The Congestion Approach to Rational Programming

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Conventional sufficiency ratings are subjective and arbitrary in the assigning of point values, and fail in the comparison of rural with urban facilities. A proposed priorities rating formula for the Commonwealth of Pennsylvania, based on rational sufficiencies, resolves most of these difficulties, and is arbitrary only in accepting desirable speeds as 50 mph (legal) in rural and 30 mph in urban areas.

The formula does not use safety as an independent factor, believing its containment in the structural and functional elements of rating to be a proper evaluation and not to be duplicated within a rating system. Non-uniformity of accident reporting, and non-separability of driver psychology from road characteristics as accident causation further determined this decision.

"Structural" and "functional" factors are evaluated in dates of retirement rather than points.

Date of structural obsolescence is found from the survivorship curves of the BPR Road Life Study, utilizing the area under the curves between 1959 and expiration to determine the average life of the unretired mileage of the applicable road surface. The date obtained is correctible by field observation of visible abnormal failures.

Functional obsolescence is determined by the calculated year in which forecasted demand volumes equal the capacity of the road section. Capacity of rural roads is computed by the method described in "Public Roads", June 1958, using Pennsylvania's "policy" speeds. Comparable urban capacities were not available, necessitating a research study which found average capacities of city streets at a desired speed of 30 mph.

Because of deferred construction, a significant portion of mileage is currently operating above capacity. An additional technique to determine priority for these road segments calculates the total vehicle delay, using curves of the aforementioned method and the urban study to find average travel speeds for varying volumes of using traffic. All hourly volumes exceeding the hourly capacity volume are analyzed for vehicle-hour delays and accumulated.

Hourly percents of ADT's are necessary to the computations; which required the updating of records from Pennsylvania's 55 permanent count stations. Charts of these findings are contained in the paper.

A modified benefit-cost ratio is obtained by dividing total vehicle-hours delay cost (which represents a relative measure of benefit to be achieved by reconstruction) by the estimated cost of the improvement. This ratio indicates the congestion that can be alleviated per dollar expenditure.

Road sections are tabulated by years of obsolescence, and in descending values of this ratio, insuring that appropriations will be expended to alleviate the greatest amount of vehicle delay. The "needs" study by years is thus unfolded, and, balanced against appropriations, a construction program is established.

Mass data processing is obligatory to such a project, and compromises are obligatory to mass data processing. Available records must be used for expediency, and average conditions assumed generally. Periodic reruns for programs will use updated and amplified records, and indicated research will refine its methods.

● THE SUFFICIENCY rating concept as evolved in 1947 (1) was probably the foremost achievement of a century in highway administration. It lifted highway evaluation from the realm of speculation to a position of factual analysis. Its acceptance among progressive organizations was immediate, but due to the great amount of data needed, its implementation was tardy. In fact the data collection seemed so insurmountable to some organizations, that, at least until recently, they have continued their evaluation on an "I guess", speculative, basis.

Acceptance of the details of the original rating did not meet with unanimity. This was to be expected. Probably no group of highway engineers assembled would assign the same relative importance (point values) to the eleven roadway elements defined in the system, and to the three categories of consideration. Some users also disagreed with the placement of an element in an original category. The cutting and filling that followed the original theory is well documented (2). The disagreements are far from destructive, they are the constructive forces of revolutionary process. It is significant to note that later evolution has become increasingly aware of the category of functional sufficiency and has placed increasing importance upon it. The break-away trend of motor vehicle usage in the past decade has been compelling, and has forced the revision of values. In the opinion of the writer, the 30 points originally assigned to functional sufficiency in 1947, are obsolete in 1960.

An inherent difficulty of the point value system of sufficiency rating is the subjectiveness involved in the field rating. On a large highway system where it is not feasible for one rater to evaluate the entire system, there arises the human error. Even with one rater operation, is the writer's experience unusual that his assignment of values becomes biased with the increasing number of valuations? That at the start, road surfaces appear low in points, but as the number of low ratings accumulates in quantity, the rater arbitrarily feels that his previous rating of "5" should be "7" and he thereafter uses the rating of "7" without changing the previous "5's"?

A further difficulty the writer has experienced with conventional sufficiency ratings, is the inability to compare urban with rural highways. In an urbanized state, with the urban and rural interests in a continual condition of controversy, this problem attains high significance.

The formula described in this paper seeks to reconcile the difficulties of conventional sufficiency rating, and to extend the rating to a determination of priorities for programming improvements.

GENERAL REMARKS

The formula does not bring any originality into the field of highway administration, but it does combine and make a composite of techniques and methods not usually related to each other. It accepts the three conventional categories of sufficiency rating, namely structural, safety and functional. At the present time, no valid means of evaluating the safety category in Pennsylvania has been found which would not distort the over-all rating. Accident ratings as collected are not uniform nor complete, the responsibilities for reporting being scattered between local and state jurisdictions. Further there is no delineation in accident records to separate driver deficiencies from road deficiencies. And who has not been cognizant of the fact that the most hazardous road section is the most accident free section? Again, evaluations of structural and functional sufficiency in themselves rate safety, at least in part. In short, accounting for safety in this system has been relegated to later modifications of the system. The formula therefore confines its consideration to the categories of structural and functional sufficiency.

With many thousands of miles of highway to be analyzed, a rating system must be adaptable to mass data processing; is therefore subject to the use of averages; and cannot consider specifics. For example, in using capacity it cannot, at least at present, recognize that at Broad and Main Streets in Squeedunk Township there is a 20 percent left turn movement east bound to south bound. These inaccuracies in the "averaging" of parameters is believed to be small in percentage, and, within the programming by "years", will be negligible, except for very exceptional conditions.

The method determines the dates in years in which each road section will reach structural retirement and functional obsolescence respectively, and where these dates are significantly different, evaluates and selects the less costly to the road user of (a) continuing congestion compared to (b) increased annual cost by building additional capacity into the structure.

It is obvious that deferred construction and maintenance for years previous to the rating establishes a large percentage of roads having functional obsolescence dates prior to the rating year, and that, in the ultimate objective of programming, these roads will generally lie in the top bracket of priority. In Pennsylvania and probably other states, this percentage of roads can absorb all the legislative appropriations for many years to come.

An additional technique is therefore used to find the degree of congestion that has accrued to functionally obsolete highways. This is accomplished in terms of delay time measured with respect to desired travel time. The term "congestion delay" is used to symbolize this measurement.

"Congestion delay" can be re-defined by saying it is the amount of delay time accruing from the degree of functional obsolescence of a highway. Evaluated in dollars, it would represent the cost the road user is paying for the deficiency, and conversely the savings or benefit that would result from its correction. Knowing the cost of improving the roadway, a modified benefit-cost ratio exists, and if the greatest benefit is to be derived from the funds available, priority should be in descending values of this modified benefit-cost ratio.

As an illustration, suppose Road A has a benefit (congestion) of $300,000, and would cost $500,000 to improve; Road B has a benefit of $500,000 and an improvement cost of $700,000; while Road C has a benefit of $600,000 and an improvement cost of $1,200,000. If priority was determined on benefit (congestion) alone, Road C would be constructed. But examination reveals that for the same expenditure, $1,200,000, there will be $300,000 plus $500,000, or $800,000 of benefits from constructing Roads A and B, as compared to $600,000 of benefit from Road C. Some programming

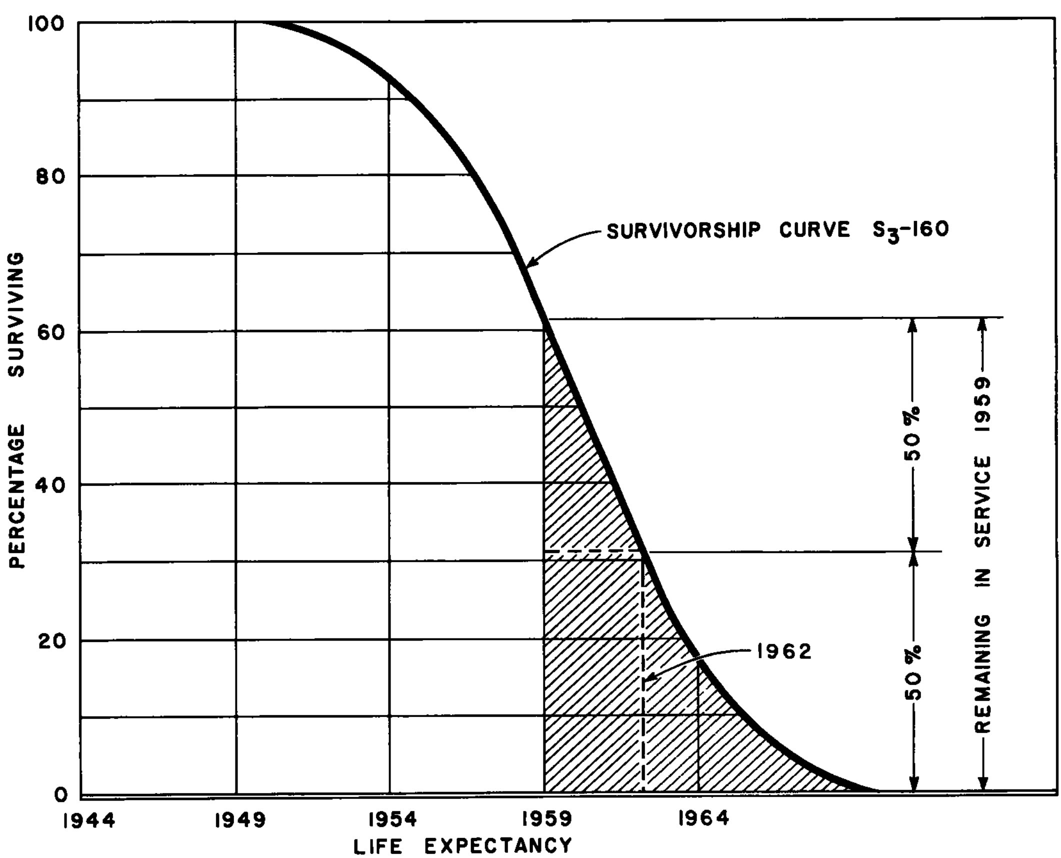

Figure 1. Life expectancy—bituminous penetration built 1944.

