by a group of lifts =

$$\frac{1.75}{(o-b) \times F \times N}\left(A_n t_n + A_{n-1} t_{n-1} + A_{n-2} t_{n-2} + - - - - - - A_2 t_2 + A_1 t_1\right) \tag{17}$$

It is difficult to assess the impact of Gumpel's efforts as they were not published in an engineering journal or the proceedings of an engineering society – they were published in *Buildings and Building Management*, which described itself as "the only magazine in existence dealing with building construction, building operation and management from the owners' standpoint." However, as will be seen, one of the most important early works on lift traffic also appeared in this publication.

5 1920 - 1929

At the 1920 annual meeting of the Elevator Manufacturers' Association, Howard B. Cook (1888-1971), a young engineer associated with the Warner Elevator Company of Cincinnati, presented a paper titled "Passenger Elevator Service" [13]. This paper marked the first time a member of the lift industry offered a mathematical means of determining lift service. Cook used a number of constants that addressed a typical range of lift operation characteristics (Table 7). He also used a surprisingly small number of variables (Table 8). His formula to determine single trip time (Eq. 18) served as the basis for his formula to determine round trip time, in which Cook doubled the single trip time and added 10 seconds to account for the lift starting and stopping at the first floor (Eq. 19).

Table 7 Cook, Lift Formula Constants (1920)

Distance between floors	12 feet
Elevator speed	400 feet per minute (6.66 ft. per sec.)
Rate of acceleration and retardation	4 ft. per second per second
Average speed during period of acceleration or	3.33 feet per second
Time required for lift acceleration or	1.67 seconds
Time required to travel one floor at full speed	1.8 seconds
Number of stops	Equal to the number of passengers unless the number of passengers per trip exceeds the number of floors above the first floor
Upper floors: time required to open and close the car/shaft doors	3 seconds
First floor: time required to stop/start, open and close car/shaft doors, and to equalize the schedule between lifts due to traffic fluctuation	7 seconds
Time required for one passenger to enter or exit the car	3 seconds
Average total first floor time (passengers + start/stop time)	10 seconds

Table 8 Howard, Lift Formula Variables (1920)

R	Round Trip Time
F	Number of floors above first floor
P	Number of Passengers
T	Number of passengers carried per
E	Number of elevators

$$1.8F + 1.67P + 3P + 3P \quad \text{simplified to} \quad 1.8F + 7.67P \tag{18}$$

$$R = 2(1.8F + 7.67P) + 10 \quad \text{simplified to} \quad R = 3.6F + 15.34P + 10 \tag{19}$$

However, Cook stated that his round trip formula would not provide accurate results if the number of passengers per trip exceeded the number of floors above the first floor. To adjust for this situation Cook added 4 seconds to the round trip time for each additional passenger exceeding the number of floors. He did not, however, explain how he determined that 4 seconds was an appropriate adjustment nor did he explain how he derived the formula to determine the round trip time for this situation (Eq. 20).

$$R = 3.6F + 15.34F + 4(P - F) + 10 \quad \text{simplified to} \quad R = 14.94F + 4P + 10 \tag{20}$$

Cook apparently began with a baseline where the number of passengers equaled the number of floors ($P = F$), then he substituted F for P in Equation 19 and he expressed the need to account for additional passengers and their associated additional time as $4(P - F)$.

He next sought to determine the number of passengers carried per hour, which he stated was “equal to the number of round trips per hour multiplied by the number of passengers per trip” (Eq. 21) [13]. Cook then derived the value of P in terms of F and R from the round trip formula (Eq. 22), which allowed him to determine number of passengers carried per hour in each direction, in terms

$$T = \left(\frac{3600}{R}\right)P \quad (21)$$

$$P = \frac{R - 3.6F - 10}{15.34} \quad (22)$$

of the round trip time and the number of floors above the first floor when the passengers per trip did not exceed the number of floors (Eq. 23). He also generated a formula that accounted for when the number of passengers per trip exceeded the number of floors above the first floor (Eq. 24).

$$T = \frac{3600}{R} \times \frac{R - 3.6F - 10}{15.34} \qquad \text{simplified to} \qquad T = \frac{235(R - 3.6F - 10)}{R} \quad (23)$$

$$T = \frac{900(R - 14.94F - 10)}{R} \quad (24)$$

Cook stated that: "Good elevator service demands that the round trip time shall not be excessively long and there are rather well defined limits which should not be exceeded. The time spent by a passenger waiting for a car usually causes as much if not more uneasiness than the same time spent in reaching the top floor" [13]. He assumed a maximum round trip time of two minutes, which set a design limit for *R* (Eq. 25). In his final formulas Cook employed the maximum round trip time and

$$\frac{R}{2} + \frac{R}{E} = 120 \qquad \text{modified as} \qquad R = \frac{240E}{E + 2} \quad (25)$$

used the value of *R* from Equation 25 to provide a means of solving for *T* in both passenger load scenarios (Eq. 26 & 27). Cook also claimed that the maximum traffic volume occurred early in the morning, at noon, and in the evening, was generated solely by the building's occupants, and was "never" due to visitors [16].

$$T = 235 - \frac{235(3.6F + 10)(E + 2)}{240E} \quad (26)$$

$$T = 900 - \frac{900(14.94F + 10)(E + 2)}{240E} \quad (27)$$

Cook's paper was published by the Warner Elevator Company and also appeared as a three-part series in *Buildings and Building Management* [13 & 14]. He published an additional paper, on express lift service, in *Buildings and Building Management* in 1922, and published an article titled "Rates of Starting and Stopping Elevators and Their Effect on Service" in *Power* in 1926 [15, 16]. The latter article offered an interesting discussion of lift acceleration and deceleration speeds and their impact on passengers and service. He also addressed the challenges of accurately calculating these rates, noting that the "necessary assumptions render the results of doubtful value" [16]. Perhaps his most interesting observation regarding this subject was his statement that the traction lift "is, in fact, just a large example of an Atwood machine, widely used in physics for demonstrating the laws of motion" [16].

