The Road Capacity of City Centers

R. J. SMEED, Professor of Traffic Studies, University College, University of London

•IN September of last year, a paper was presented by the writer at an International Study Week in Barcelona, Spain, on the road capacity of city centers (1). This paper develops aspects of the same subject which were not dealt with in the previous paper. Considering first the numbers of vehicles that can use the roads of a city per unit time under various conditions, it might reasonably be expected that this number would depend on many factors, including the nature of the city and of its road system and on the types of journey that are made there. It is, of course, necessary to consider the matter quantitatively.

THE AREA OF ROAD REQUIRED FOR TRAVEL

Suppose that the capacity of a road of width W is Q vehicles per unit time. Then one may regard each vehicle using the road in unit time as requiring a width of road W/Q. If a vehicle makes a journey of length d on such a road, it may be said to require an area Wd/Q of carriageway. Suppose, in the first instance, that the value of W/Q is the same for all roads in a Central Business District. Then, if N vehicles use the roads of the CBD per unit time, and if the average distance traveled is $\bar{d}$, the total area of carriageway required for these journeys is $NW\bar{d}/Q$. If the fraction of the carriageway area in the CBD used for traffic movement of the type under consideration is J, if f is the fraction of the ground area of the CBD devoted to roads and if A is the total ground area of the CBD, it follows that

$$\frac{N\bar{d}W}{Q} = JfA,$$

and therefore that

$$N = \frac{JQ}{W} \cdot \frac{fA}{\bar{d}}$$

The Value of $\bar{d}$

The value of $\bar{d}$, the average distance traveled, depends on the type of road network, the distribution of origins and destinations, etc. This paper is, however, concerned with the capacity of a road network and therefore mainly with travel at peak travel periods. At such times, journeys are predominantly between points on the outskirts of a CBD and points inside it. It is, therefore, convenient to assume initially that origins are equally distributed among the points at which the roads leading into the CBD meet the boundary of the CBD and that destinations are distributed either uniformly along the sides of the roads of the CBD or uniformly within the area. Under such conditions, it is possible to calculate the average distance traveled on the roads of any given CBD, assuming that journeys are made by the shortest possible route. Approximate calculations have been made for a number of idealized and real road systems, and the results given in Figures 1 to 5.

Figure 1 gives the results for four routing systems in circular CBD's in which it is assumed that roads are infinitely close together and that destinations are distributed uniformly throughout the area. Figures 2, 3 and 4 are for idealized road systems, in

Paper sponsored by Special Committee on International Cooperative Activities and presented at the 46th Annual Meeting.

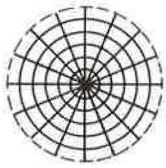
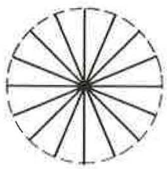
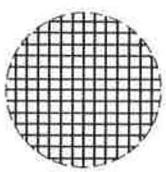
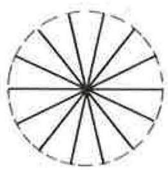
Route	Road network	Average distance
Radial Arc Vehicle travels along the radial through O, the point of arrival at the outskirts of the central area, until it reaches the circular road on which its destination lies, and then along this road until it reaches its destination.		$\frac{1}{3}\left(\frac{1}{\pi^{1/2}} + \pi^{1/2}\right) A^{1/2} = 0\cdot78 A^{1/2}$
Radial Vehicle travels along radial from O to center of central area and then turns on to radial on which destination lies.		$\frac{5}{3\pi^{1/2}} A^{1/2} = 0\cdot94 A^{1/2}$
Rectangular Vehicle travels along one of the two roads through point of arrival at outskirts of the central area until it reaches the perpendicular road on which its destination lies and then along this road.		$\frac{128}{9\pi^{2\cdot5}} A^{1/2} = 0\cdot81 A^{1/2}$
Ring Vehicle travels along a ring road on the outskirts of the central area until it reaches the radial on which its destination lies, and then along this radial.		$\left(\frac{\pi^{1/2}}{2} + \frac{1}{3\pi^{1/2}}\right) A^{1/2} = 1\cdot07 A^{1/2}$

Figure 1. Effect of road and routing system on average distance traveled—vehicles assumed to travel from random points on the outskirts of a circular central area to random points inside circle (roads assumed to exist at all origins and all destinations).

which it is assumed that destinations are uniformly distributed along the roads and that the road network consists of two sets of parallel roads, one set being perpendicular to the other. Figure 5 gives the results for a number of actual road networks in England and it is again assumed that destinations are uniformly distributed along the sides of the roads.