TABLE 1

HIGHWAY COST SECTION ROAD LIFE STUDIES AVERAGE LIFE DATA

Construction Year	Construction Miles	Miles Remaining 1/1/53	Type Curve and Average Life
	Soil Surfaced		
1936			
1936	1 13	00	S6- 7 0A
1937	2 50	2 50	None 16 0
	Gravel or Stone		
1904 & Pr	27 79	45	S3- 22 1A
1905	62 01	00	L5- 11 2A
1906	107 13	00	L4- 11 1A
1907	113 92	00	L5- 9 1A
1908	196 37	00	L4- 8 4A
1909	144 59	00	L4- 7 5A
1910	61 82	00	L3- 6 8A
1911	26 61	00	L3- 5 0A
1912	20 31	00	L3- 4 9A
1913	3 83	00	S6- 5 4A
1914	5 22	00	R5- 10 6A
1915	36 06	00	R1- 5 8A
1916	5.26	00	S6- 6 0A
1917	8 16	00	L5- 5.1A
1918	4 70	00	R5- 18 6A
1920	23 92	00	L5- 4 6A
1921	16 52	00	L4- 3 6A
1922	10 99	33	L4- 4 6A
1923	28.17	00	L3- 3 1A
1924	17.09	00	L2- 4 4A
1925	29	16	None 27 6A
1926	2 29	00	S6- 11 0A
1928	09	09	None 25 0
1930	33	00	L5- 1 8A
1931	3 89	00	R5- 11 8A
1932	8.26	3 91	S1 - 16 5A
1935	2 68	2 51	None 18 7A
1936	2.91	2 84	None 18 3A
1937	15 74	1 52	S6- 4 8A
1938	11 79	5 46	None 9 7A
1939	9 54	00	L5- 2 8A
1941	5.74	00	S6- 1 0A
1945	11.12	7 97	S6- 8 0
1946	8 42	8 42	S6- 8 0
1947	4 87	3 22	S1- 6 5
1948	13 60	13 13	S3- 8 0
1949-52	42 74	52 74	S3- 18 0
	Bituminous Surface Treated		
1904 & Pr	9 79	57	None 34 1A
1907	8 27	00	L4- 25.8A
1908	4 97	00	L3- 19.1A
1909	2 46	00	S6- 33.7A
1910	69 73	39 13	R3- 38.8
1911	6 30	98	L0- 16.0
1912	39 82	11 36	L0- 23 7
1913	3 62	2 37	None 34 0
1914	197 41	19 89	L0- 14 7
1915	553 09	121 19	L0- 20 1A
1916	237 96	40.36	L0- 19 6A
1917	188 98	58 39	L0- 23 6A
1918	121 08	12 22	L0- 13 4A
1919	204 37	30 65	L0- 14 8A
1920	159 60	21 84	L0- 16 9A
1921	283 13	56 79	L0- 20 1A
1922	345 29	75 67	L0- 17 6A
1923	248 49	89 97	L0- 20 6A
1924	237 94	84 86	L0- 21 2A
1925	184 91	73 26	L0- 21 0A
1926	198 64	83 42	S0 - 23 5
1927	280 47	133 28	S1 - 24 5
1928	189.39	136 70	R2- 30 0
1929	111 95	89 38	R3- 30 0
1930	455 40	375 16	R4- 27 5
1931	608 44	451 63	R3- 25 5
1932	479 69	283 58	R2- 21 5
1933	220 58	165 45	R2- 25 0
1934	166 69	123 69	R2- 23 5
1935	86 37	72 76	R2- 28 0
1936	54 34	31 56	S3- 17 5
1937	10 61	6 41	S1- 17 5
1938	31 45	22 67	S0- 20 0
1939	56 99	50 42	R5- 19 5
1940	60 47	37 79	R1- 14 5
1941	69 47	64 93	R4- 17 5
1942	36 29	32 63	R3- 17 5
1943	33 01	31 71	R3- 17 5
1944	9.51	9 08	R3- 17 5
1945	62 56	46 72	L4- 9 0
1946	70 08	68 46	R3- 17 5
1947	49 15	46 47	R2- 15 0
1948	66 30	60 83	S0- 14 0
1949	39 21	36 93	S0- 14 5
1950	19 57	19 57	S2- 15 0
1951	11 66	11 58	S1- 15 0
1952	85 43	85 43	S1- 15 0

Construction Year	Construction Miles	Miles Remaining 1/1/53	Type Curve and Average Life
	Bituminous Penetration		
1905	3 38	00	L5- 26 4A
1906	4 25	00	R5- 29 2A
1907	55	00	R5- 28 7A
1909	1 30	00	S6- 19 0A
1910	4 26	1 91	None 30 0A
1911	7 70	95	L3- 21 3A
1912	5 62	1 74	L3- 25 7A
1913	50 13	17 74	S1- 28 0A
1914	44 54	20 79	S1- 30 0A
1915	17 17	9 70	R3- 33 0A
1916	2 90	2 90	None 37 0
1918	5 16	4 45	None 33 7A
1919	38	00	S6- 31 0A
1920	11 55	2 42	S0- 16 8A
1921	41 92	10 63	S1- 24 5
1922	59 95	4 83	S0- 19 0A
1923	59 31	13 45	L1- 16 8A
1924	166 51	59 78	S0- 20 5A
1925	70 30	34 38	R1- 25 0
1926	29 69	17 56	R1- 27 5
1927	48 57	18 35	L1- 20 0
1928	39 90	30 67	R4- 27 0
1929	21 44	15 71	R3- 25 0
1930	13 97	9 34	R3- 23 0
1931	104 71	58 50	R1- 22 0
1932	201 37	132 85	R2- 21 5
1933	82 52	59 67	S2 - 23 0
1934	158 37	136 08	S3 - 25 0
1935	52 89	39 66	R2- 22 0
1936	58 55	48 56	R2- 23 0
1937	51 66	41 68	R2- 22 5
1938	49 34	40 81	R2- 22 0
1939	48 01	46 09	R4- 22 0
1940	58 79	55 67	S3 - 20 0
1941	58 47	57 28	S3 - 20 0
1942	8 07	6 36	R1- 17 0
1943	3 37	3 04	S2 - 16 5
1944	1 03	1 02	S3 - 16 0
1945	3 76	3 76	S3 - 16 5
1946	24 94	24 40	S2 - 16 5
1947	12 55	11.42	S0 - 16 5
1948	23 67	22 52	S0 - 16 0
1949	33.57	33 33	S1 - 16 0
1950-52	16 80	16 80	S1 - 16 0
	Bituminous Concrete		
1904	13 43	85	S4 - 23 3A
1905	09	00	S6 - 9 0A
1906	2.75	28	S6 - 26 3A
1907	55	00	S6 - 23 0A
1908	2 83	00	S6 - 27 0A
1909	9.23	5 79	None 37 8A
1910	27.56	5 19	S4 - 25 5A
1911	2.26	1 68	None 42 0A
1912	19 67	1 16	L3- 26 3A
1913	47 60	9 22	L3- 24 3A
1914	15 60	2 61	L2- 19 5A
1915	30 88	5 11	S0 - 22 0A
1916	6 34	2 91	None 25 3A
1917	5 37	1 00	S5 - 31 0
1918	17 26	1 23	R1- 17 5
1919	37 49	4 87	S0 - 21 0
1920	43 39	12 19	L1- 20 6A
1921	62 50	20 40	S1 - 26 0
1922	61 45	8 16	S1 - 21 0
1923	36 09	17 80	S0 - 28 5
1924	44 74	15 76	S1 - 24 5
1925	24 83	20 84	R5- 31 0
1926	14 19	11 05	R4- 30 5
1927	20 61	14 72	R3- 28 5
1928	6 34	2 77	S1 - 23 0
1929	11 14	3 27	L1- 16 0
1930	10 70	1 38	S3 - 17 0
1931	5 50	00	S6 - 20 5A
1932	18 25	9 29	S1 - 15 8A
1933	18 11	17 49	S6 - 22 5
1934	53 10	28 80	S1 - 19 0
1935	15 88	11 78	S2 - 22 0
1936	102 71	60 45	R3- 17 0
1937	141 18	88 10	L2- 20 0
1938	342 28	226 51	L2- 19 0
1939	106 99	83 30	L2- 21 0
1940	92 84	67 96	L2- 19 0
1941	106 11	94 71	S2 - 19 5
1942	51 99	50 99	S3 - 20 0
1943	62 84	43 34	None 16 2A
1944	103 90	88 89	L1- 20 0
1945	120 19	110 25	S1 - 19 0
1946	170 70	156 39	S0 - 20 0
1947	178 22	172 57	S1 - 20 0
1948	278 28	267 70	S0 - 20 0
1949	289 23	274 01	L0- 20 0
1950	307 73	304 04	S0 - 20 0
1951	314 66	313 89	S0 - 20 0
1952	389 51	388 42	S0 - 20 0

TABLE 1 (continued)

HIGHWAY COST SECTION ROAD LIFE STUDIES AVERAGE LIFE DATA

Construction		Miles Remaining	Type Curve
Year	Miles	1/1/53	and Average Life
	Portland Cement Concrete		
1910 & Pr	45	30	None 31 2A
1911	41	00	S6 - 18 0A
1912	28	28	None 41 0A
1913	2 84	1 44	None 30 2A
1914	2 36	2.15	None 39.5A
1915	3 67	15	R5 - 21 0A
1916	9 55	.73	R5 - 30 2A
1917	6 05	23	L5 - 19 3A
1918	13 80	5 43	None 23 8A
1919	59 09	2 79	L3 - 20 3
1920	179 90	28 34	S2 - 24 5
1921	598 28	169.21	S2 - 26 5
1922	344 90	123 12	S3 - 28 0
1923	427 58	170 44	S3 - 28 0
1924	412 20	121 34	S2 - 24 5
1925	750 57	294 89	S1 - 25 0
1926	495 65	216 49	S1 - 25.0
1927	451 74	302 93	S2 - 29.5
1928	406 42	278 80	S2 - 29.5
1929	367 31	282 45	S3 - 28.5
1930	878 99	708 26	S3 - 28 5
1931	155 15	125 94	S3 - 27 5
1932	74 10	64 33	S3 - 28 0
1933	172 52	132.35	S1 - 28 5
1934	121.33	110 01	S2 - 31 0
1935	95 75	81 16	S2 - 26 0
1936	116 15	89 85	S1 - 24 5
1937	150 42	118 09	S1 - 23.5
1938	110 81	98 07	S2 - 23 5
1939	93 57	81 30	S1 - 23 5
1940	75 19	68 77	S2 - 22.5
1941	174 91	172 77	S3 - 25 0
1942	103 69	100 36	S2 - 24 5
1943	72 63	60 63	S2 - 15.0
1944	20 98	20 88	S2 - 25 0
1945	5 24	4 50	R1 - 19.5
1946	27 00	26 15	R3 - 17 0
1947	65 04	64 18	S1 - 25.0
1948	123 06	122 90	S2 - 25.0
1949-52	340 55	340 55	S3 - 25 0
	Brick or Block		
1904 & Pr	5 98	2 72	None 41 0A
1905	25	25	None 49 0A
1906	86	37	L4 - 36 2A
1907	4.06	34	L4 - 28 2A
1908	9 74	06	S2 - 24 3A
1909	5 43	02	S3 - 24 8A
1910	6 67	03	L5 - 26 6A
1911	5 41	00	L5 - 14 9A
1912	8 44	00	R4 - 15 4A
1913	15 34	7 96	None, 33 4A
1914	11 95	1 00	R3 - 21 7A
1915	10 87	2 00	L3 - 26 0A
1916	8 33	5 14	None 34 8A
1917	10 97	00	L5 - 19 4A
1918	2 22	08	R2 - 18 6A
1919	14 38	38	L3 - 21 7A
1920	17 71	09	L3 - 21 8A
1921	29 79	2 87	R2 - 22 0
1922	12 35	1 65	S2 - 22 0
1923	10.98	3 33	S2 - 25 0
1924	5 58	80	L5 - 23 0
1925	4 05	88	R3 - 22 5
1926	1 06	93	None 25 0A
1927	.25	25	None 26 0A
1929	14 29	41	R5 - 14 4A
1930	77	01	S6 - 17 1A
1931	1 38	22	L5 - 9 5A
1934	2.16	2 04	S5 - 23 0
1938	22	21	R4 - 23.0
1946-50			
1950	1 56	1 56	S4 - 25 0
	Mixed Bituminous		
1925	3 70	00	S6 - 26 0A
1927	24	24	S6 - 26 0
1933	31 54	26.47	R3 - 27 0
1934	73 47	59 74	R4 - 22.5
1935	84 17	67 04	S2 - 24 0
1936	25 47	22 44	R3 - 24.5
1937	25 02	10.33	S4 - 15.0
1938	53 29	50 56	R4 - 23.5
1939	19.45	17 83	R3 - 23.5
1940	40 34	35 84	S3 - 18.0
1941	79 18	76 44	R4 - 19.5
1942	25 11	20.03	S0 - 19.0
1943	10 67	9 73	S2 - 17.0
1944	4 01	4 01	S4 - 17.0
1945	7 54	7 54	S4 - 17.0
1946	19 16	18 53	S2 - 15.0
1947	30.74	28 87	S1 - 15.0
1948	53 47	53 88	S1 - 15.5
1949	63 00	62 22	S1 - 16.5
1950	50 47	48 77	S0 - 15.0
1951-52	210 63	210 63	S2 - 15.0
	Bituminous Penetration		
1917	92	00	S6 - 7 0A
1920	6 50	00	R5 - 7.4A
1921	4 12	1 54	None 17 5A
1922	15 23	4 58	None 17.1A
1923	3 77	54	None 8 4A
1924	68 75	8 26	L0 - 13.5
1925	73 20	27 30	R1 - 17.7A
1926	39 87	13 65	R3 - 23.3
1927	22 62	15.12	R2 - 24 0A
1928	7 11	2 18	None 17 7A
1929	1 32	00	S6 - 11 0A
1930	6 76	5 75	None 23 2A
1931	34.89	24 30	R4 - 20 6A
1932	2 87	2 71	None 22 9A
1934	3 48	3 23	None 20 0A
1940	7 04	7 04	S6 - 16.0

formulas overlook this principle. Arranged in descending values of modified benefit-cost ratio, the priority becomes

