Methods of Locating Automatic Signals

Practice Developed by the Interborough Rapid Transit for New York Subway and Elevated Lines

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The extraordinary growth of traffic on the subway and elevated lines in New York City has given rise to many engineering problems of the first magnitude. Among them is the problem of providing a signaling system adequate to meet the unusual traffic conditions, not only as they exist at the time of the installation, but also to provide for conditions which will probably come up in the future, due to increases in traffic. In order to determine the probable future requirements, a considerable amount of engineering work is necessary. The tendency has been constantly toward longer trains, higher speed and closer headway, or toward the maximum efficiency consistent with safe operation.

If, however, the signal system is to provide for safety and for maximum efficiency, a scientific study must be made of the location and the control of the signals. The data and formulæ necessary for such a study have been obtained from various sources, and such as best fitted the conditions on subways and elevated lines were used in compiling curves and tables, forming the basis of the studies of signal layouts. The results to be obtained may be classed under two general heads—safety and efficiency. The factors which enter into the final result are so numerous and diversified that it will be impossible to discuss in detail how each factor affects the final result, but an effort will be made to show how the data resulting from these factors is interpreted and applied to the signal layout.

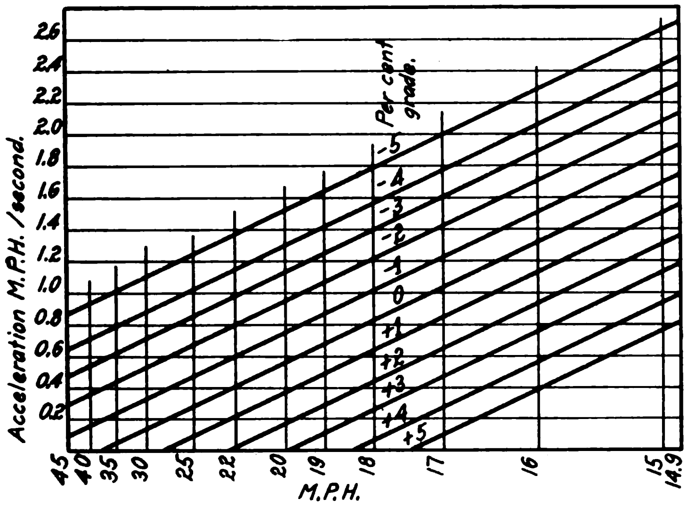

Fig. 1. Accelerations for Various Grades and Speeds.

To insure safety of operation requires that signals be so located and controlled that a train will always be protected by a stop signal in the rear of the train a distance at least equal to emergency braking plus a factor of safety, which is usually assumed as 50 per cent, the braking distance in each case being taken for the maximum attainable speed considering the grade of the track at each location.

To provide efficiency of operation requires that the signals be so located as to facilitate traffic to the highest degree or to permit the track to be used up to a maximum capacity. Since the capacity of a line is limited by the capacity through the stations, it is necessary to make a special study of station signaling. It was to facilitate traffic entering stations that brought into use the speed control or closing-in signal system, described later.

FUNDAMENTAL DATA.

The fundamental data entering into a study of signal locations may be classified as follows: (1) Acceleration; (2) deceleration; (3) track conditions (curves, grades); (4) stations and station stops; (5) headway, and (6) length of trains.

Acceleration.—From motor characteristics and car equipment data, an acceleration chart as shown in Fig. 1 may be compiled, using the formula:

$$a = \frac{T - (f + d\,h)\,W}{91.1\,(W + Y)}, \text{ where}$$

a = Acceleration in m.p.h./sec.
T = Tractive effort of motor in lb.
d = Degree of grade.
h = Factor = 20 lb. per ton per deg. of grade.
W = Weight per motor in tons.
Y = Factor of inertia = 15 per cent of W.
$f = A + B\,V + C\,V^2$ lb. tractive effort per ton of W due to train resistance, windage, etc. (Taken from the American Hand-book for Electrical Engineers.)
V = Speed in m.p.h.

The chart, Fig. 1, shows accelerations for speeds from 14.9 m. p. h. to 45 m. p. h. on all grades from 5 per cent down to 5 per cent up. Below 14.9 m. p. h., the rate of acceleration is taken as constant, hence is not shown on the chart. This point of change from constant to varying acceleration depends on the motor characteristics, the car equipment and the make-up of trains.