He concluded the article with a discussion of a "simple way to compute traveling time" [16]. Cook claimed that: "The space required for acceleration and retardation is multiplied by the number of stops and this result is added to the length of travel. The sum of these quantities is divided by the normal speed in feet per second. The result will be the traveling time, in seconds, required to make the trip" [16]. Cook stated that this method was "true because the average speed during acceleration and retardation is one-half of the normal speed, and by adding this distance to the actual distance and dividing by the normal speed, the true traveling time is obtained" [16].

Cook's 1920 effort was followed by an article that is referenced in almost all post-1960 works on lift traffic analysis: Bassett Jones' "The Probable Number of Stops Made by an Elevator," published in the August 1923 issue of the *General Electric Review*. This article is, in fact, the only pre-1960 work referenced in contemporary works on lift traffic analysis. Jones' basic assumptions about lift operation paralleled those of earlier authors. He noted that the round trip time was determined by the distance the lift traveled, the number of passengers carried, and the number of stops made [17]. A key factor was the interval of travel, which determined the available loading time at the ground floor, which in turn set the maximum number of passengers carried, and thus fixed the car's size. Jones further defined the round trip in terms of: "(1) *running time*, or the total time the car is normally in motion between stops and is a direct function of the velocity-time data for the type of equipment adopted, (2) *standing time*, or the total time the car is standing at floors including the interval, and (3) *lost time*, or the time consumed by false stops if any, the time consumed by limit slow-downs, and the synchronizing time, or the time allowed for maintaining the schedule when an abnormal number of stops occur, or for other reasons" [17].

Jones stated that the "object" of his article was "to explain a method based on the theory of probabilities, for determining the number of stops" [17]. He described the theory of probability as "the only known intelligent method of guessing" [17]. His formulas relied on only three variables: *N* – the number of passengers that will enter the car on the ground floor, *n* – the number of floors the car served, and *S* – the probable number of stops. Jones first established formulas for the probability that a single passenger will exit at a particular floor (Eq. 28) and for the probability that she will not wish to exit at that floor (Eq. 29). He then modified the formulas to account for *N* passengers (Eq. 30 & 31), which led him to his formula for the probable number of stops (Eq. 32).

$$\frac{1}{n} \tag{28}$$

$$\frac{n-1}{n} \tag{29}$$

$$\left(\frac{1}{n}\right)^{N} \tag{30}$$

$$\left(\frac{n-1}{n}\right)^{N} \tag{31}$$

$$S = n\left\{1-\left(\frac{n-1}{n}\right)^{N}\right\} \tag{32}$$

Jones demonstrated the efficacy of his formula via a "dice analogy" and illustrated a means of determining the odds of a given dice face turning up when the dice was thrown. He also noted that the "only criterion of legitimacy" for the theory of probability "is the test of experience, and in this regard, it has proved to be quite satisfactory" [17]. In this instance, "experience" was defined as follows: "For a long period it has been the custom, based on observed stops, to assume that during the morning arrival traffic peak the cars would stop at 0.8 of the floors on the up motion while delivering the passengers loaded on the ground floor" [17]. Jones provided a chart that illustrated the results of the application of his formula and he observed that "It is interesting to note how much of the data presented … averages $S = 0.8n$" [17].

Jones' decision to use 0.8 is intriguing in that it connects to Reginald Bolton's 1908 work. In his review of *Elevator Service*, William Bryan offered the following explanation of Bolton's theory: "Having placed the average number of passengers per trip each way at 0.4 the number of floors served, *f*, the provision that this number may be increased 80% when all are carried one way, together with a margin of 10% for emergencies, fixes the number of people to be provided for per trip at 0.8 the number of floors served" [9]. Thus, Jones' key assumption used to verify his theory relied on "custom" and the "Bolton rating," which was derived primarily from observation.

Jones formula for determining the probable number of stops does not, however, represent the first such attempt. In a 1932 article Howard Cook offered the following definition of probable stops and a formula for their calculation: "The probable number of stops made by an elevator is less than the number of passengers taken on at the first floor. If the number of persons per floor is the same for all the floors at which stops may be made and of the car always stops at the top floor then the probable number of stops made on the trip is found from the equation where *S* equals the number of possible stops above the first floor and *P* equals the number of passengers taken at the first floor. *This equation was developed by S. Margles in 1922*" (Eq. 33) [18].[2]

$$\text{Probable stops} = S - \left(S-1\right) \times \left(\frac{S-1}{S}\right)^{P} \tag{33}$$

Unfortunately, Cook offers no further explanation of this formula or its origins. "S. Margles" was Samuel G. Margles (1889-1978), an engineer with the Otis Elevator Company. He joined Otis following his graduation from Cooper Union and, in 1959, he described his career at Otis as follows: "I entered the employ of the Otis Elevator Company late in in 1911 as a structural draftsman in the construction department. In 1918, I was transferred to the engineering department, where I have been ever since; that is, until the date of my retirement in August 1954. I began work on escalators in 1919 and, subsequently, I have been in charge of complete design, invention, and construction of escalators"[19]. This brief autobiography only raises more questions: Why would an engineer focused on escalators devise a formula for the probable number of lift stops? When and where would Cook have encountered Margles and his formula? And, finally: If Cook's dating of Margles' effort is accurate, was Jones aware of his work? This event also marks another, albeit very limited, glimpse into the approach that Otis was taking toward solving this problem.

In 1924 British engineer Howard Marryat (1871-1944), co-founder of Marryat & Scott, presented a paper to the Institution of Electrical Engineers that included a more substantive glimpse into the lift industry's approach to traffic analysis – from the British perspective. He claimed that "given the necessary particulars of a building, the lift engineer will be able to calculate the probable traffic" [20]. However, Marryat also noted: "It must be admitted … that the lift engineer himself does not usually employ any scientific method in arriving at the number of passengers per minute which will require lift service on each particular floor during the busy part of the day" [20]. Instead of relying on a "scientific method" the typical lift engineer drew "upon his own experience and home-made formulae" [20]. At this point Marryat opined that, if the various "home-made formulae" used by British lift manufacturers "could be collated, the general advantage would be served and many mistakes avoided" [20].