Road B — 0.714
Road A — 0.600
Road C — 0.500

The complexity and mass of data to be handled for any but the smallest of highway systems, compels the use of electronic data processing. Any attempt to use manual processing would find the information obsolete before the program could be issued. It is therefore incumbent on the development of a formula to have that formula capable of being electronically processed. In the following discourse, the reader will quite often question the use of "averages," "short cuts" and items of a similar nature. The author hopes such questions can be answered as due to the characteristics of electronic data processing.

SUFFICIENCY RATING

Structural Retirement Date

The method seeks to determine the calendar year in which a roadway will require improvement, and ignores detail deficiencies which in reality are maintenance items or are factors modifying capacity. Hereafter, the term "structural retirement date" will be used.

The structural retirement date or structural (in) sufficiency of a roadway is its life expectancy as determined from the road life curves for Pennsylvania highway surfaces. These curves have been plotted from data collected by the Department of Highways as analyzed by the Bureau of Public Roads. Review of the referenced material (3) is suggested for any readers unfamiliar with the subject. Table 1 lists the types of paving by year of construction, and their survivorship curves. From reconstruction of the curves such as that shown in Figure 1 for bituminous penetration built in 1944, the average life expectancy remaining in service after 1959 may be determined by projecting the bisector of the 1959 ordinate horizontally to intersect the curve. The ordinate of the intersection is the year of the average remaining life, which in Figure 1 is 1962.[1]

Typical of such a set of curves is the spread of remaining life, approximately ten years in the illustration. Although other factors are involved, it is believed that traffic volume and truck usage are overwhelming determinates of these spreads. Since no study was available to determine the factual relationship, an empirical set of factors was promulgated (4) as shown in Table 2.[2]

The structural retirement date of a specific section of highway, then, is the algebraic sum of (a) the year of average life expectancy and (b) the truck-volume correction in years.

This date of structural retirement is to be supplemented by a field examination. Only in cases of visible failure will the date be voided.

TABLE 2

TRUCK–VOLUME CORRECTIONS

Vehicles per Day	Commercial Vehicles (Percent)	Correction (Years)
0 - 500	10 or less	+4
501 - 3000	10 or less	+3
501 - 3000	More than 10	+2
3001 - 5000	10 or less	+1
3001 - 5000	More than 10	0
5001 - 7500	10 or less	-1
5001 - 7500	More than 10	-2
7501 - up	10 or less	-3
7501 - up	More than 10	-4

Stated in another way, the author contends that the expected life of a road surface cannot be usually determined with reasonable accuracy by even the most experienced personnel, except where failure already exists. And by corollary, no "paper" determination can dispute evident failure.

Digressing because of the mass data processing requirements, a saving of "machine" time was found by converting the average lives of the road surfaces into equations. For each type of surface, the date of retirement was plotted against the date of construction and the linear curve of best fit determined by the method of least squares. Figure 2 shows the plotting for cement concrete pavements and Figure 3 shows the composite curves.

Functional Obsolescence Date

In the concept of this paper, functional obsolescence is defined as the date when forecasted traffic volumes will equal the capacity of the highway section at desirable operating speeds. "Desirable operating speeds" are the policy, legal, or terrain speeds established.

Pennsylvania's legal speed limit of 50 mph thus becomes its "desirable operating

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[1] Bisecting the area under the curve is the accurate method. The method shown is within tolerable error.

[2] A research project is intended to compare actual retirement with the empirical, to accurately determine the relationship between the three factors.

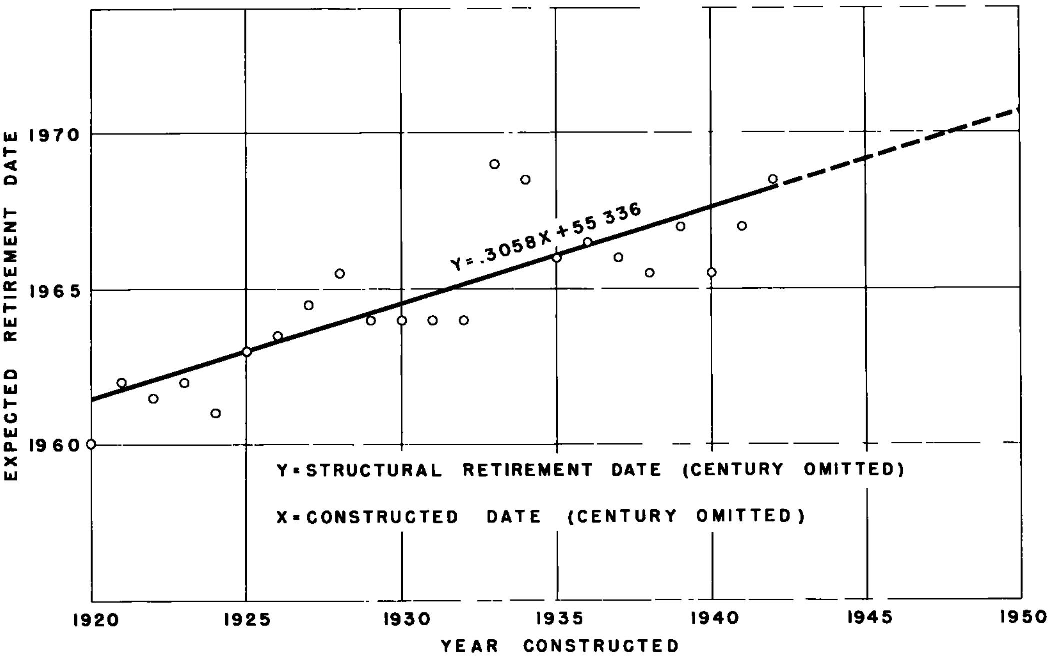

Figure 2. Life expectancy—concrete pavement type 70.

speed," except where the cost of mountainous or rolling construction dictates a lower speed, or where urban areas necessitate reduced speeds. For emphasis, the definition is restated: All highways should have a capacity, such that, at all times, vehicles will be able to operate at the legal rate of speed or at the maximum rate of speed which economics and terrain permit.

TABLE 3

OPERATING SPEEDS—60 MPH DESIGN SPEED HIGHWAY

Equivalent Volume VPH	Operating Speed MPH					
	Sight Distance %					
	0	20	40	60	80	100
100	52.5	56	57.5	58	58.5	59
200	50.5	53	55.5	56.5	57	57.5
300	48	50.5	53	54.9	56	56.5
400	45	48.5	51	53	54	55
500	42.5	45.5	48	52.5	53	53.5
600	40	42.5	46	49	51	52.5
700	38	40	42.5	46.5	48.5	50
800	37 5	38.5	40	43	46.5	48.5
900	36.5	37.5	38	40	43.5	46
1,000	36	36	37.5	39	41.5	43
1,100	34	35	36	37 5	38.5	40
1,200	33.5	34	34 5	35	36	37.5
1,300	32.5	33	33.5	33.5	34	34.5
1,400	32	32.5	32.5	33	33	33.5
1,500	-	-	-	-	-	-

For the purpose of this paper, the following policy levels, hereinafter designated as the "desirable operating speed" are used:

Rural, Flat Terrain - 50 mph
Rural, Rolling Terrain - 40 mph
Rural, Mountainous Terrain - 35 mph
Urban Streets - 30 mph

It follows then that "capacity" as used for definition, is the number of vehicles that the road section will pass at these desired operating speeds.

The research of Schwender, Normann and Granum (5)[3] provide the means for determining this relationship for rural roads. Their curves (5) can be converted to provide the parameter. The ADT is obtained from "a 30th highest hourly volume during the year of 12 percent of the average daily traffic." Table 3 has been developed from their curves for 60 mph Design Speed Highways, using miles per hour as the operating speeds, and vehicles per hour as volume (12 percent of ADT).

[3] The reference omitted shoulder width correction factors, which are: 0 ft, 90 percent; 2 ft, 97 percent; 4 ft, 100 percent; and 6 ft or more, 107 percent.

TABLE 4

URBAN STREET CAPACITIES

Width Curb-to-Curb Ft	Downtown Parking Permitted VPH	Other Parking Permitted VPH	Width Curb-to-Curb Ft	Downtown Parking Permitted VPH	Other Parking Permitted VPH
30	246	246	66	414	533
32	250	257	68	430	552
34	253	268	70	445	571
36	257	278	72	461	593
38	261	289	74	477	615
40	265	300	76	492	638
42	272	318	78	508	660
44	279	336	80	524	683
46	286	354	82	543	706
48	293	372	84	562	729
50	300	390	86	581	753
52	314	408	88	601	776
54	328	425	90	620	800
56	341	443	92	640	826
58	355	460	94	661	851
60	369	478	96	682	769
62	384	496	98	703	903
64	399	515	100	723	928

As an example of the use of this table: find the capacity of a road at a desirable speed of 50 mph in rural flat terrain having a design speed of 60 mph and a 1, 500 ft sight distance of 60 percent.

Entering the table under the column for 60 percent sight distance, operating speeds of 52.5 mph and 49 mph are found to correspond with 500 vph and 600 vph, respectively. Interpolating, 50 mph capacity is found to be 572 vph.

No comparable data for relating volumes to operating speeds of urban streets could be found in the literature. It was therefore necessary to conduct a field study (6) to obtain this relationship. Table 4 is an adaptation from this study, showing the urban street capacities in vph at the desired operating speed of 30 mph for various street widths, curb to curb, parking permitted.