Examination of the results shows that, despite the wide range of kinds of road network and of shapes of central area, the average distance traveled varies only from $0.62A^{1/2}$ to $1.07A^{1/2}$, the more realistic cases varying from 0.77 to $1.07A^{1/2}$. All the results obtained are within 30 percent of the mean value $0.85A^{1/2}$, while 88 percent of the results are within 12 percent of $0.87A^{1/2}$. It seems likely, therefore, that if we substitute $0.87A^{1/2}$ for $\bar{d}$, the result will, in practice, not usually be subject to large error.

The Capacity per Unit Width of Road

A number of investigations have been carried out in various countries to find the road capacity of city streets. The recently published Highway Capacity Manual (2) devotes some attention to it and gives graphs showing that, in the absence of parking, and for apporach widths larger than a certain amount, the number of vehicles that can pass through a single-controlled intersection per hour of green time is approximately

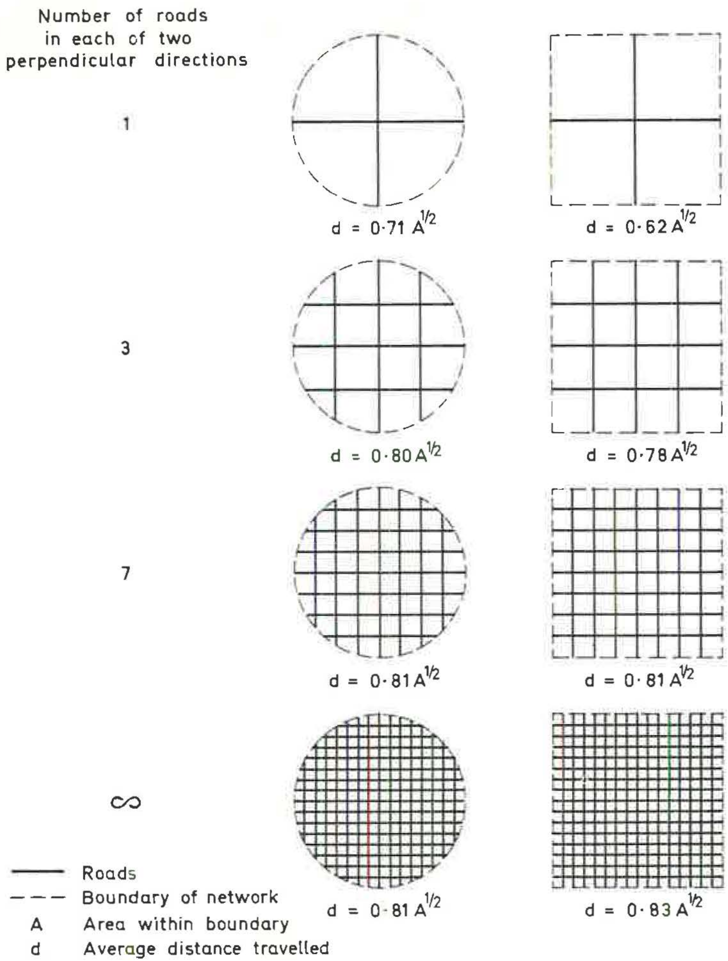


Figure 2. Effect of density of roads on average distance traveled assuming uniform density of destinations per unit length of road (rectangular routing).