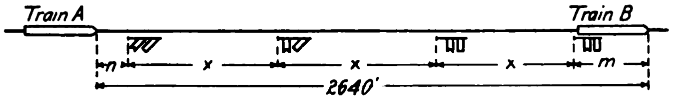

Fig. 2. Train Spacing for 90-Second Headway.

Under fundamental data it will be noted that "track conditions" is divided into two factors, grades and curves. The grade of track is included as a factor in the acceleration formulæ. Curves, however, are not so included as a factor in the formulæ, since it is not a general condition. Where a layout includes a curve, it is customary to subtract a factor of curve resistance from the acceleration as obtained for straight track. This factor of curve resistance varies with the radius of curvature of the track.

HEADWAY.

The location or spacing of signals in any given layout depends on the desired headway and the speed at which this headway can be maintained. Where no unusual conditions or requirements exist, the signal system is arranged to provide for a 90-sec. headway at a minimum operating speed of from 20 to 25 m. p. h. Referring to Fig. 2, assuming trains A and B to be spaced for a 90-sec. headway at 20 m. p. h., train A at a speed of 20 m. p. h. would reach position of train B in 90 sec. The distance corresponding to 20 m. p. h. for 90 sec. is 2,640 ft. Assuming that for this speed, the distance, n, that the distant signal will clear ahead of train A equals 100 ft., m, length of train, equals 400 ft. and x equals the length of block, we have $3x + n + m$ equals 2,640 ft., $3x$ equals $2{,}640 - 400 - 100$, or x equals 713 ft., the maximum average length of block at which a 90-sec. headway can be maintained at 20 m. p. h. If the speed is increased, the length of block will be correspondingly increased. The distance x must in each case be at least 150 per cent of emergency braking distance for the maximum speed. Thus, the signals are so located as to provide for safety up to the maximum speed obtainable, and also to provide for a 90-sec. headway at speeds as low as 20 m. p. h.

DOUBLE-TRACK LAYOUT.

A typical layout of signals for traffic in one direction, using a 400-ft. elevated train, is shown in Fig. 3. At each signal location it is necessary to know the braking distance for maximum speed—hence the speed-distance curve (a), which represents the front end of a train running from station A to station B, is computed from accelerations as obtained from the chart, Fig. 1, the grades being given on Fig. 3. It is assumed that the weight is concentrated at the center of the train, hence the point where the acceleration or deceleration changes in curve (a), due to a change in grade, is 200 ft., or half a train length, beyond the point of change of grade in the direction of running from station A to station B.

The method of compiling the speed-distance curve is shown in table 1, in which V equals speed in m. p. h.; a equals acceleration as taken from Fig. 1; A equals average accelerations or averages of successive values of a; t equals time in seconds required to accelerate from 2 m. p. h. to 4 m. p. h., or from 4 m. p. h. to 6 m. p. h., etc.; T equals total time from starting, or summation of t; v equals average speeds or averages of successive values of V; F equals feet per second, corresponding to values of v; d equals distance in ft., equals F x t, and D equals total distance or summation of values of d.

By plotting values of V as ordinates and D as abscissæ, the curve a is obtained. The table gives only the portion of the curve up to 21 m. p. h. Since time is a factor in speed we may, by integrating the speed-distance curve or by plotting values of T and D, table 1, obtain a time-distance curve, b, which gives the running time between stations if the maximum speed is maintained.

TABLE I.

V MPH	a Acc. Sec. MPH	A Avg. Acc.	t Time Sec.	T Total Sec.	v Avg. MPH.	F Speed F.P.S	d Dist. Feet.	D Total Dist.
2	1.74	1.74	1.15	1.15	1.0	1.46	1.7	.....
4	1.74	1.74	1.15	2.30	3.0	4.4	5.1	6.8
6	1.74	1.74	1.15	3.45	5.0	7.3	8.4	15.2
8	1.74	1.74	1.15	4.60	7.0	10.3	11.8	27.0
10	1.74	1.74	1.15	5.75	9.0	13.2	15.2	42.2
12	1.74	1.74	1.15	6.90	11.0	16.1	18.6	60.8
14	1.74	1.74	1.15	8.05	13.0	19.0	21.8	82.6
15	1.70	1.72	0.58	8.63	14.5	21.3	12.4	95.0
16	1.32	1.51	0.66	9.29	15.5	22.8	15.0	110.0
18	0.82	1.07	1.86	11.15	17.0	25.0	46.0	156.0
21	0.48	0.65	4.63	15.78	19.5	28.6	132.0	288.0