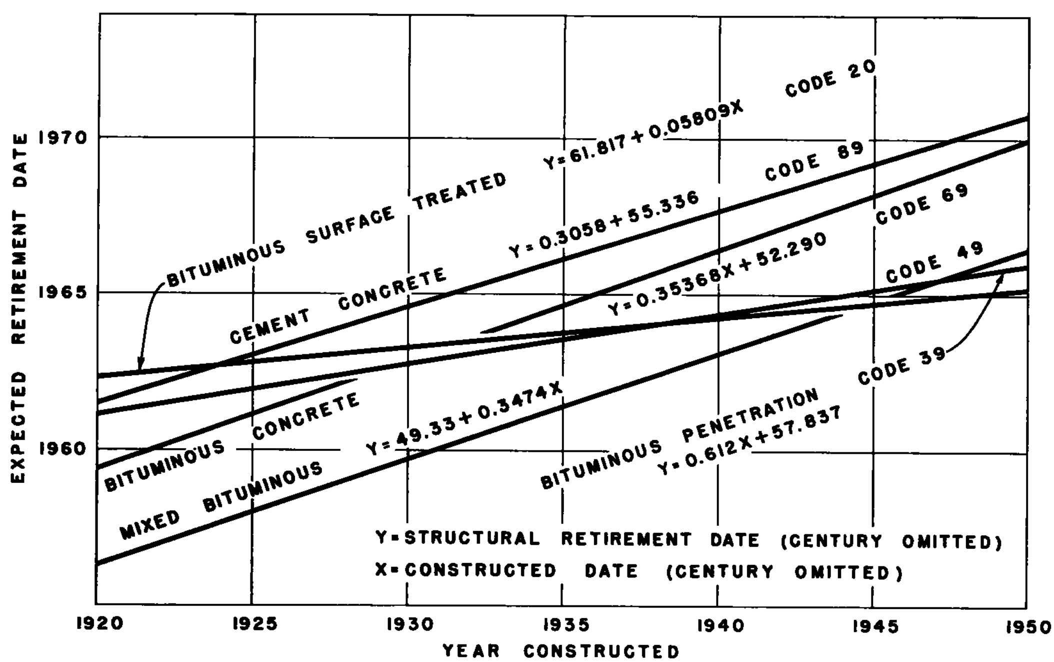

Figure 3. Composite life expectancy chart.

Future traffic volumes are forecasted from past experience in growth patterns. Pennsylvania maintains 55 permanent traffic count stations which supply the data for establishing growth factors in each of 67 counties. Short counts are made on a continuing program supplemented by special assignment counts.

The year of equality of traffic volume and road capacity (functional obsolescence date) is given by the formula [4]

$$X = Y + \frac{\log C/V}{\log (1+e)}$$

where

X = equality year

Y = year of known ADT

C = capacity of road section

V = ADT of the known year

e = annual expansion factor for the region

Thus, if a road section of 5,000 ADT capacity had a traffic volume of 2,500 vehicles a day in 1956, and the annual expansion factor for the region was 0.05, it would reach capacity in

$$X = 1956 + \frac{\log \frac{5000}{2500}}{\log\ 1.5}$$

$$= 1956 + 14.2 = 1970$$

According to the writer's definition, the functional obsolescence for this road would therefore be 1970.

RECONCILIATION OF SUFFICIENCY DATES

Thus far, in this process of road evaluation, two critical years have been found. Most often, these dates will be separated; sometimes widely. A decision must be made on which date is to prevail. For example, suppose the road section is structurally retired in 1963, but will not be functionally obsolete until 1970. Should the road be resurfaced in 1963, and, assuming a 15-yr life expectancy, suffer congestion between 1970 and 1978? Or should it be reconstructed in 1963, providing unneeded and wasted capacity from 1963 to 1970? Reversing the above dates, suppose the road will be functionally obsolete in 1963 and structurally retired in 1970. Should the congestion be tolerated for seven more years, or should the road be reconstructed, losing seven years of its structural life?

---

[4] Expansion of traffic volumes is compounded as follows:

$$C = V\,(1+e)^{X-Y}$$

$$\frac{C}{V} = (1+e)^{X-Y}$$

$$\log \frac{C}{V} = (X-Y) \log (1+e)$$

$$X - Y = \frac{\log \frac{C}{V}}{\log (1+e)}$$

$$X = Y + \frac{\log \frac{C}{V}}{\log (1+e)}$$

TABLE 5A

VEHICLE DELAY FACTOR

Design Speed 60 MPH — Desired Speed 50 MPH

Equivalent Volume (VPH)	Sight Distance % 0	20	40	60	80	100
100	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
200	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
300	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
400	.0021	.0005	0.0000	0.0000	0.0000	0.0000
500	.0035	.0019	.0007	0.0000	0.0000	0.0000
600	.0049	.0035	.0016	.0003	0.0000	0.0000
700	.0062	.0049	.0035	.0014	.0005	0.0000
800	.0067	.0059	.0049	.0032	.0014	.0005
900	.0075	.0067	.0062	.0049	.0029	.0016
1000	.0079	.0079	.0067	.0055	.0040	.0026
1100	.0093	.0085	.0079	.0067	.0059	.0049
1200	.0098	.0093	.0089	.0085	.0079	.0067
1300	.0107	.0102	0098	.0098	.0093	.0089

Design Speed 50 MPH — Desired Speed 50 MPH

Equivalent Volume (VPH)	Sight Distance % 0	20	40	60	80	100
100	0.0004	0.0002	0.0000	0.0000	0.0000	0.0000
200	.0027	0.0008	0.0002	.0000	0.0000	0.0000
300	.0050	.0022	.0008	0.0004	0.0000	0.0000
400	.0063	.0038	.0017	.0008	0.0004	0.0004
500	.0070	.0050	.0027	.0011	.0006	0.0004
600	.0078	.0056	.0038	.0022	.0011	.0008
700	.0082	.0066	.0053	.0036	.0022	.0013
800	.0086	.0070	.0063	.0044	.0033	.0022
900	.0094	.0082	.0070	.0056	.0044	.0033
1000	.0099	.0086	.0082	.0063	.0056	.0047
1100	.0103	.0094	.0086	.0078	.0070	.0063
1200	.0108	.0103	.0099	.0086	.0078	.0074
1300	.0113	.0108	.0103	.0099	.0094	.0090

TABLE 5B

VEHICLE DELAY FACTOR

Design Speed 40 MPH — Desired Speed 50 MPH

Equivalent Volume (VPH)	Sight Distance % 0	20	40	60	80	100
100	0.0060	0.0053	0.0050	0.0050	0.0050	0.0050
200	0.0070	0.0060	0.0056	0.0053	0.0050	0.0050
300	0.0082	0.0063	0.0056	0.0056	0.0050	0.0050
400	0.0094	0.0067	0.0060	0.0056	0.0053	0.0050
500	0.0099	0.0070	0.0063	0.0060	0.0056	0.0050
600	0.0103	0.0077	0.0067	0.0060	0.0056	0.0053
700	0.0108	0.0086	0.0070	0.0063	0.0060	0.0056
800	0.0108	0.0094	0.0077	0.0067	0.0063	0.0060
900	0.0113	0.0099	0.0090	0.0074	0.0070	0.0063
1000	0.0118	0.0103	0.0094	0.0082	0.0070	0.0067
1100	0.0118	0.0108	0.0099	0.0090	0.0082	0.0074
1200	0.0118	0.0113	0.0108	0.103	0.0094	0.0090
1300	0.0118	0.0113	0.0108	0.0103	0.0103	0.0099

Design Speed 40 MPH — Desired Speed 45 MPH

Equivalent Volume (VPH)	Sight Distance % 0	20	40	60	80	100
100	0.0037	0.0030	0.0027	0.0027	0.0027	0.0027
200	0.0047	0.0037	0.0033	0.0030	0.0027	0.0027
300	0.0059	0.0040	0.0033	0.0033	0.0027	0.0027
400	0.0071	0.0044	0.0037	0.0033	0.0030	0.0027
500	0.0076	0.0047	0.0040	0.0037	0.0033	0.0027
600	0.0080	0.0054	0.0044	0.0037	0.0033	0.0030
700	0.0085	0.0063	0.0047	0.0040	0.0037	0.0033
800	0.0085	0.0073	0.0054	0.0044	0.0040	0.0037
900	0.0090	0.0076	0.0067	0.0051	0.0047	0.0040
1000	0.0095	0.0080	0.0071	0.0059	0.0047	0.0044
1100	0.0095	0.0085	0.0076	0.0067	0.0059	0.0051
1200	0.0095	0.0090	0.0085	0.0080	0.0071	0.0067
1300	0.0095	0.0090	0.0085	0.0080	0.0080	0.0073

TABLE 5C

VEHICLE DELAY FACTOR

Design Speed 50 MPH — Desired Speed 45 MPH

Equivalent Volume (VPH)	Sight Distance % 0	20	40	60	80	100
100	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
200	0.0005	0.0000	0.0000	0.0000	0.0000	0.0000
300	0.0028	0.0000	0.0000	0.0000	0.0000	0.0000
400	0.0041	0.0016	0.0000	0.0000	0.0000	0.0000
500	0.0048	0.0028	0.0005	0.0011	0.0000	0.0000
600	0.0056	0.0034	0.0016	0.0000	0.0000	0.0000
700	0.0060	0.0044	0.0032	0.0014	0.0000	0.0000
800	0.0064	0.0048	0.0041	0.0022	0.0011	0.0000
900	0.0072	0.0060	0.0048	0.0034	0.0022	0.0011
1000	0.0077	0.0064	0.0060	0.0041	0.0034	0.0025
1100	0.0081	0.0072	0.0064	0.0056	0.0048	0.0041
1200	0.0086	0.0081	0.0077	0.0064	0.0056	0.0052
1300	0.0091	0.0086	0.0081	0.0077	0.0072	0.0068

Design Speed 40 MPH — Desired Speed 45 MPH

Equivalent Volume (VPH)	Sight Distance % 0	20	40	60	80	100
100	0.0037	0.0030	0.0027	0.0027	0.0027	0.0027
200	0.0047	0.0037	0.0033	0.0030	0.0027	0.0027
300	0.0059	0.0040	0.0033	0.0033	0.0027	0.0027
400	0.0071	0.0044	0.0037	0.0033	0.0030	0.0027
500	0.0076	0.0047	0.0040	0.0037	0.0033	0.0027
600	0.0080	0.0054	0.0044	0.0037	0.0033	0.0030
700	0.0085	0.0063	0.0047	0.0040	0.0037	0.0033
800	0.0085	0.0073	0.0054	0.0044	0.0040	0.0037
900	0.0090	0.0076	0.0067	0.0051	0.0047	0.0040
1000	0.0095	0.0080	0.0071	0.0059	0.0047	0.0044
1100	0.0095	0.0085	0.0076	0.0067	0.0059	0.0051
1200	0.0095	0.0090	0.0085	0.0080	0.0071	0.0067
1300	0.0095	0.0090	0.0085	0.0080	0.0080	0.0073

TABLE 5D

VEHICLE DELAY FACTOR

Design Speed 40 MPH — Desired Speed 40 MPH

Equivalent Volume (VPH)	Sight Distance % 0	20	40	60	80	100
100	0.0009	0.0002	0.0000	0.0000	0.0000	0.0000
200	0.0019	0.0009	0.0005	0.0002	0.0000	0.0000
300	0.0031	0.0012	0.0005	0.0005	0.0000	0.0000
400	0.0043	0.0016	0.0009	0.0005	0.0002	0.0000
500	0.0048	0.0019	0.0012	0.0009	0.0005	0.0000
600	0.0052	0.0026	0.0016	0.0009	0.0005	0.0002
700	0.0057	0.0035	0.0019	0.0012	0.0009	0.0005
800	0.0057	0.0043	0.0026	0.0017	0.0012	0.0009
900	0.0062	0.0048	0.0039	0.0023	0.0019	0.0012
1000	0.0067	0.0052	0.0043	0.0031	0.0019	0.0016
1100	0.0067	0.0057	0.0048	0.0039	0.0031	0.0023
1200	0.0067	0.0062	0.0057	0.0052	0.0043	0.0039
1300	0.0067	0.0062	0.0052	0.0052	0.0052	0.0048

Design Speed 35 MPH — Desired Speed 40 MPH

Equivalent Volume (VPH)	Sight Distance % 0	20	40	60	80	100
100	0.0044	0.0044	0.0040	0.0040	0.0036	0.0036
200	0.0049	0.0044	0.0044	0.0040	0.0036	0.0036
300	0.0053	0.0049	0.0049	0.0044	0.0040	0.0036
400	0.0053	0.0049	0.0049	0.0044	0.0040	0.0036
500	0.0063	0.0053	0.0049	0.0044	0.0040	0.0040
600	0.0067	0.0058	0.0049	0.0044	0.0040	0.0040
700	0.0067	0.0058	0.0053	0.0044	0.0040	0.0040
800	0.0073	0.0058	0.0053	0.0044	0.0040	0.0040
900	0.0073	0.0063	0.0053	0.0049	0.0044	0.0044
1000	0.0073	0.0063	0.0058	0.0053	0.0049	0.0044
1100	0.0073	0.0063	0.0048	0.0053	0.0049	0.0049
1200	0.0078	0.0067	0.0063	0.0053	0.0049	0.0049
1300	0.0078	0.0067	0.0067	0.0063	0.0058	0.0058

The analysis to find which answer is more economical to the highway user is laborious. Carried out manually for 54,000 miles of highway, it would seem impractical. But with electronic data processing, it becomes a few hours of machine time.