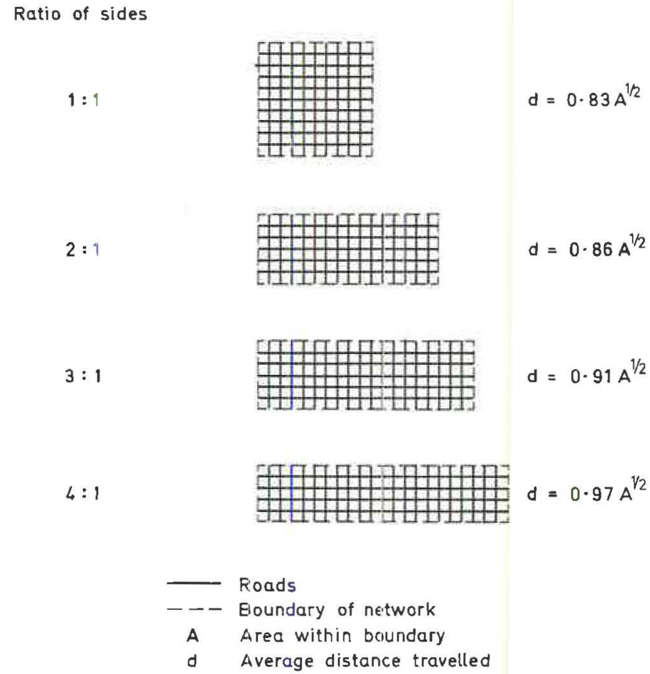
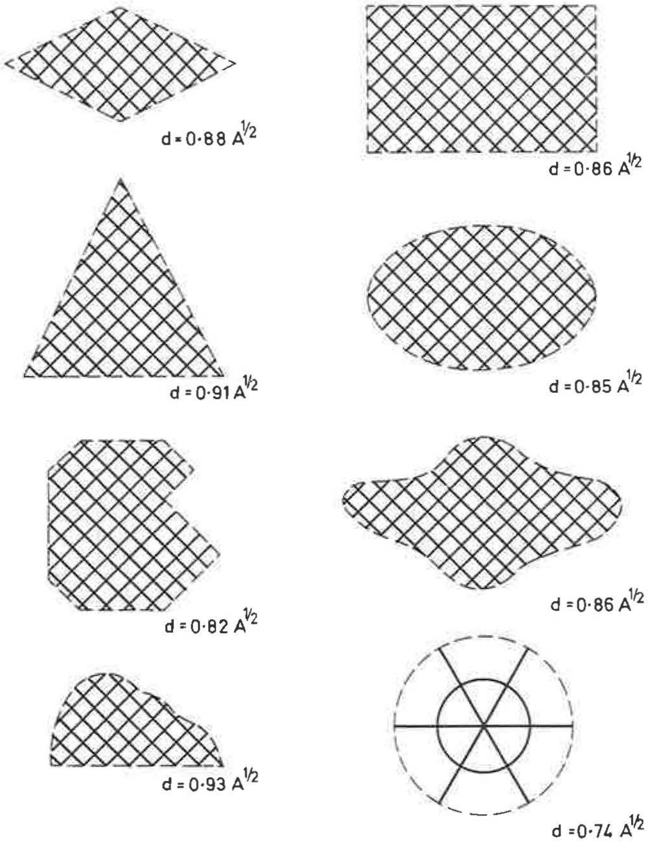


Figure 3. Effect of length/breadth ratio on average distance traveled in a rectangular-shaped CBD (roads infinitely close together and parallel to sides of CBD).



—— Roads
– – – Boundary of network
A Area within boundary
d Average distance travelled

Figure 4. Average distance traveled on some miscellaneous imaginary networks (number of destinations per unit length of road uniform).