This curve b is not used, however, for locating the signals as trains running at less than the maximum speed could not then maintain the predetermined headway, which we will assume for the layout shown in Fig. 3 to be 90 sec. The signals are therefore spaced so that a headway of 90 sec. may be maintained by trains running at speeds as low as 20 to 25 m. p. h. This minimum operating speed may be varied between 20 and 25 m. p. h., depending on the distance between stations, grades, curves, location of crossovers, etc. In Fig. 3, a minimum operating speed of 20 m. p. h. is used, giving lines c and d for the front and rear of a train N, running from station A to station B, and curve f for the front end of train M, which leaves station A 90 sec. later than N.

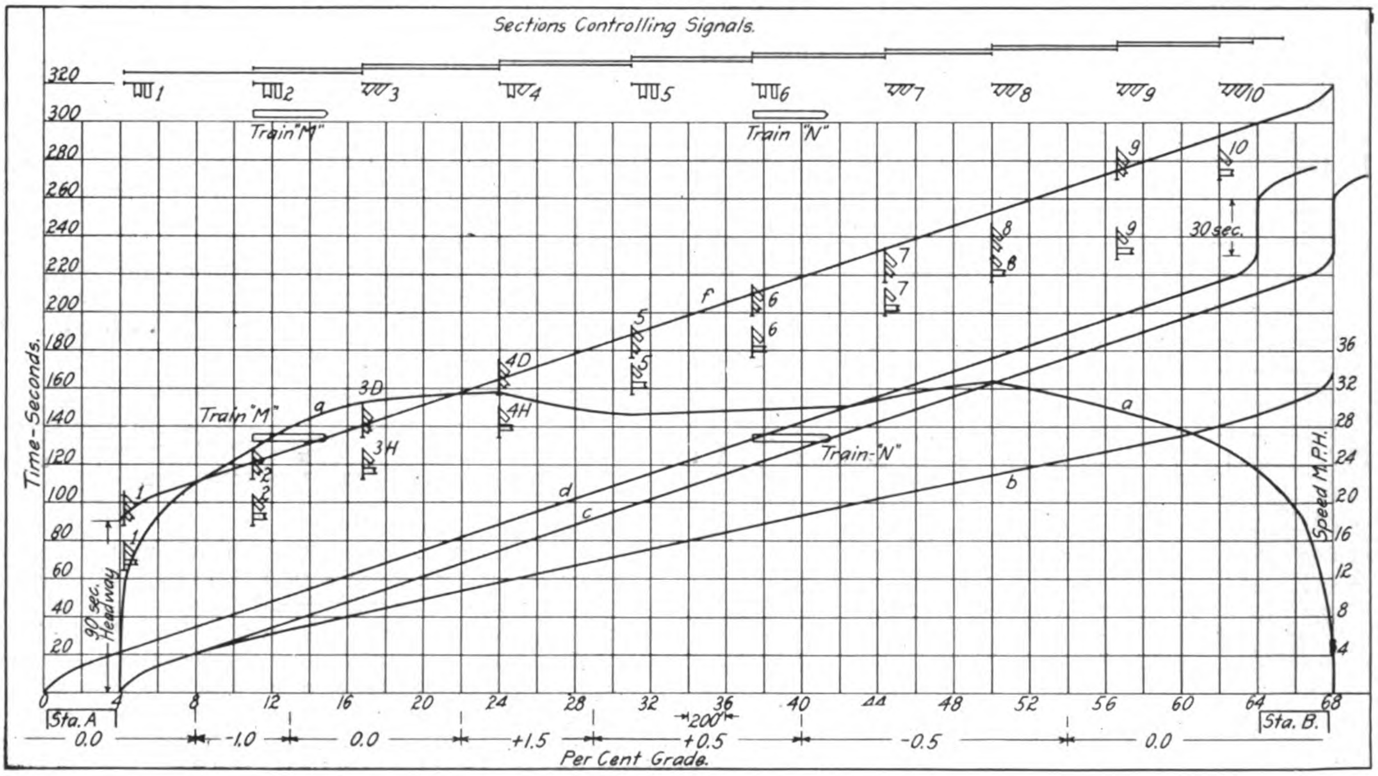

Fig. 3. Method of Laying Out Signals for Traffic in One Direction.