[2] Italics added by author.

In his paper Marryat reported that the "only English pronouncement" he could find on lift traffic was found in "a paper read recently by Mr. C.H.J. Day before the Association of Engineers-in-Charge, in which he says … that in buildings where tests have been made, the rate of traffic flow at the busiest time of the day has been found to be such as to include the equivalent of the entire population of the building in 45 minutes, and that the passenger traffic can be predetermined by allowing for a period of rush from 15 to 20 minutes, during which time a number equal to one-third of the population of the building is dealt with" [20]. While Marryat stated that his observations did not align with Day's, he also noted that "although I have been investigating the subject for some considerable time I have not yet amassed sufficient data to permit of my making an authoritative pronouncement" [20]. None-the-less he offered two formulas designed to calculate a building's lift capacity and round trip time, which used five basic constants (Table 9). Marryat provided a detailed

Table 9 Howard Marryat Lift Formula Constants (1924)

A	Rental floor area above the first floor (in thousands of sq. ft.)
N	Number of circular trips, including stoppages, per lift per hour
L	Number of lifts
R	Running speed of lift (in ft. per min.)
T	Total travel of lift in feet in one direction

description of his data gathering strategy, which included using different approaches for different types of buildings and reflected differences in use patterns. He reported that: "In taking this census of traffic in existing occupied buildings, I have at the outset been faced with the fact that existing lift accommodation is, in almost every instance, insufficient. It has been necessary, therefore, to count not only persons using the lifts but also those using the staircases" [20]. He provided several data tables, one of which addressed the issue of insufficient service in London office buildings (Table 10). From this he determined that an average lift capacity of 9.6 passengers per 1,000 sq. ft. of rental floor area above the first floor was a reasonable figure, which allowed him to propose a formula to find the lift capacity required in an office building (Eq. 34).

Table 10 Howard Marryat Lift Service in London Office Buildings (1924)

Lift capacity in persons per hour per 1,000 sq. ft. rental floor area above first floor	Number of minutes during the day when lift capacity will be insufficient
7	84
7.5	56
8	33
8.5	14
9	5
9.5	1

$$\text{Lift Capacity} = \frac{9.6\text{A}}{\text{NL}} \tag{34}$$

Because the round trip time was, in large part, dependent on the interval of service, Marryat felt it necessary to define this key factor: "As about 30 seconds represents the limit of patience to be expected of the average city man waiting for a lift, a building cannot be considered to be adequately served when the occupants or visitors are asked to wait longer" [20]. He also recognized that he needed to known the overall lift speed – "allowing for all stoppages" [20]. While he found that "the number of stoppages a lift may be required to make in the course of a return journey from the ground floor and back again varies considerably," in most London office buildings the number of stops was "found to average about one stop for every 42 ft. of running" [20]. Marryat also allowed

“12 seconds per stop for loss in acceleration, deceleration, opening and closing of gates and for the time taken by the passengers in entering and leaving the car” (Eq. 35) [20]. In addition to lift traffic

$$\text{Round Trip Time} = \frac{60 \times 2T}{R} + \frac{2T \times 12}{42} \tag{35}$$

Marryat’s paper (the first draft was completed in July 1923), addressed a wide range of topics concerning electric lifts and in his introduction he noted that it was “remarkable that so little has been written or published upon the subject in this country, although there are a large number of works dealing with cranes, conveyers, etc.” [20].

In 1923 British engineer Ronald Grierson (1886-1955) published *Electrical Lift Equipment for Modern Buildings*. Marryat’s comment on lift publications reflected his lack of awareness of Grierson’s forthcoming book. However, had he known, he might have questioned the decidedly American bias reflected in much of the book’s content (it was published in the United States in 1924 as *Electrical Elevator Equipment for Modern Buildings*). In fact, the book’s bibliography lists only nine sources and it includes only American publications. Grierson addressed lift traffic in Chapter II: “Estimating Service Requirements” [21]. The chapter presented information gleaned from several sources (including Bolton), contained no formulas, and offered readers only a general introduction to this important topic. However, this was, in fact, more information than Fred A. Annett provided in the first edition of *Electric Elevators: Their Design, Construction, Operation and Maintenance*, published in 1927, where he made no mention of lift traffic analysis.

6 1930 - 1939

By the early 1930s the methodology used for gathering data needed to substantiate the development of lift traffic formulas and related metrics appeared to have been well defined. In a 1930 article Luther J. Kinnard discussed a traffic study worksheet that included 29 data points (Table 11). Kinnard’s worksheet appears to represent a comprehensive list of the factors associated with lift traffic design. While he provided a few basic formulas and charts that followed the pattern of prior work, he also noted that: “There has been a general demand among architects for a *Rule of Thumb* by which one could determine in a few seconds how many elevators were needed in a prospective building” [22]. Kinnard observed that a reliable rule of thumb depended on an accepted definition of satisfactory lift service, however, because there was no universal agreement on a definition due to variations in service required by different building types as well as differing expectations in similar buildings in different parts of the country, such a rule was impossible.

Howard Cook continued his work on traffic analysis in the 1930s, contributing additional articles to *Power* magazine and serving as a consultant to the second edition of Annett’s *Electric Elevators: Their Design, Construction, Operation and Maintenance*, which appeared in 1935 [23 & 24]. Whereas Annett’s first edition had ignored this subject, the second edition included a chapter devoted to lift traffic: “Selecting Elevators for Office Buildings” [24]. In a footnote Annett acknowledged that: “Howard B. Cook supplied a large part of the material in this chapter, and ” the majority of the chapter’s text and illustrations came directly from Cook’s articles [24]. Annett’s book thus served as means of disseminating Cook’s work and, perhaps most importantly, given its publication and distribution by a major publishing firm (McGraw Hill), attempted to set an American standard for lift traffic analysis.