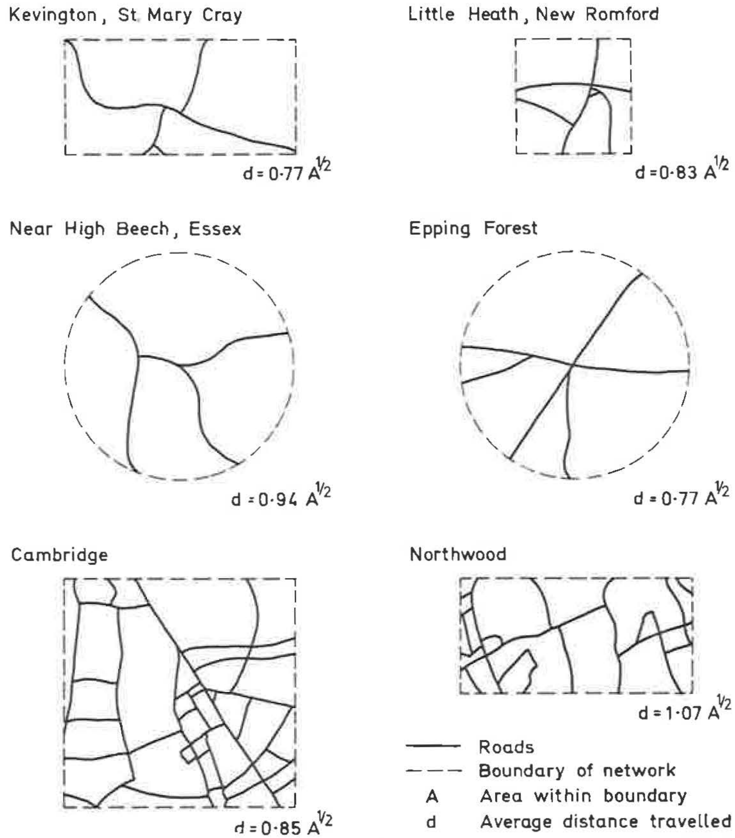


Figure 5. Average distance traveled on some real road networks (number of destinations per unit length of road assumed constant).

proportional to the approach width. A similar result has been obtained in Great Britain (3). Since the intersections are, in general, the factors limiting the capacity of urban streets, it follows that the capacity of urban streets is approximately proportional to their widths, as was assumed above. The factor of proportionality is perhaps best obtained from an investigation carried out in Great Britain, where a relationship has been obtained between the average speed of traffic and its amount for roads of given width. In an earlier paper (1) this relationship was put into algebraic form, and it was found that, provided the average speed is not too small, more than 4 mph, say, the capacity per unit width per hour, Q/W, is given approximately by

$$\frac{Q}{W} = 58 - 0.0052v^3$$

where v is the average journey speed in miles per hour and capacity is measured in pcu's, i.e., passenger car units. According to "Research on Road Traffic" (3), the pcu values appropriate to urban streets are

Cars and light vans	1.0
Medium commercial vehicles	1.75
Heavy commercial vehicles	2.5
Buses and coaches	3.0
Motorcycles	0.75
Bicycles	0.33

The Value of J

The value of J, the effective proportion of the total carriageway used during peak travel periods, depends mainly on the proportion of the total carriageway suitable for general movement during such periods and on the extent to which both sides of the roads are in use. Since in many towns large areas of carriageway are only suitable for serving neighboring buildings, and because travel is predominantly in one direction in peak periods, a value of J considerably less than unity and perhaps between ⅓ and ½ is generally to be expected. Further investigation is required on this point, but the effect on road space required of travel being predominantly in one direction was examined (4) for some cases of idealized towns. The results of calculations given (4) show that, for circular towns and for ring, radial-arc and rectangular routing, as defined in Figure 1, the proportions of through carriageway fully used during peak periods were 85, 81, 83 and 77 percent respectively.

An Approximate Theoretical Formula for the Road Capacity of City Centers

It has been found that:

1. $N = \frac{JQ}{W} \cdot \frac{fA}{\bar{d}}$
2. $\bar{d} = 0.87A^{1/2}$, approximately, for a wide range of cases.
3. $Q/W = 58 - 0.0052v^3$, provided that Q/W is measured in passenger car units per hour and per foot width of carriageway and that v is measured in miles per hour.

It follows that

$$N = (58 - 0.0052v^3)\, fA^{1/2}/0.87 = J(67 - 0.0060v^3)\, fA^{1/2}$$

approximately, for a wide range of cases, provided that N and v are expressed in the above units and A in square feet.

Assuming J to be between ½ and ⅓, the analysis therefore suggests that the maximum number of vehicles that can usefully circulate per hour in a CBD with a normal

TABLE 1

VALUES FOR $N/fA^{1/2}$ FOR VARIOUS CBD'S

N = pcu's per hour, one way
A = Area of CBD (sq ft)
$f = \frac{\text{carriageway area}}{\text{total area}}$