It consists of determining the summation of the annual costs which will accrue from each alternative, and selection of the less costly.

Annual costs of construction are computed by conventional methods, allowing for overhead and maintenance and using average life expectancies of the road surfaces. The author prefers the useful life as being the sum of the lives of the original surface and one resurfacing, where the traffic volume expansion is not expected to greatly exceed the ultimate capacity. On high volume roads, the useful life is taken as that of the original surface. Because annual costs are peculiar to each particular state or jurisdiction, this paper will not present those found in Pennsylvania.

Annual costs of congestion delay are not so readily calculated. It will be necessary at this point to depart from the central theme to what must be an extensive description of computing congestion delay costs.

TABLE 5E

VEHICLE DELAY FACTOR

Design Speed 35 MPH — Desired Speed 45 MPH

Equivalent Volume (VPH)	Sight Distance % 0	20	40	60	80	100
100	0.0072	0.0072	0.0068	0.0068	0.0064	0.0064
200	0.0077	0.0072	0.0072	0.0068	0.0068	0.0064
300	0 0081	0.0077	0.0077	0.0072	0.0068	0.0064
400	0.0081	0.0077	0.0077	0.0072	0.0068	0.0064
500	0.0091	0.0081	0.0077	0.0072	0.0068	0.0068
600	0.0095	0.0086	0.0077	0.0072	0.0068	0.0068
700	0.0095	0.0086	0.0081	0.0072	0.0068	0.0068
800	0.0101	0.0086	0.0081	0.0072	0.0068	0.0068
900	0.0101	0.0091	0.0081	0.0077	0.0072	0.0072
1000	0.0101	0.0091	0.0086	0.0081	0.0077	0.0077
1100	0.0101	0.0091	0.0086	0.0081	0.0077	0.0077
1200	0.0106	0.0095	0.0091	0.0081	0.0077	0.0077
1300	0.0106	0.0095	0.0095	0.0091	0.0086	0.0086

CONGESTION DELAY COST

Congestion Delay Time

It is axiomatic that vehicle operating speeds decrease as traffic volumes increase. The relationship has been established in varying degrees by many researchers (5, 6, 7, 8).

Since travel time is an inverse function of speed, a corollary of the axiom follows that travel time increases with increasing traffic volumes.

At some critical point in the relationship "congestion" is encountered. That critical point is the point at which actual operating speeds equal desired operating speeds. It is the point of "capacity" as defined above. If the actual operating speed falls below the capacity speed, "congestion delay" is encountered. From the research of Schwender, Normann and Granum (5), and of Coleman (6), come the tools for finding the delay for any degree of congestion measured in vehicle hours.

To demonstrate, assume the desired operating speed to be 40 mph on a 60-mph design-speed rural highway, having a 40 percent sight distance. Table 3 shows that operating speeds drop to 40 mph at a volume of 800 vph. This is the capacity as defined. If the volume increases to 1,100 vph, the operating speed falls to 36 mph. At

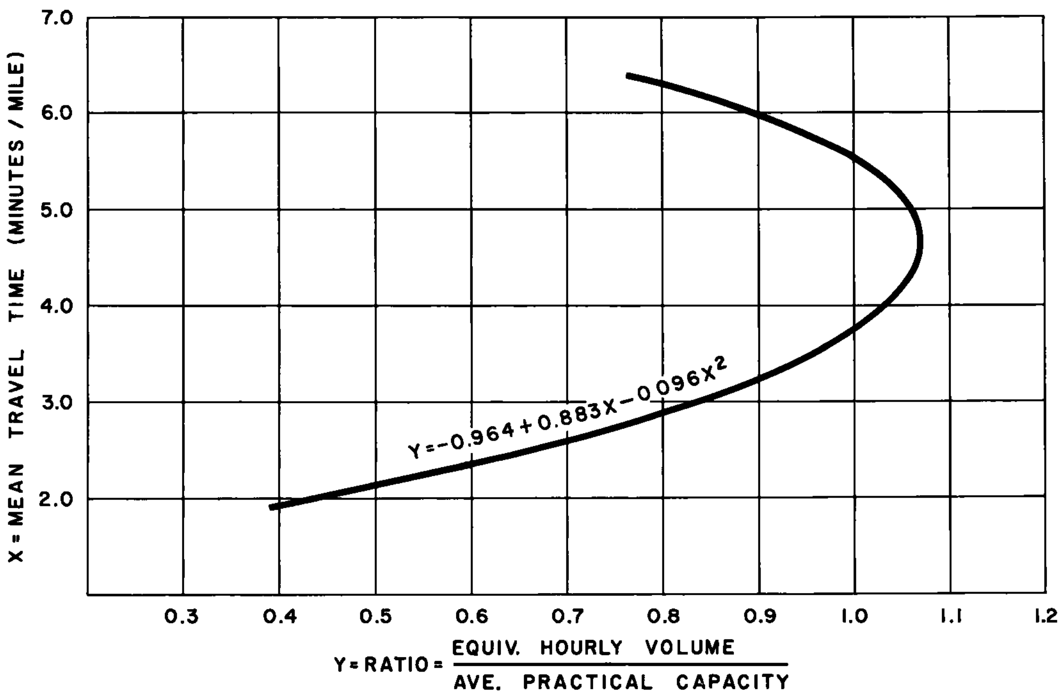

Figure 4. Travel time—arterial two-way streets.

40 mph, 0.025 hr will be required to travel one mile, and at 36 mph 0.028 hr is required. The difference of 0.003 hr to 1,100 vehicles amounts to 3.30 vehicle hours of congesting delay during that hour.

As a manual operation, such calculations would be prohibitive for a highway system of any great mileage. With electronic data-processing, however, it becomes feasible, and to save machine time, the calculation method is altered. The difference in travel time is the difference in the reciprocals of the speeds.

Expressed as an equation:

$$D = \frac{1}{AS} - \frac{1}{DS}$$

where

D = delay in hours to one vehicle

AS = actual operating speed at the volume level

DS = desired operating speed

Tables can be prepared for D for each value of traffic volume and for each desired speed condition. Tables 5A through 5E are those applicable to Pennsylvania's requirements.

For example, an existing road has a 40-mph design speed with 100 percent sight distance. What is the delay to 1,000 vph if 50-mph is the desired speed? Entering the table for 40-mph design speed and 50-mph desired operating speed, the delay is 0.0067 vph to one vehicle and 1,000 x 0.0067 = 6.7 hours total congestion delay time.

Correction Factors

It is to be noted that the left hand column of Tables 5A through 5E is titled "Equiv-

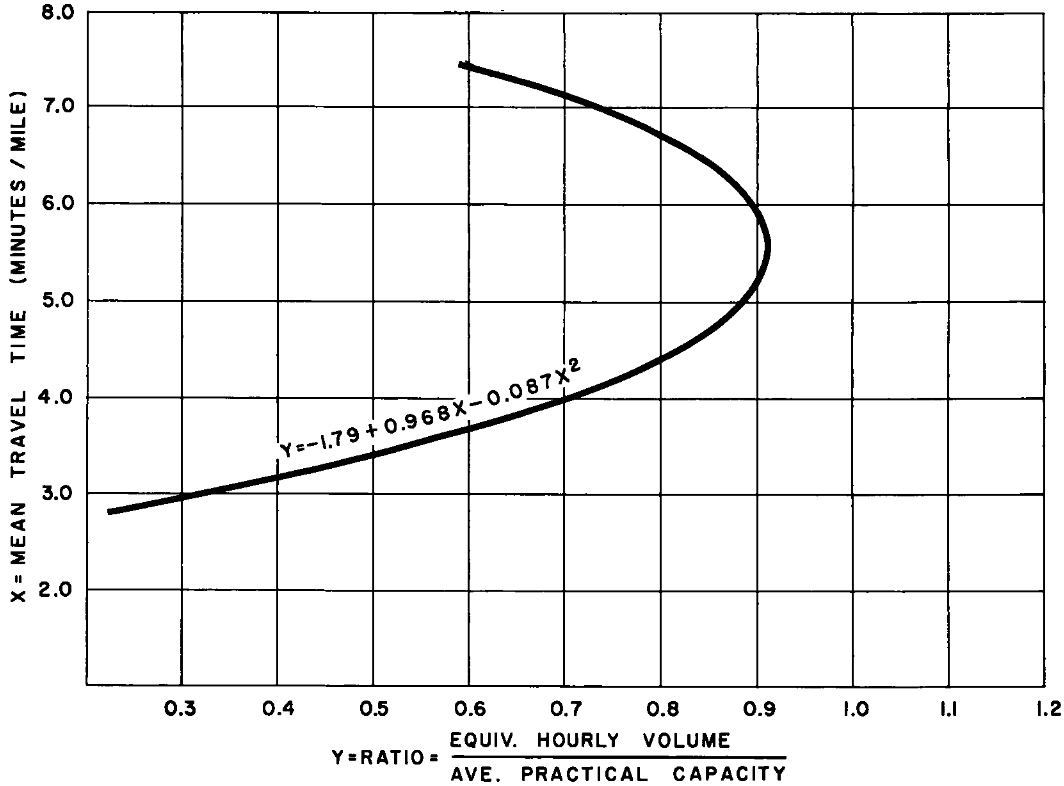

Figure 5. Travel time—arterial one-way streets.