Lift traffic was described as dependent on morning and evening traffic peaks, with the “five-minute morning peak of traffic as the controlling factor” in lift design “unless some peculiar conditions exist” [24]. According to Cook and Annett “the morning traffic peak is used as the basis for calculating elevator requirements even though the evening peak is higher, because passengers congregating in the evening on the upper floors is not so objectionable as crowding at the first floor" [24]. They also stated that: "in a well-diversified office building the five-minute traffic peak

Table 11 Luther J. Kinnard, Traffic Study Worksheet

Traffic Study	
Name of Building:	Location:
1. Number of floors served including main floor)	
2. Travel, Round Trip (Ft.)	
3. Rentable Area, per floor (Sq. Ft.)	
4. Rentable Area, above Main floor (Sq. Ft.)	
5. Population, above Main floor	
6. Service (local or Express)	
7. Number of Elevators in Bank	
8. Full speed of cars (F.P.M.)	
9. Capacity (Pounds)	
10. Capacity (Passengers)	
11. Type of control	
12. Type of Door Operators	
13. Time to open and close doors, each stop (Seconds)	
14. Extra time to Accelerate & Decelerate, each stop (Seconds)	
15. Standing time, Main floor (Seconds)	
16. Standing time, Top Floor (Seconds)	
17. Passengers carried per round trip, each car	
18. Stops per round trip, each car	
19. Loading time per passenger (Seconds)	
20. Standing and loading time, each car (Seconds)	
21. Door operations, round trip, each car (Seconds)	
22. Full speed Time, round trip (Seconds)	
23. Extra Time, Accelerate & Decelerate, round trip (Seconds)	
24. Extra Time, slowdown in limits (Seconds)	
25. Time for False Stops, round trip (Seconds)	
26. Total time of round trip (Seconds)	
27. Interval of Departure (Seconds)	
28. People Handled in One Hour	
29. Time to Empty Building (Minutes)	

will usually not exceed one-ninth of the building's population" [24]. The chapter included discussions of well-known topics such as round trip time, time for passengers to enter and leave the car, and the probable number of stops. Cook once again discussed Margles' 1922 formula and it is interesting to note that he made no reference to Jones' 1923 article. Cook did address a few additional areas of lift traffic and provided a means (Eq. 36) to calculate the rate of acceleration, where t is the time per stop in seconds, S is the average distance in feet between stops and a the rate of acceleration. The steady increase in the development of automatic door operating systems led to the development of a formula to calculate hoistway door operation time, which was described as dependent on the "weight of the door, the width of the opening and the forces applied." [24]. Thus, the formula (Eq. 37) included: T the time required for operating any sliding door, W is the weight of the door in pounds, D the door movement in inches, and F the force in pounds [24].

$$t = \sqrt{\frac{4S}{a}} \tag{36}$$

$$T = \sqrt{\frac{WD}{96.6F}} \tag{37}$$

Annett also published a detailed chart Cook had devised that illustrated four possible traffic scenarios during the morning 5-minute peak. The chart depicted "the round-trip time and the number of passengers carried per car in 5 min. … for 10, 12, 15, and 18 passengers per trip … to be carried during the morning peak of traffic by cars having capacities of 2,000, 2,500, 3,000, and 3,500 lb., respectively" [24]. Cook and Annett agreed that: "no definite standard has been formulated to measure the quality of elevator service" [24]. This did not, however, stop them from attempting to establish such standards: "After considerable investigation of this subject, it has been determined that when one-half of the interval between cars plus one-fourth of the round-trip time is equal to 45 sec. the service may be classed as excellent. When the sum of these quantities is 52.5 sec. the service may be called good. When the sum is 60 sec. the service is only fair" [25]. Cook provided a chart (first published in 1931) that gave "values for determining the quality of elevator service" (Fig. 3) [23 & 24].

The 1930s closed with the publication of the first edition of Reginald S. Phillips' *Electric Lifts*. Unlike Ronald Grierson's *Electrical Lift Equipment for Modern Buildings*, which had a decidedly American bias, Phillips' book relied almost exclusively on British sources. He offered his readers a brief introduction to the subject of lift traffic, which was included in his first chapter titled "Provision" [25]. He provided a broad definition of round trip time, noting that it was composed of several "varying factors" including: the car's maximum running speed, the rates of acceleration and retardation, the average number of stops made per journey, the average distance between stops, and the time required of passengers to enter and leave the car. Phillips provided definitions for each these factors as well as three basic formulas (Eq. 38, 39 and 40).

$$\text{Number of passengers carried during the peak period} = (\text{Number of passengers carried per journey}) \times (\text{Number of journeys made during the peak period}) \tag{38}$$

$$\text{Number of cars in the bank} = \frac{\text{Number of passengers carried}}{\text{Number of passengers per car}} \tag{39}$$

$$\text{Number of cars} = \frac{\text{Round trip time}}{\text{Waiting Interval}} \tag{40}$$