Towns of Great Britain	
Edinburgh	12
Bradford	14
Maidenhead	15
Darlington	15
Liverpool	17
Hull	19
Nottingham	19
Leeds	21
Sheffield	21
Cardiff	24
Birmingham	24
Coventry	25
Watford	25
Bristol	25
Reading	25
Leicester	25
Maidstone	27
London	29
Towns Outside Great Britain	
Salisbury, S. Rhodesia	11
Dublin, Eire	12
Hamburg, Germany	14
Lisbon, Portugal	14
Tel Aviv, Israel	14
Denver, U. S. A.	17
Stockholm, Sweden	18
Goteborg, Sweden	24
Washington, U. S. A.	26
The Hague, Netherlands	28
Copenhagen, Denmark	29
Los Angeles, U. S. A.	30

type of road network is between $20fA^{1/2}$ and $30fA^{1/2}$ if the speed is 10 mph and between $22fA^{1/2}$ and $33fA^{1/2}$ if the speed is 5 mph or less. If the speed of traffic is higher, the numbers of vehicles that can circulate would be expected to be less. If the speed is 15 mph, the number would be expected to be between, say, $15fA^{1/2}$ and $23fA^{1/2}$, and at 20 mph, between $6fA^{1/2}$ and $9fA^{1/2}$.

Summing up, it would appear that the number of vehicles (expressed pcu's) that can usefully circulate per hour in a central business district would be expected to be very roughly $(33 - 0.003v^3)fA^{1/2}$ or, as v is usually in the range of 5 to 20 mph, between $6fA^{1/2}$ and $33fA^{1/2}$.

A number of authorities have kindly supplied data on the numbers of vehicles of various types entering particular CBD's during peak travel periods, on the total area and on the area of carriageway within the CBD's. Other data have been collected from various sources. All the complete sets of data for CBD's available at the time of writing this paper are summarized in the Appendix to this paper. From these data, the values of $N/fA^{1/2}$ have been calculated and are given in Table 1. (Some data given in Ref. 1 have been omitted, because they include large areas outside the CBD's, or because full details of the types of vehicles were not available or, as in the case of some United States cities, because only estimates were available for the value of f. There are some differences between the data in Table 1 and those given in Ref. 1 because other sets of data were subsequently obtained, sometimes with different definitions of CBD's, and because rather different pcu values were used.)

The theoretical analysis suggests that the number of vehicles (pcu's) that can usefully enter a town center would lie between 6 and 33 $fA^{1/2}$. The data in Table 1 for the 30 towns for which information is available suggest that the number of vehicles (pcu's) that actually enter lies between 12 and 30 $fA^{1/2}$. All of the data available are consistent with the theoretical analysis made above. This suggests that the formula obtained for the capacity of a CBD network has some value, but it does not prove the complete validity of the formula. For this, values of J, v and $\bar{d}$ must be obtained for a number of towns, and the results analyzed.

FURTHER INVESTIGATIONS REQUIRED

Sufficient evidence is given to make it possible to draw the conclusion that, for a number of towns, the numbers of vehicles that enter (or leave) the CBD's per hour is given, very approximately, by the formula

$$N = (33 - 0.003v^3)\, fA^{1/2}$$

It is likely, however, that the formula can be improved and more exact conditions under which it is likely to apply specified. The subject to which the formula applies is important and the further research needed requires information from many towns. The information primarily required for any CBD is:

1. The numbers of vehicles of various kinds entering or leaving the CBD per hour during peak travel periods.
2. The area of the CBD.
3. The area of carriageway within the CBD.
4. The area of carriageway carrying very little traffic, e. g., cul-de-sacs.
5. The average speed of the traffic.
6. The average distance traveled by the vehicles within the CBD.

Many highway authorities and others throughout the world have a great deal of this information and it would be very difficult for any single researcher to obtain it independently. The author of this paper would be very grateful if anyone having relevant information would send it to him even if, as will generally be the case, they have only a part of the information required.

Some Limitations on the Applicability of the Formula

Care should, of course, be taken not to use the expression for the range of possible capacities of a CBD for circumstances in which it would not reasonably be expected to apply. For example, if the policy of widening the intersections in a CBD were adopted, the capacity of the intersections could be made more nearly equal to the capacity of the roads leading into them, and the capacity of the whole network would be greater than that indicated by the formula. Again, if there were a ring road of adequate capacity around the CBD with adequate intersection capacity, the formula would have to be materially modified if the area of the ring road were not included as part of the CBD. The formula would also not apply if a high proportion of the carriageway area were high-capacity roads, such as freeways.