The signals are first spaced approximately 700 ft. apart, and then adjusted as the conditions of headway and braking distance require. The clearing positions of the home and distant signals as regards time, are then located as shown between lines d and f. This may be brought out more clearly by an example. The rear of train N, as shown, has just passed the insulated joint at signal 6, and clears home signal 4, shown at 4H, and distant signal 3, shown as 3D. In other words, the intersection of line d with a vertical line through the location of signal 6 gives the position of home signal 4 and distant signal 3 as regards the ordinate time. If signal 6 is moved 50 ft. toward station B, then the signals 4H and 3D will be two seconds later in clearing. For the signal layout, it is assumed that the distant signals will clear at least 100 ft. ahead of the following train. If in locating the clearing position, it is found that one of the distant signals clears less than 100 ft. ahead of line f, which represents the front of the train M, it is necessary either to move that signal or to move the signal to which its control extends.

Assume now that the train N has stopped in the position shown; train M, disregarding signals and traveling at maximum speed passes clear signal 3, distant signal 4 and home signal 5 at maximum speed or 29 m. p. h., as shown by curve a. At signal 5 the automatic stop operates the emergency brakes and the train is brought to a stop before reaching signal 6. For train N to be protected, with the factor of safety allowed, block 5-6 must be long enough for train M to be brought to a stop from the highest attainable speed in two-thirds the length of the block, or the block length must be 150 per cent emergency braking distance. The same method is applied to each signal in the layout, allowing in each case a block length of at least 150 per cent emergency braking.

SINGLE-TRACK OPERATION.

Where the track is used for traffic in both directions (as for example a certain section of track may be used in the morning rush hours for traffic toward the congested business district of lower Manhattan, and in the evening, in the reverse direction to carry the crowds away from the business district) another factor is brought into the problem of locating the signals. A similar signal layout would be required in the reverse direction as from station B to station A, Fig. 3. In signaling for both directions, it is desirable to locate signals for opposing directions opposite, so as to eliminate complications in wiring necessary when signals are staggered, and also to make it possible to use a smaller number of track circuits.

Having in one direction an up-grade, resulting in a low speed and short braking distance, and permitting a shorter length of block and closer headway, we find that in the opposite direction the grade is down, resulting in a longer braking distance, due not only to the down-grade, but also to the fact that the maximum attainable speed is higher, and, therefore, resulting in a correspondingly greater length of block. It is therefore evident that the signal layouts cannot be worked out as separate problems, but for both directions as a combined problem, in order to arrive at the best results.

CLOSING-IN SIGNAL SYSTEM.

Since, as previously stated, the headway over a given line is limited by the headway through the stations, it is usually necessary to make a special study of the station layout. If a train is held in the station longer than the allowable length of time for a station stop, the next train approaching the station will find the signals protecting the station at danger, and will be compelled to stop with a resulting loss of time. It was to reduce this loss of time to a minimum that the "speed-control" or "closing-in" signal system was brought into use, so that trains approaching an occupied station might either keep moving at a slow rate of speed or, if compelled to stop, to come as close as possible to the station, consistent with safety.

A typical station layout using a 500-ft. subway train is shown in Fig. 4, in which lines J and K are time-distance curves, representing the front and rear of train A leaving station H, the abscissæ being distance in steps of 100 ft., and the ordinates, time in seconds. L is a time-distance curve of the front end of train B entering station H after a stop at signal 3, and F a time-distance curve of a train entering the station under free running conditions, the term "free running" being used as referring to train operation with distant signals clearing 600 ft. ahead of the train. A speed-distance curve of a train entering the station at maximum speed is shown at f, the ordinates in this case being speed in m. p. h.

In order that train A, while in the station, may be protected, it is necessary to have signal 2 at stop, as the distance from signal 2 to the insulated joint at e, just outside the station platform, is braking distance—with a factor of safety—for the speed, as shown by curve f.