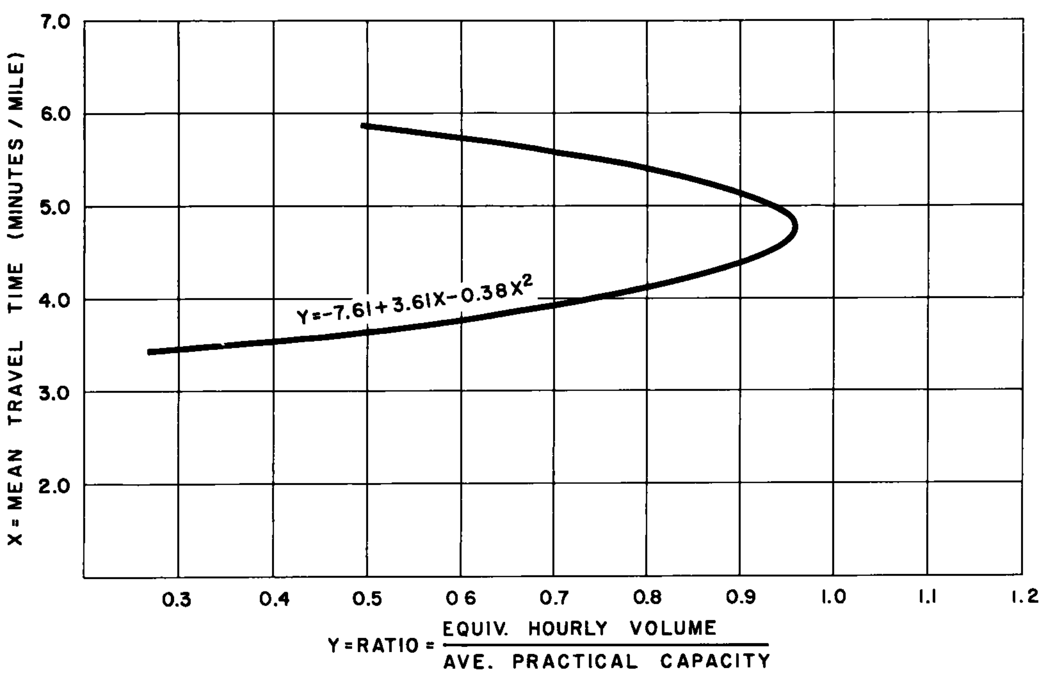

Figure 6. Travel time—local two-way streets.

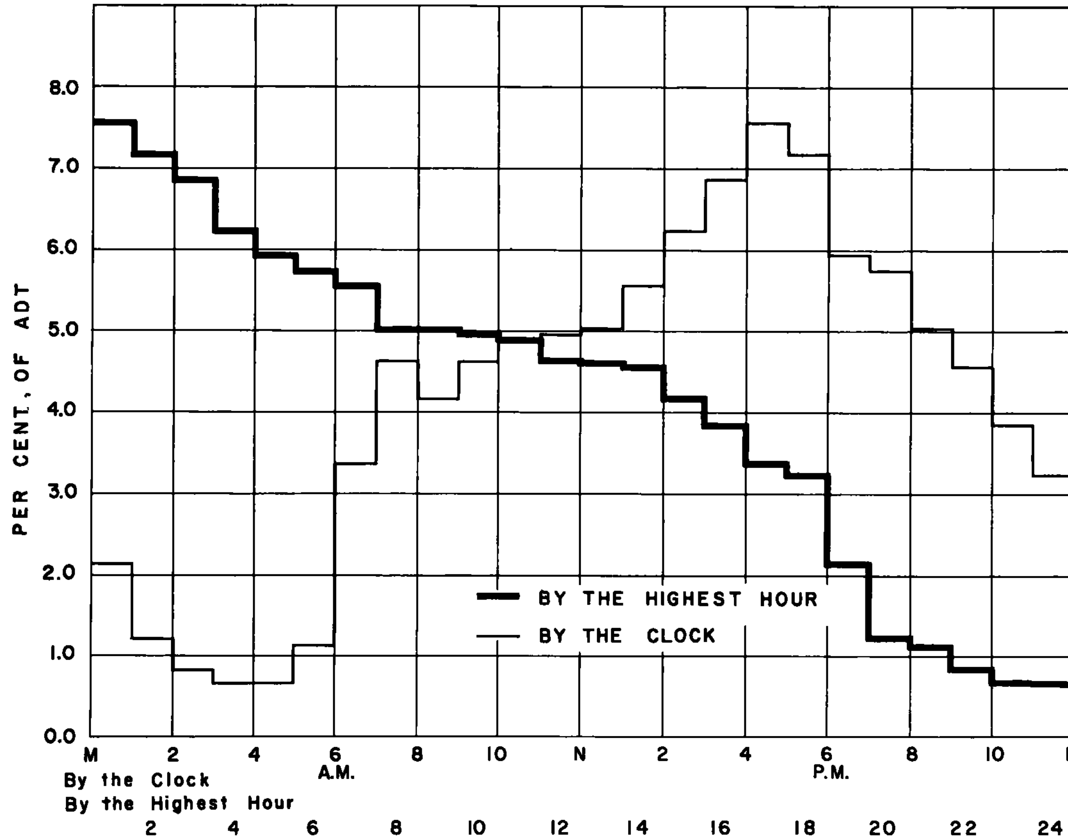

Figure 7A. Hourly volumes in percent of ADT primary rural.

lent Volume." So far the demonstration has been confined to "ideal" conditions: 12-ft lane width, level terrain, 5 percent commercial vehicles, etc., the "ideal" conditions stated in Schwender, Normann and Granum's paper (5). Any deviations from the ideal find their adjustment in terms of increases in numbers of vehicles that would be required on the "ideal" highway. The adjustments are treated at length in their paper and reiteration here is unnecessary. It should be noted, however, that the delay time from the tables accumulates to the actual number of using vehicles and not to the equivalent volume. Thus, if on other than an ideal facility, a volume of 500 vehicles has an equivalent volume of 700 vehicles, and a delay time of 0.002 hours is indicated, the total delay time is 500 x 0.002 hours and not 700 x 0.002 hours.

Congestion delay for urban streets is computed by using certain of the charts from Coleman's paper (6). The essential portions of these charts are reproduced here as Figures 4 through 6.

Figures 4 and 5 apply to state highways, Figure 6 is reproduced for the benefit of jurisdictions which may be concerned. In explanation of Coleman's charts, the parameter of equivalent hourly volume is the passenger car equivalent of the combination of passenger cars and commercial vehicles. The average practical capacity is that found in the Highway Capacity Manual (pp. 84, 86) as recently revised. (The revised charts are herewith reproduced as Figures 9 and 10). Selection of the percent of green time is at the decision of the individual user. Again, because of the mass data processing, a compromise between actual signal timing and average signal timing is mandatory. The author has assumed that the characteristics of a state highway are such that a 65 percent green time is not an unreasonable average. Average travel time in minutes is plotted as the abscissa.

Note that the curves are parabolic in form and that for an ordinate value, two travel times are possible. The upper value lies on the "saturation" portion of the curve resulting from the well-established principle that any demand above possible capacity results in increased travel time for the using volume.

It is therefore prerequisite to using these charts to first determine whether the indicated volume-capacity ratio exceeds the curve reversal points, 1.068 in Figure 4 and 0.91 in Figure 5. (See Appendix A for treatment of values on the upper leg.) This is demonstrated as follows: It is desired to know the total delay time for a one-mile section of arterial street, two-way, parking permitted, having a curb-to-curb width of 60 ft when the volume is 700 vph, the percent commercial being such that the equivalent volume is 900 vph, using 65 percent green time.

Entering Figure 9 at 30 ft (½ of 60 ft), the approach traffic volume is read as 1,400 vph green time; 1,400 x 0.65 gives 910 average practical capacity. Equivalent Hourly Volume ÷ Average Practical Capacity = 900 ÷ 910 = 0.99 and this value lies on the lower leg of the curve. Entering Figure 4 with this ratio value, 3.74 min or 0.0623 hr is found to be the mean travel time and 0.0623 x 700 = 43.6 hr total congestion delay.

Accumulation

The above has treated the mechanics of determining the congestion delay for any single hour. For many highways and streets, congestion may occur during the evening peak, or during the morning peak, or both, and in some cases, during the full 24 hours of the day. Quite often analysts will fall into the error of limiting their considerations to peak hour volumes. If all highways were equal in their geometrics, the peak hour comparison of one highway with all other highways would be valid for a functional rating. But geometrics do vary. A 5,000 ADT highway with 9-ft lanes in mountainous terrain will certainly have congestion spread over a greater number of hours than a 5,000 ADT, 12-ft lane highway over flat terrain. In the functional rating process, it is necessary

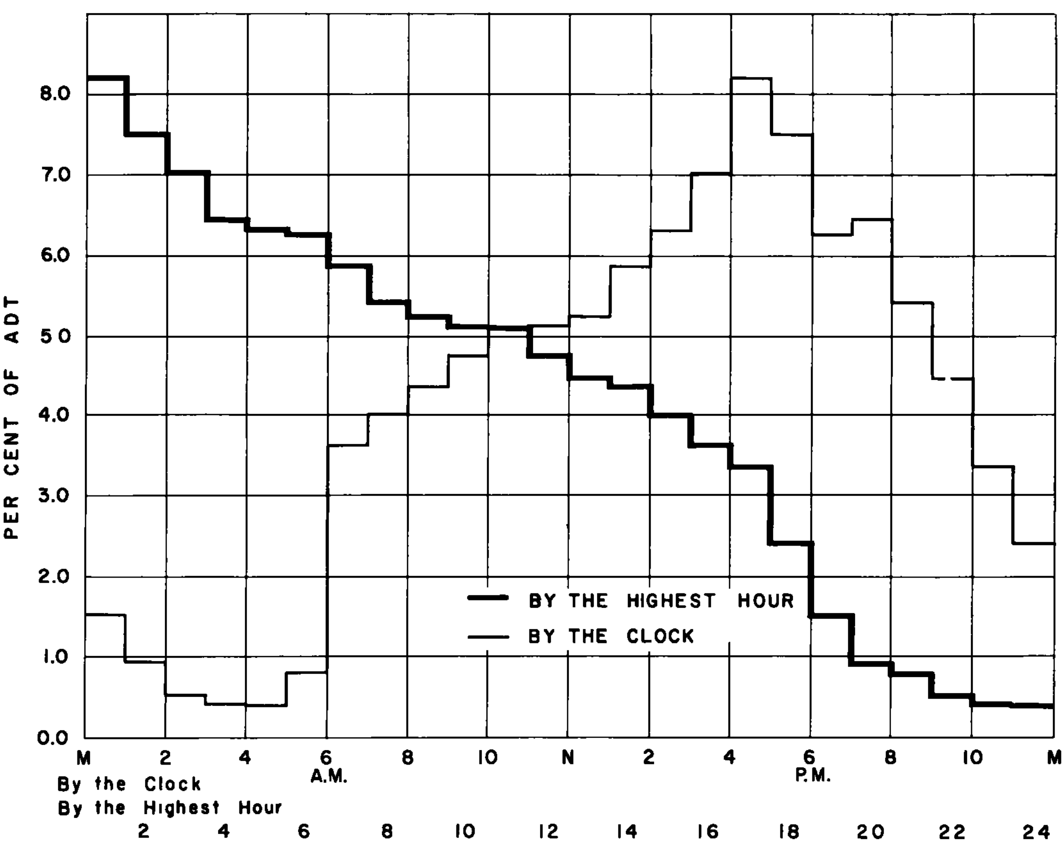

Figure 7B. Hourly volumes in percent of ADT secondary rural.

to accumulate the congestion delay over a 24-hr period. To do so the hourly distribution of the annual average daily traffic must be known.

The data collected from Pennsylvania's permanent traffic counter stations is analyzed and tabulated in many different forms, one of which is the hourly distribution in percent of annual average daily traffic.

For the purpose at hand, data from these stations was grouped into four classifications, averaged, and plotted as the light lines in Figures 7A through 7D. The classifications are: (a) primary rural, (b) secondary rural, (c) recreational and (d) urban.