ACKNOWLEDGMENTS

In the previous paper on the subject (1), the writer acknowledged the great assistance he had received from a number of authorities in supplying basic data. Since the earlier paper was written, he has received further information, and is indebted to H. Cooke, City Engineer of Bradford; N. H. Stockley, City Engineer of Liverpool; A. L. Hobson, City Engineer of Kingston upon Hull; H. D. Gauntlett, City Engineer of Cardiff; W. R. Shirrefs, City Engineer of Leicester; F. M. Little, City Engineer of Nottingham; C. R. Warman, City Engineer of Sheffield; J. B. Bennett, City Engineer of Bristol; P. van Hoffen, Senior Assistant Traffic Engineer of Salisbury, Rhodesia; R. C. Thomas, Assistant Traffic Engineer of Denver, Colorado; R. Lovret, City Planner of Los Angeles, California; Dan Hanson of the Highways Department, Washington, D. C..

The author is also indebted to J. Dawson of the Geography Department of University College, London, for making estimates of the area of carriageway in a number of towns and, especially to Miss G. O. Jeffcoate for assistance in the calculations and particularly for calculating the value of $\bar{d}$ in a high proportion of the cases shown in Figures 2, 3, 4 and 5.

REFERENCES

1. Smeed, R. J. Road Capacity of City Centres. Traff. Engng. and Control, Nov. 1966; Int. Road Saf. and Traff. Rev., Jan. 1967.
2. Highway Capacity Manual, 1965. HRB Spec. Rept. 87, 1965.
3. Research On Road Traffic. H. M. S. O., 1965.
4. Smeed, R. J., and Holroyd, E. M. Some Factors Affecting Congestion in Towns. Paper presented at Engineering for Traffic Conference, July 1963.

Appendix

COMPLETE CBD DATA

Town	Area Within Cordon (10^6 sq ft) (A)	Proportion of Carriageway (f)	Vehicles Crossing Cordon During Peak Hour, One Way							Total pcu's (N)	$\frac{N}{fA^{1/2}}$
			Cars, Taxis, Light Goods	Heavy Commercial	Medium and Heavy Commercial	All Goods	P.S.V.'s	Motorcycles	Bicycles		
Great Britain											
Edinburgh	43.6	.19	9,781		679		934	1,044	1,102	15,091	12
Bradford	14.3	.20	7,263		532		547	509		10,349	14
Maidenhead	3.1	.14	2,695		95		75	235	800	3,553	15
Darlington	3.6	.19								5,375	15
Liverpool	31.2	.18	10,260		1,550		800	1,675		17,010	17
Hull	8.4	.17	5,814		532		333	1,105	2,036	9,384	19
Nottingham	19.6	.17	7,200			2,800	1,000			14,400	19
Leeds	12.8	.21	10,855		745		1,060	500	140	15,947	21
Sheffield	44.8	.12	11,664		879		748	1,272	478	16,779	21
Cardiff	9.2	.12	5,338			707	472	684	1,784	8,922	24
Birmingham	10.2	.15								11,750	24
Coventry	11.5	.17	10,837		1,279		165			13,890	25
Leicester	30.3	.11								15,100	25
Watford	4.74	.096	3,980		160		125	530	585	5,267	25
Bristol	85.1	.11	18,220		1,978		925	2,262		26,647	25
Reading	4.2	.15	5,610		255		255	725	1,340	7,875	25
Maidstone	2.4	.12	3,902	174			144	512		5,153	27
London	348	.15	55,675		5,445		2,025	7,880	3,305	79,652	29
Rest of World											
Salisbury, Rhodesia	13.6	.38								15,000	11
Dublin, Ireland	14.5	.12	10,000		1,000		675	2,000	6,500	17,700	12
Hamburg, Germany	46.3	.19								17,900	14
Lisbon, Portugal	10.8	.20	5,765			651	772	514		9,300	14
Tel Aviv, Israel	64.6	.12	7,893		584		787	2,289	1,839	13,750	14
Denver, Colo., U. S. A.	10.1	.26								14,200	17
Stockholm, Sweden	36.6	.12	10,500			1,000	300			12,900	18
Goteborg, Sweden	9.7	.18								13,445	24
Washington, D. C., U. S. A.	44.6	.24								41,152	26
The Hague, Holland	22.1	.16	9,980			1,274	198	813	23,387	20,890	28
Copenhagen, Denmark	61.4	.13	19,409		1,099		1,197	4,457	4,558	30,059	29
Los Angeles, Calif., U. S. A.	34.8	.23								40,000	30