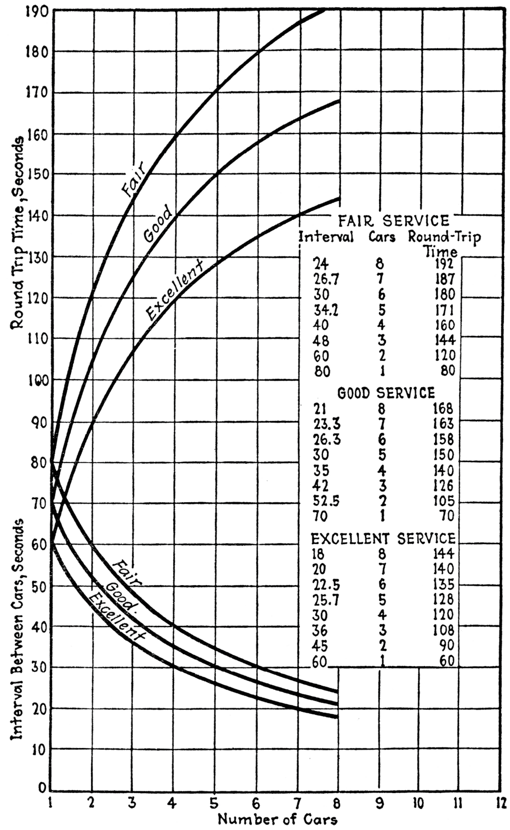

Figure 3 Cook, Values for Determining the Quality of Lift Service (1931)

Phillips claimed that his formula for determining the number of cars was accurate "irrespective of the capacity of each car" [25]. And, he concluded that: "The quality of service given by an installation is measured by the time of the waiting interval together with the time for the car to arrive at an average floor, the latter being a function of the round trip time. Waiting intervals of say, 20, 30, and 40 sec. may be considered, but a passenger should never be expected to wait more than 40 sec. before the arrival of a lift" [25].

7 1940 - 1960

The third British book on electric lifts appeared in 1941: *Electric Lifts: A Practical Treatise on their Construction, Operation and Maintenance* [26]. The author of the book, somewhat vaguely, was simply identified as "Contractor," with Edward Molloy listed as the General Editor. Molloy was also listed as the editor of the *Electrical Engineer*, and he served as the editor for a wide range of engineering books published by George Newnes Limited of London. Thus, the actual author (or authors) of this book are unknown. This is unfortunate as the book holds a partial answer to the mystery of Samuel Margles' 1922 formula for probable stops.

Chapter one includes a section titled "Traffic Analysis" which, as expected, includes a disclaimer that the "exact determination of lift requirements is extremely difficult, because so many variables have to be taken into account and it is almost impossible to estimate what conditions may be encountered in the future" [26]. Variability in service was illustrated by a description of lift traffic conditions: "In office buildings the peak traffic occurs in the morning, at lunch time, and in the evening, and the heaviest peak will depend upon the class of business, luncheon facilities, discipline, and similar factors, which vary with each building. Generally the morning peak is the heaviest, and in some buildings the lifts may have to handle as much as one-third of the population in five minutes when filling the building, whilst in others the lifts need not carry more than from one-tenth to one-twelfth of the population in the same time. The peaks vary between these values, depending upon the specific conditions of the building" [26]. The various factors discussed included the "suitable time-interval between car arrivals, determining the most satisfactory car size, methods of operation for car and landing doors, time-allowance for attendants' faults, time required for passengers to move in and out of cars, and probable stops" [26].

The section's unknown author states that: "by resorting to the *mathematics of probability* a formula can be evolved to determine the average number of stops that will be made to discharge passengers in the peak period of filling the building" [26].[3] The proposed formula relied on a discrete number of variables (Table 12). The constant n was defined as the total number of persons going into the building, thus equal to the number of people occupying the building (Eq. 41). The number of probable stops was defined relative to the occupancy of each floor (Eq. 42) with "the total number of minus terms being equal to s" [26]. If we assume that each floor has the same number of occupants, then a = b = c = d, which means that $sa = n$, thus, according to our unknown author,

Table 12 Probable Number of Stops Formula Variables (1941)

n	Total number of persons going into the building
a	Number of persons on one floor
b	Number of persons on another floor
c	Number of persons on another floor, etc.
p	Number of passengers in the car at loading floor
s	Total number of possible stops to discharge passengers

$$n = a + b + c \text{ ... etc.} \tag{41}$$

$$s - \left(\frac{n-a}{n}\right)^p - \left(\frac{n-b}{n}\right)^p - \left(\frac{n-c}{n}\right)^p \text{… etc.} \tag{42}$$

Eq. 42 may be simplified (Eq. 43) and, when one of the stops "is a fixed stop" the final formula matches the one Cook attributed to Margles (Eq. 44). It should be remembered that standard practice during peak service times required the car to travel to the top floor regardless of need (a "fixed stop") in order to maintain the interval of travel.

$$s - s\left(\frac{s-1}{s}\right)^p \tag{43}$$

$$s - (s-1)\left(\frac{s-1}{s}\right)^p \tag{44}$$

The book includes a chart that illustrates the "number of probable stops in the peak period of filling a building, assuming that the same number of persons is on each floor served by the lift" (Fig. 4) [26]. The unknown author claims that: "the results from the above formula compare favourably with those found in actual practice, and the formula has the advantage of giving a definite basis for comparison of different types of lifts" [26].

[3] Italics added by author.

The appearance of Margles' formula prompts several questions: Are the text and chart the work of Samuel Margles? And, if it is Margles, how was Molloy able to access this material? Molloy (and "Contractor") expressed in the introduction their "indebtedness to the leading lift manufacturers for having assisted us by supplying illustrations of the most modern types of lift equipment" [26]. These companies doubtless included Waygood-Otis and thus, if the companies provided more than images, it is possible that Waygood-Otis supplied Margles' work to Molloy, book's editor. This would, perhaps, imply that Margles wrote a paper on this topic in 1922, perhaps for internal consumption at Otis. The search for answers to this mystery will continue as it may shift our understanding of the origins the probable stop formula as well as how the lift industry was approaching this problem in the 1920s.