The heavy line on these charts rearranges the distribution into descending numerical values of the percent. To demonstrate the use of these charts, assume another example: An urban street has a capacity of 250 vph and a 5,000 ADT. During what hours of the day is it congested? From the previous discussion, it is known that congestion occurs in every hour that the volume exceeds 250 vph. Since the division line is $\frac{250}{5000} = 5\%$ a line is drawn across Figure 8 at 5 percent. All hours above this line are congestion delay hours, as shown by the cross hatching.

The convenience of the descending values of percent should now be evident. These values are entered into the computer as a table, and the computer need make only ten searches. Using a "clock" table, the computer would have to compare 24 values. Using a descending percent table the computer needs only to compare those values above the capacity equivalent. In many cases there will be no congestion, or a single hour of congestion, and the machine need make only one or two searches, respectively.

Annual Congestion Delay Cost

The total congestion delay hours having been accumulated for each hour of congestion delay, it is necessary to the author's method to translate it into yearly congestion delay

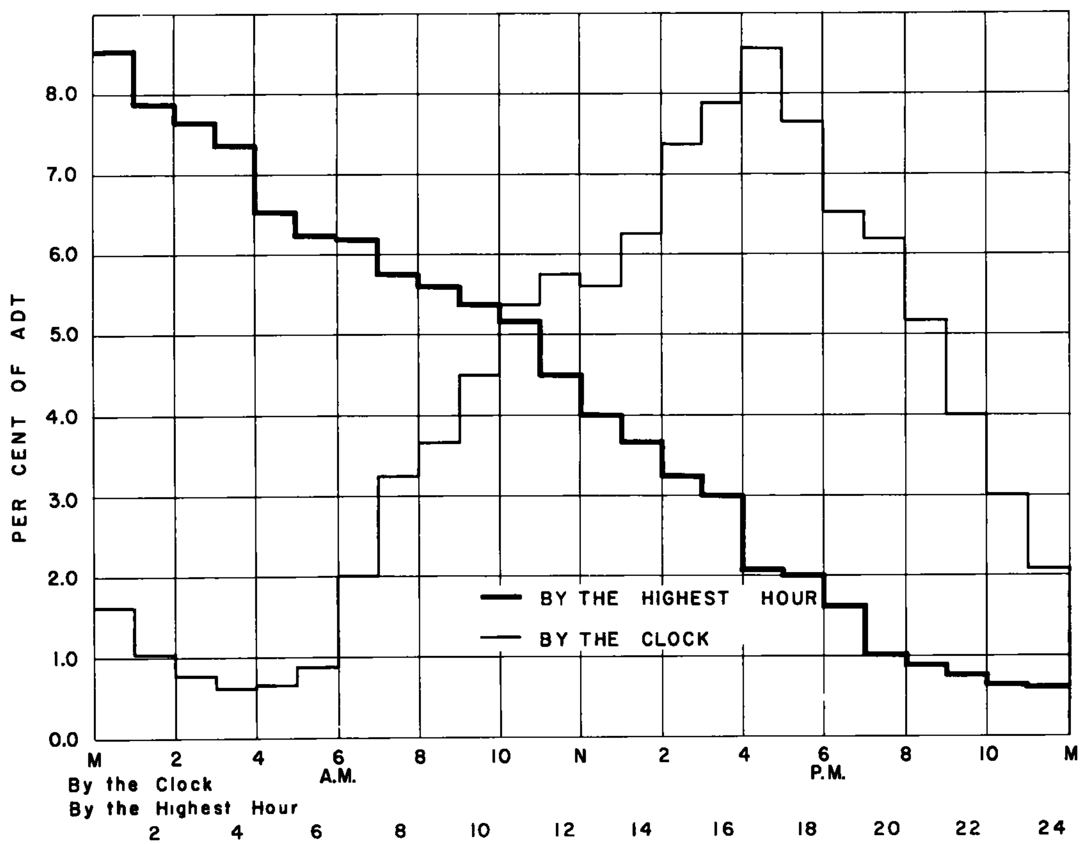

Figure 7C. Hourly volumes in percent of ADT recreational.

cost. This requires no stretch of the imagination, being the hourly cost of vehicle operation times daily congestion vehicle hours times 365 days.

Hourly cost of vehicle operation does require a stretch of the imagination. The pros and cons of its make-up have been debated in the market place many times in many years. The author makes no contribution to that literature. Suffice it to say that each jurisdiction should compute its own rate, and rest in the assurance that, for the immediate purpose, no serious error will be introduced, since here one highway is evaluated against another, and any error will be constant.

In fact, the cost of delay, except in the reconciliation of structural and functional dates, could be eliminated and the end result attained. The author feels, however, that "dollars" are more meaningful to the administrator and the legislator than "congestion delay hours." Just as "125,325 congestion delay hours" are more meaningful to the author than "16 points functional sufficiency."

RECONCILIATION OF SUFFICIENCY DATES — RESUMED

Returning to the central theme, the purpose was to determine the less costly to the road user of the alternates of: (a) reconstruction, thus, eliminating congestion delay, or (b) tolerating congestion for the remaining structural life of the facility. Annual costs of reconstruction have been briefly discussed.

The cost of alternate 2 may be found by computing the sum of the congestion delay cost for the number of years between the functional obsolescence date, and the structural retirement date, using expanded ADT's for each year and dividing by the number of years to find the average annual cost, to which is added annual maintenance and overhead. (A short cut is available by using the average ADT for the period of years. It is pointed out that such treatment could "lose" or gain clock hours of congestion delays. Compare Figure 8.) The author holds that interest is a proper charge to be

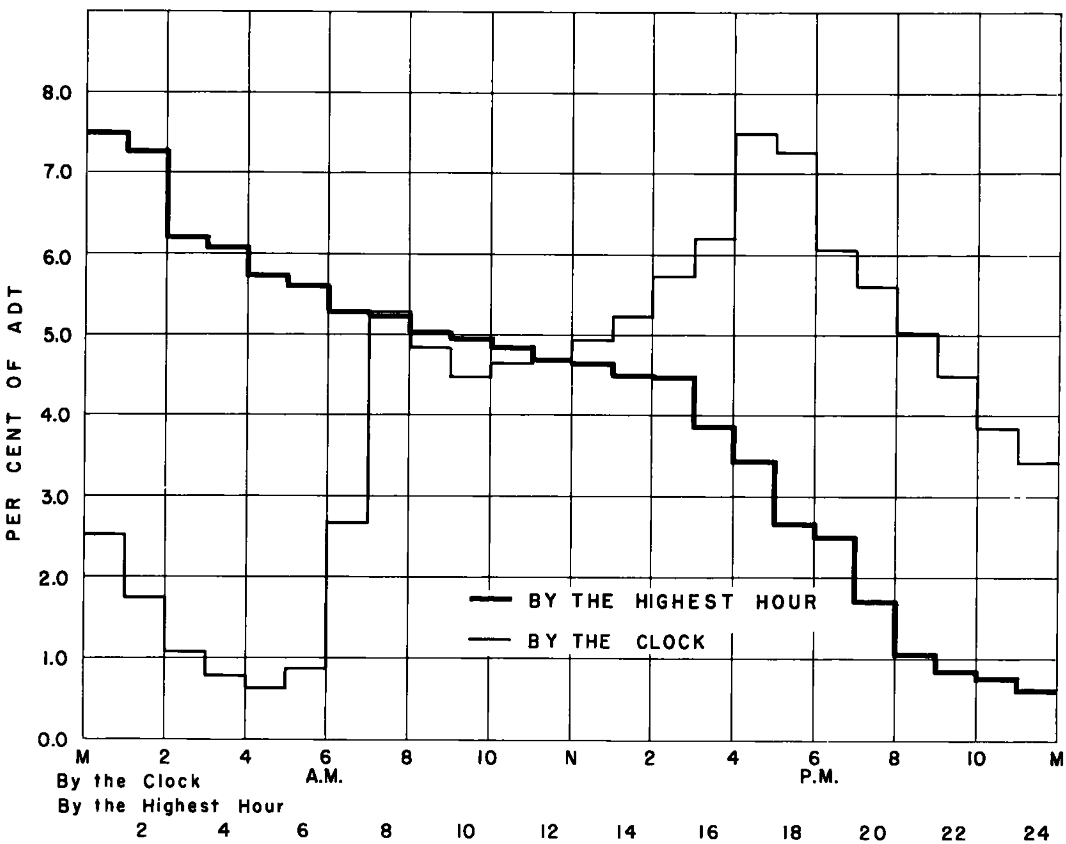

Figure 7D. Hourly volumes in percent of ADT-urban.

added to alternate 1, since it represents an immediate investment which could be deferred.

The annual costs of the alternates can now be compared either in dollars or in ratio. If the cost of reconstruction is equal to or less than the cost of congestion delay, it is obvious that the facility should be reconstructed during the year of its functional obsolescence date. If the reconstruction cost is the greater, then the facility should be reconstructed during the year of its structural retirement date.

But certain qualifications for policy decision should be interposed at this point. Some allowance should be considered in the cost differential for the following facts:

1. Improved alignment and distance shortening has not been evaluated.
2. Comfort and safety are desirable assets.
3. Acquisition costs for additional right-of-way will probably be higher if deferred.

The author will not offer any dollar value for such differentials. It is a judgement factor for each jurisdiction, but, again for mass data processing, it should be expressed as a percentage.

The case of structural retirement being reached before functional obsolescence occurs is different only in that resurfacing of the facility on the structural retirement date is considered. If the resurfaced life extends beyond the functional obsolescence date, the annual costs of the projected congestion delay should be added to the annual cost of resurfacing and the total compared with the annual cost of immediate reconstruction. The reader will at this point detect other alternatives, including stage construction by widening, but it is not the purpose of this paper to explore too many facets of a many faceted subject.

A year of action has now been determined, and the cost of remedial treatment found.

PROGRAMMING

Needs Study

After the entire highway system has been evaluated by the foregoing operations, it

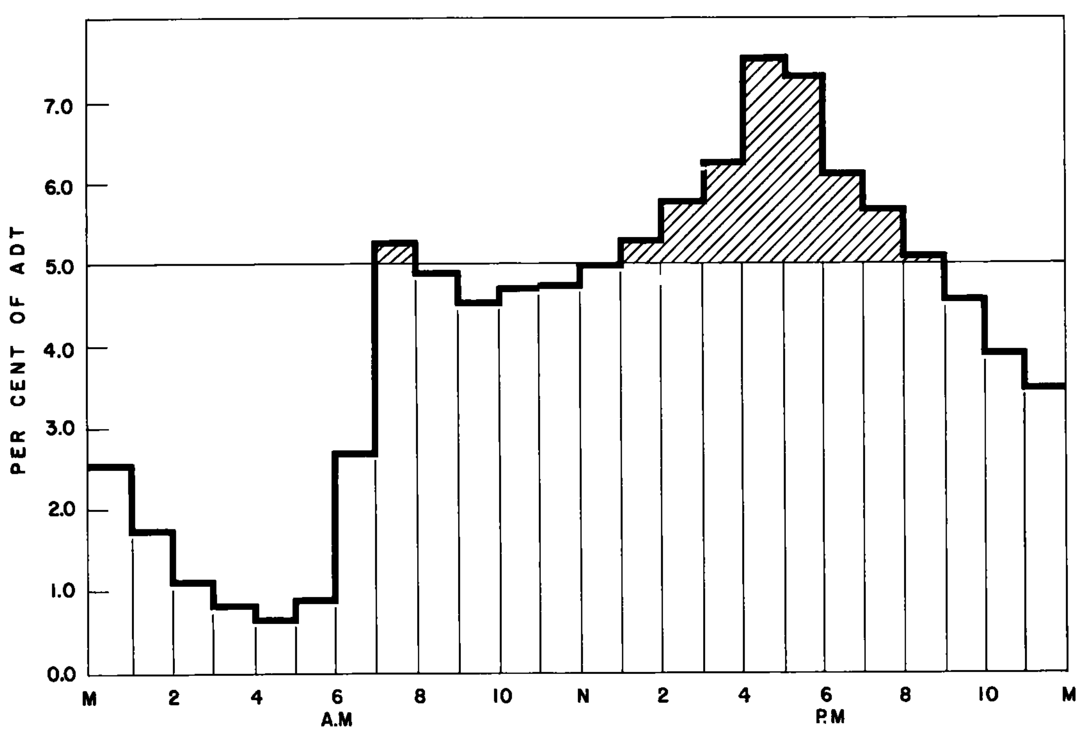

Figure 8. Congestion hours—urban street.

is possible (it may be practical in some cases) to make a "print out" tabulation showing the needed improvements by years and their costs. What better "needs" study is required, and what better picture can be presented of the financing required? And since the "solutions" are on tape or cards, the "print out" can be arranged and rearranged in many ways. A suggested way is in sequence of road route numbers, so that the administrator has immediately at hand the long range picture of any portion of any highway. Little imagination is needed to visualize the power of such a tool when the administrator is being approached by pressure groups.