Assuming that train A leaves the station H with no train approaching, then the dotted signals show clearing positions and E-E shows the track sections controlling the signals. If, however, train A remains in the station, train B approaching the station receives a distant indication at signal 1, signals 2, 3, 4, 5 and 6 being at stop. A train in passing signal 1 sets in operation a time relay, which, after a predetermined time, will close a circuit clearing signal 2, provided no track section between signal 2 and the station is occupied. If, therefore, the speed of train B has been reduced so as to consume this interval of time within the section 1-2, then signal 2 will clear and train B can proceed to signal 3, which will not clear until train A has started out of the station. If, on the other hand, the speed of train B in section 1-2 is too high, the train will reach signal 2 before the time relay has completed its operation; and, therefore, the signal is at stop and the train is tripped by the automatic stop applying the emergency brakes. Thus for higher speeds a train in the station is protected by signal 2, whereas if the speed of the approaching train has been sufficiently reduced with a correspondingly shorter braking distance, it is safe to allow the train to proceed to signal 3. The track sections controlling the signals under speed control operation are shown at F-F.

As train A leaves the station, train B, which is shown as having stopped at signal 3, proceeds into the station as shown by the time-distance curve L and comes to a stop in the station just 60 sec. after the train A has started. Allowing for a station stop of 30 sec., this would give a headway through the station of 90 sec.

It will be noted in the layout that with signals operating automatically, as shown by the control sections E-E, signal 2 clears when the rear of train A has passed the insulated joint at d, while with speed control operation (control sections F-F) it clears when train A is standing in the station with the rear of the train past the insulated joint at e, or the operation of the time relay cuts section e-d from the control of signal 2. The same is true of signals 3 and 4, the control section of each being shortened by the operation of the time relays. Under speed control operation, signals 3 and 4 each clear five seconds earlier than when the time relays are not brought into operation.

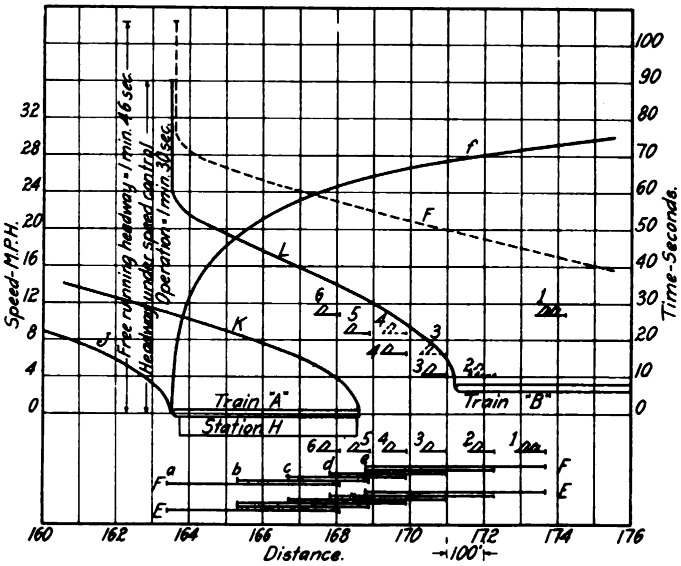

Fig. 4. Laying Out Station Signals to Facilitate Traffic.

As between stations, the problem here is also complicated if the track through the station is used for both directions of traffic, as it is then necessary to so locate the insulated joints inside the station limits that they will give satisfactory operation of the signals from both directions.

For steam road practice, while the general method could be followed, it would necessarily vary widely, as the factors entering into an analysis of a signal layout would vary and the results to be obtained, while basically the same, differ widely in degree from the results to be obtained in subway operation. There is at the present time, however, much data available for various equipment, such as rates of acceleration for steam and electric locomotives, and rates of deceleration for various types of brake equipment, as well as experimental and computed data for curve resistance, friction and windage factors, etc., all of which, coupled with track conditions, may be used as an aid in laying out a safe and efficient signal system.

A VOTE AGAINST LONGER RAILS.—In reference to the item in the December issue of *The Signal Engineer* in regard to the tendency to use rails longer than 33 ft., a correspondent who has apparently been engaged in bonding track at piece work rates, objects that longer rails would make it necessary to cover more track to reach the same number of joints.