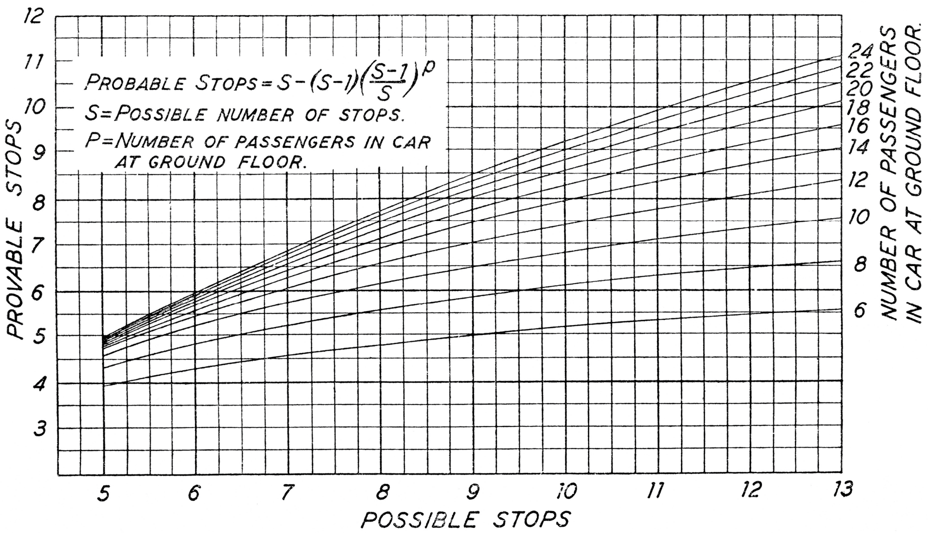

Figure 4 Number of probable stops in the peak period of filling a building (1941)

The second edition of Reginald Phillips' *Electric Lifts* appeared in 1947. It included a bibliography (a feature missing in the first edition) that was composed almost exclusively of British sources (the exceptions were the America A17 code and an associated Inspectors' Manual). Phillips made no reference to Molloy's book and, perhaps surprisingly, also made no changes to the lift traffic material that had appeared in the first edition. The book's third edition (1951) had an expanded bibliography that included two articles by Howard Cook ("A Measuring Stick for Elevator Service" and "Selecting Elevators for an Office Building") and two articles by Bassett Jones ("Time-velocity Characteristics of the High-speed Passenger Elevator" and "Note on Probable Number of Stops Made by an Elevator"). It is important to note that the Jones' article was not his 1923 article on probable stops, but a follow up article written in 1926 [27]. The reason why Phillips chose this article instead of the original is unknown. It is also curious that he references Cook but ignores Annett's work; likewise Molloy's book remained absent.

Phillips did, however, use these new sources to update the book's first chapter, which was renamed "Design and Traffic Analysis" [28]. He added a new section addressing "grade of service" in which he provided several formulas designed to determine the quality of lift service [29]. These formulas used three variables (Table 13). Phillips first established an initial formula for the grade of service

Table 13 Phillips, Graded Lift Service Formula Variables (1951)

W.I	Waiting Interval (maximum time a person may have to wait for a lift)
R.T.T.	Round Trip Time
N	Number of Lifts

in terms of the waiting interval and round trip time (Eq. 45). He then determined the waiting interval for *N* lifts in a bank (Eq. 46), which he used to derive his final formula (Eq. 47).

$$\text{Grade of Service} = \frac{\text{W.I.}}{2} + \frac{\text{R.T.T.}}{4} \tag{45}$$

$$\text{W.I.} = \frac{\text{R.T.T.}}{\text{N}} \tag{46}$$

$$\frac{\text{W.I.}}{2} + \frac{\text{N} \times \text{W.I.}}{4} \quad \text{simplified to} \quad \frac{\text{W.I.}}{4}(2+\text{N}) \tag{47}$$

Phillips defined four grades of service in terms of the total traveling and waiting time (in seconds) (Table 14). He also characterized the passenger's experience as follows: "A lift service which has a small *W.I.* and a large travelling time always appears to the user to be better than an equivalent service with a larger *W.I.* and a smaller travelling time, as a long wait tends to make a person impatient" [29].

Table 14 Phillips, Graded Lift Service (1951)

Excellent	45
Good	45-55
Fair	55-65
Casual	>65

As noted above, Phillips' bibliography referenced a 1926 Basset Jones' article, "Note on Probable Number of Stops Made by an Elevator," rather the original 1923 article. Phillips recreated the essential aspects of Jones' 1926 argument and published a set of formulas that lead to the original conclusion expressed in Eq. 29. However, Phillips failed to mention what prompted Jones to write a "note" to his original article. Jones reported that, following the publication of his 1923 article: "the formulas and charts therein presented have been generally accepted and have come into general use. They have been checked over and over again by observation, and have been found to give results quite as close to practice as was originally claimed for them" [27]. However, by the mid 1920s, the literal shape of skyscrapers had changed: "the increasing number of zoned or set-back buildings that are being built introduces cases where the wide variation in floor area and in distribution of population is beyond the applicability of the (original) formulas that were given" [27]. Jones therefore proposed a new set of variables (Table 5) and a new series of formulas aimed at solving this new problem.

Table 15 Jones, Variables for Probable Stop Formula (1926)

N	Total number of passengers entering the car at the ground floor for each trip during the peak period.
P	Total population served during the peak period.
n	Number of floors served above the ground floor.
P_a, P_b, P_c, etc.	Population on the first, second, third, etc. floor.

He worked through a series of steps that leaded him to a revised formula (Eq. 48), which he noted was "first developed by David Lindquist" [27]. This statement adds to the mystery surrounding the origins of the formula to determine probable stops. Lindquist (1874-1944), was one of Otis' chief engineers, and presumably would have aware of Margles work from 1922. Jones also gives no hint as to when Lindquist proposed this formula. Thus, Jones offers yet another clue that Otis was also working on solving this problem.

$$S = n - \left\{ \left(\frac{P - P_a}{P} \right)^N + \left(\frac{P - P_b}{P} \right)^N + \ldots + \left(\frac{P - P_n}{P} \right)^N \right\} \quad (48)$$

Phillips also included a new section on travel time that featured formulas derived, in part, from Jones' examination of lift time-velocity characteristics [27]. His primary focus was a formula, which used four basic variables (Table 16), which could be used to determine a lift's total travel time. He derived a series of formulas to determine the distance traveled and the time period required

Table 16 Reginald Phillips Travel Time Formula Variables (1951)

S	Number of stops made between the ground floor and the uppermost floor at which
D	Distance in feet between ground floor and this top floor
V	Contract speed in feet per second
d	Distance in feet required for acceleration from rest to contract speed (assumed to

during a lift's acceleration and retardation period (he assumed that the average speed during these periods was half the contract speed) (Eq. 49, 50, 51, & 52). He also devised formulas for the distance traveled and the time period the lift was running at contract speed (Eq. 53 & 54).