Unless the highway department has always had adequate funds at hand so that there are no deferred projects, it will be found that the "needs" in 1960 far exceed even the most optimistic estimates of income. It will be impossible to do the "needs" listed for 1960, perhaps even in 1961 or 1962. It will be necessary to give a priority rating to the 1960 list of projects, and probably 1961's list and even 1962's list. A further technique is necessary, which the author designates as the "modified benefit-cost ratio." In practice, it would be calculated at the same time as the foregoing.

Modified Benefit-Cost Ratio

In conventional analyses of "benefit costs", the predominant amount of "benefit" arises from improved travel time over the congested travel time on the existing facility. Other benefits are relatively constant per unit length of a project. The analyses assume that the congestion delay will be relieved and thus become a benefit. This paper makes the same assumption, and contends that congestion delay is a valid basis of rating one existing highway against another. The total vehicle delay cost previously

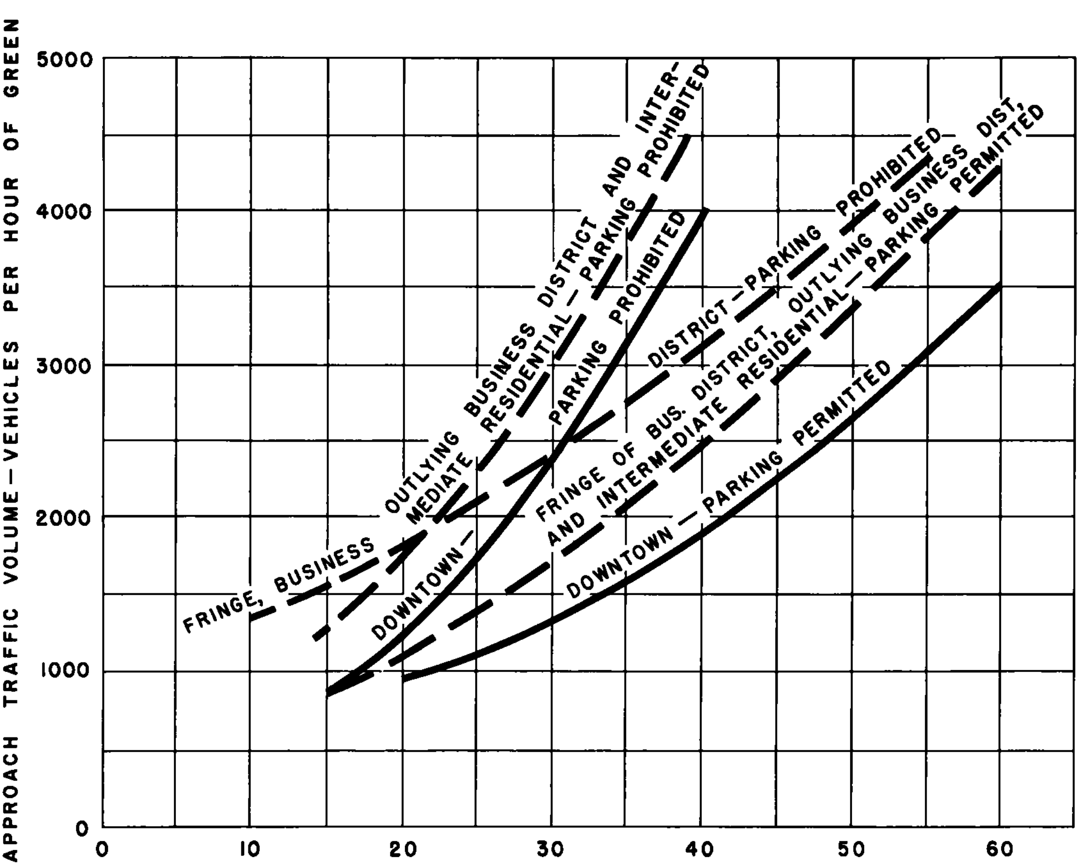

Figure 9. Intersection capacities of two-way streets fixed time signals.

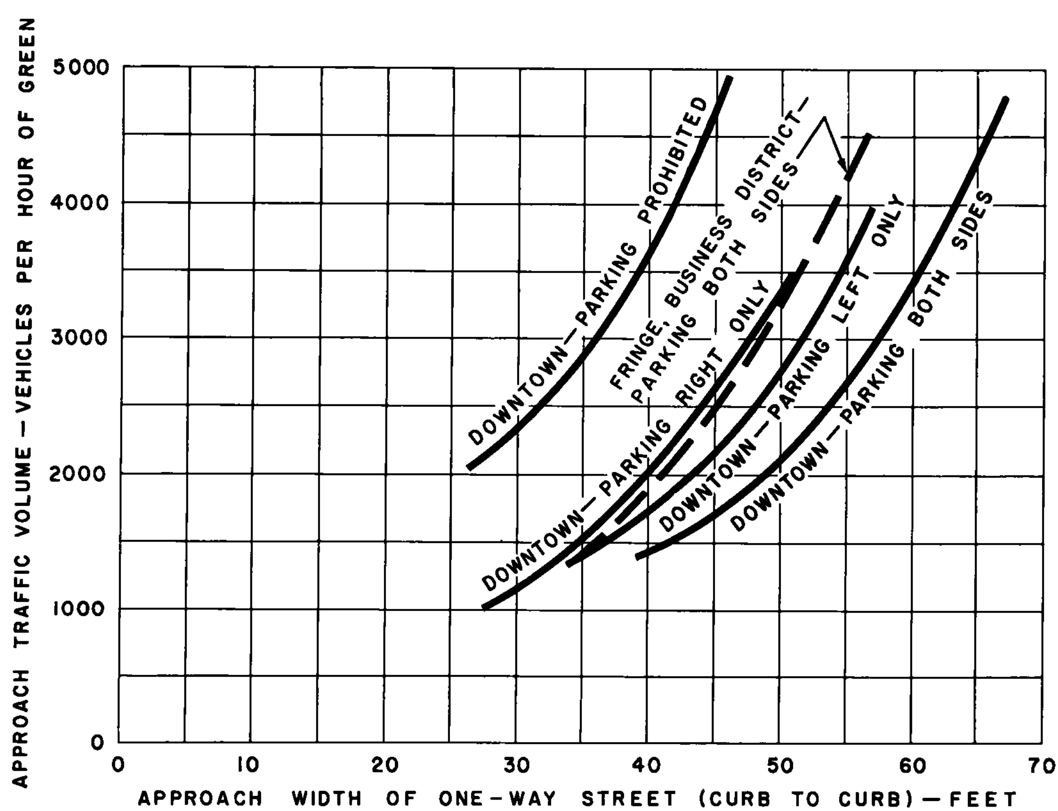

Figure 10. Intersection capacities of one-way streets fixed time signals.

computed can now be termed "modified benefit", the word "modified" being used to avoid confusion, and the term "modified benefit-cost ratio" being used to retain the well-known concept of benefit-cost analyses. The construction cost will also have been computed during the foregoing operations. Modified benefits divided by the cost gives the modified benefit-cost ratio. Examination of the parameter shows that per dollar of cost, "X" dollars worth of congestion will be relieved.

Priority, then, is positioned in the order of descending values of the modified benefit-cost ratio, insuring that the greatest amount of congestion will be relieved with the funds available.

Program

The "print-out" will now have arranged the "needs" within calendar years, and will have arranged priority within those years. If Federal Aid systems and other systems require separate treatment, or if geographic-politico distribution must be a part of programming, the "print-out" can handle these details.

Establishment of present and long range programs is then only a matter of what appropriations are available or forecasted for each year, and striking off the sub-total equal thereto in the construction cost column. It is recommended that a contingency fund be inserted in each year's program, to provide for both normal cost contingencies, and for the insertion of emergency projects: bridge collapses, the traffic changes from a new industrial plant, a depression of tax revenues, etc.

It would seem that such a program would be valid for 4 years, firm. A "rerun", however, should be made at two- or three-year intervals with up-dated information, in order that location studies and design drawings will lead the future construction years.

POST PROGRAMMING ANALYSIS

The method proposed does not obviate economic analysis of the programmed improvement. It is incumbent upon the planner, knowing an improvement is to be made, to ask the questions, "should this be on existing alignment?" or "is this commensurate with the network?" or the many questions that should be asked and solved before the new facility is constructed.

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Appendix A

TREATMENT OF VOLUMES EXCEEDING THE SATURATION

It is readily seen from Figure 4 and from the examples worked in the text, that the delay can be determined for volumes up to the volume of saturation. The literature is silent as to the parameters that determine the travel time beyond the saturation point. If in the preceding example the actual volume was 900 and the equivalent volume was 1,100 vph, the ratio value becomes 1.21. It is known that the saturation point has been passed, and that volume has decreased and travel time has increased. But to what point on the curve?

The author advances the theory that the demand volume of 1,100 vph is measured around the saturation point and back on the horizontal scale, and that the ordinate to the saturation curve denotes the saturated travel time for the saturated volume. Further, the difference between 1,100 vph and the saturation volume is carried over and added to the succeeding clock hour volume.

Applying this theory to the problem solution, the point of saturation for the stated condition occurs at

$$Y = 1.07 = \frac{\text{Equivalent Hourly Volume}}{910}$$

Solving

Equivalent Hourly Volume = 974 vehicles.

The excess of 1,100 - 974 or 126, measured backwards on the scale becomes 974 - 126 or 848. With this new equivalent volume

$$Y = \frac{848}{910} = 0.93$$

read on the saturation curve, giving a travel time of 5.76 minutes. However, this delay applies to $\frac{848 \times 900}{1100}$ = 694 actual vehicles. Then delay time is $\frac{5.76 \times 694}{60}$ = 60.62 vehicle hours and 900 - 694 = 306 actual vehicles are added to the succeeding hours volume.

It is intended to field check this theory. Meanwhile the above solution will satisfy the requirements of the problem, since these extremes are those road sections requiring the highest priority of construction. For relative positioning, the solution will be valid.