Upward distance travelled during acceleration and retardation period = 2dS (49)

Downward distance travelled during acceleration and retardation period = 2d (50)

Total acceleration and retardation periods = 2d(S + 1) (51)

Total Time during acceleration and retardation periods = $\frac{2d(S+1)}{\frac{V}{2}}$ or $\frac{4d(S+1)}{V}$ (52)

Total distance traveled at contract speed = 2D - 2d(S + 1) (53)

Time for running at contract speed = $\frac{2d - 2d(S+1)}{V}$ (54)

From these he proposed a formula to find the total traveling time (Eq. 55). He also offered a formula to find the traveling time if the distance (d_1) between any two stops was less than the distance needed to reach contract speed (where *f* is the average acceleration) (Eq. 56)

Total traveling time = $\frac{2}{V}(dS + D + d)$ (55)

$$2\sqrt{\frac{d_1}{f}} \quad (56)$$

Although Phillips expanded his bibliography in the book's fourth edition (1958), he did not edit or add to the content on lift traffic design and analysis found in the third edition.

The third edition of Fred Annett's *Electric Elevators* appeared in 1960 with a substantially revised title – *Elevators: Electric and Electrohydraulic elevators, Escalators, Moving Sidewalks, and Ramps* – and a revised chapter on lift traffic, which also featured a new title: "Automatic Dispatching of Passenger Elevators and Attendantless Operation" [29]. There is an intriguing symmetry between this publication and the first works examined in this paper in that, after 70 years of pursuing the development of lift traffic formulas, Annett's book contains no such formulas: in their place we given the "magic" of automated lift supervisory systems. These new systems were marketed under a variety of names intended to highlight the mathematical acumen hidden within the technology: Autotronic (Otis), Selectomatic (Westinghouse), Auto-Signamatic (Haughton) and Measured Demand (Montgomery).

The language of past lift traffic analysis efforts was also updated with terms such as up-peak, off-peak, down-peak, forgotten-man pickup, and zone operation now used to describe and define this topic. Annett illustrated ongoing efforts to understand lift traffic patterns in a diagram that depicted typical service demands as occurring in "waves" throughout the day (Fig. 5). He illustrated the efficiency of the new automatic systems is diagrams depicting their operation during off and up peak periods (Fig. 6). However, Annett's descriptions of these systems are also filled with references to the roles of lift supervisors and operators. These serve as important reminders that in 1960, the lift industry was effectively poised between two worlds: the "old" world where the starter and operator played key roles in lift traffic management, and the "new" world where traffic management was vested in controllers driven by hidden algorithms. The continued importance of the starter was illustrated by a diagram of a typical supervisors control unit, where the starter interacted with and directed the automatic system (Fig. 7). The hidden logic that drove a typical automatic system was illustrated by a series of definitions describing it operational parameters (Table 16). Although these definitions are clear, there is, perhaps, a certain irony in that their simplistic tone is reminiscent of the general description of lift operation from the early 20th century.

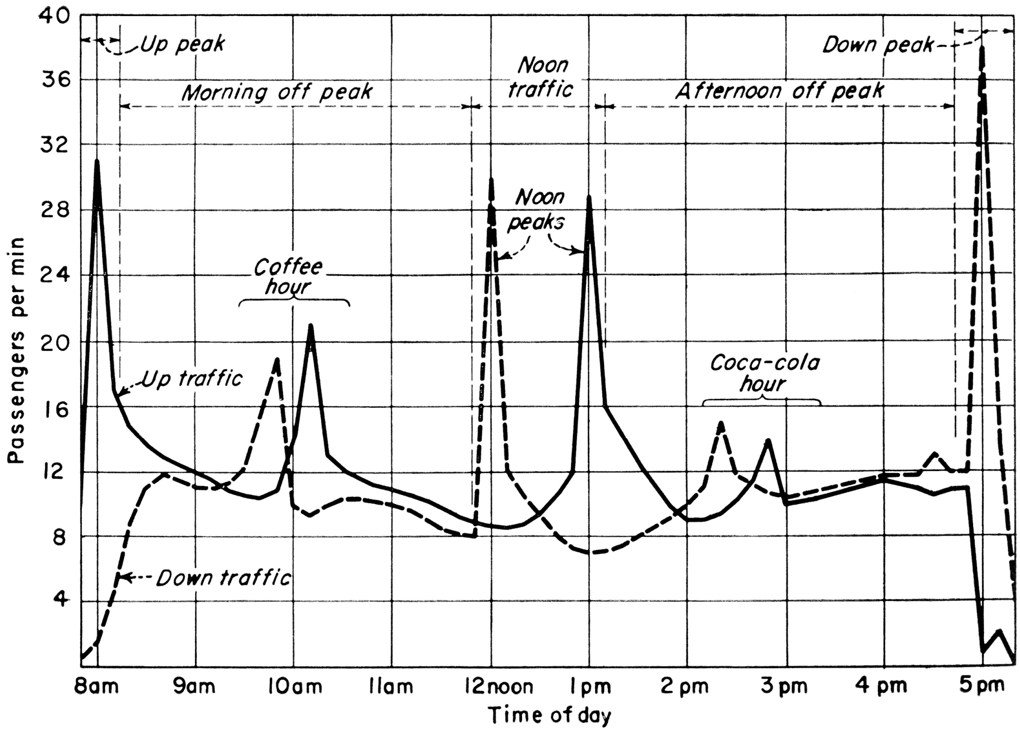

Figure 5 Annett, Typical Lift Travel Peaks in an Office Building (1960).

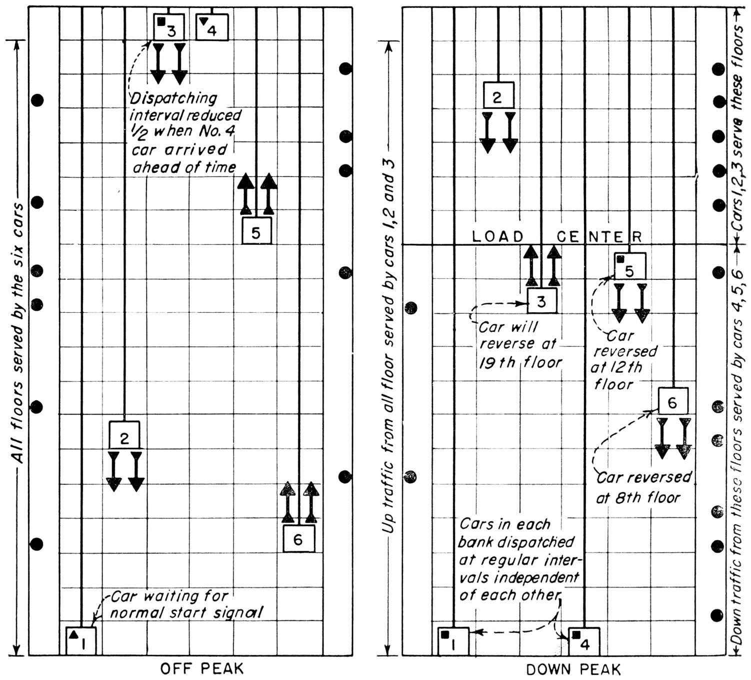

Figure 6 Annett, Off-Peak and Down-Peak Travel (1960).

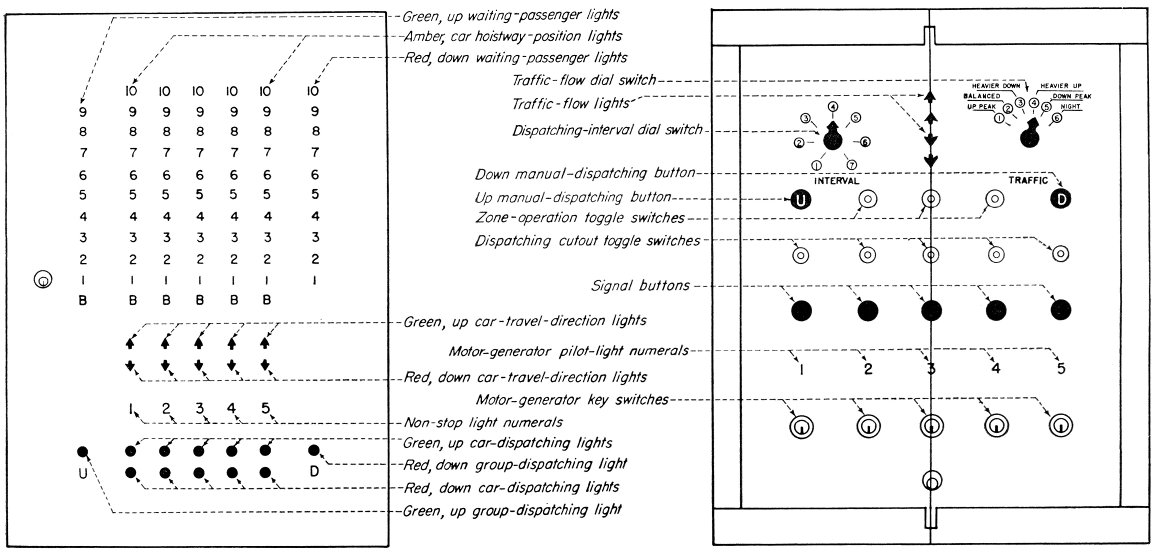

Figure 7 Annett, Typical Lift Travel Peaks in an Office Building (1960).

Table 16 Annett, Typical Lift-operating Program Definitions (1960)

Up Peak	Heavy up-traffic from the main floor with little or no interfloor or down traffic, as
Heavier Up	Heavy up-traffic plus appreciable down traffic, as during the late noon peak.
Down Peak	Heavy down-traffic with little or no interfloor or up traffic, as during the evening
Heavier Down	Heavy down-traffic plus appreciable up traffic, as during the early noon peak.
Balanced	Traffic about equal in up and down directions.
Night	Light and intermittent traffic, as during nights, Sundays and Holidays.

8 CONCLUSION

This investigation revealed two streams of development regarding lift traffic analysis that might be termed public and private (or perhaps, proprietary). While the topic was clearly recognized as important, the majority of published works on these topics were written by individuals who were either outside the lift industry or who operated as lift consultants. While evidence of the lift industry's approach to this subject was discovered during this investigation, this material, because of its proprietary nature, remained largely hidden from view. The results of industry efforts were evident in the automated traffic control system referenced above, however the mathematical concepts that underlay this work were "hidden" from pubic view.

This bifurcated approach continued after 1960 with one critical difference: the addition, beginning with the work of Dr. Gina Barney in the late 1960s (assisted by colleagues and students at the University of Manchester Institute of Science and Technology), of what may be termed the academic pursuit of lift traffic formulas and criteria. While this work has a strong connection to the lift industry and to the work of lift consultants, it represents, perhaps, a "third" parallel path of investigation.

As the history of this important topic continues to unfold it is to be hoped that industry members might be willing to share material with researchers that is "outdated" and no longer considered proprietary. This additional material will make it possible to tell the full story of the development of lift traffic analysis.

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