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79-RT-6

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"Close Headway" Operation for Bay Area Rapid Transit (BART)

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Contributed by the Rail Transportation Division of The American Society of Mechanical Engineers for presentation at the Joint ASME/IEEE Railroad Conference, Colorado Springs, Colo., April 24-25, 1979. Manuscript received at ASME Headquarters January 31, 1979.

Copies will be available until February 1, 1980.

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ABSTRACT

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NOMENCLATURE

Brake Rate (BRK) $= \dfrac{v_o^2 - v_f^2}{2S_T}$,

v_o = initial velocity

v_f = final velocity

S_T = total distance travelled

LAM = total train length (no. of cars)

Δv = total change in speed over braking interval

$$R^2 \text{ (Correlation Coefficient)} = \frac{1}{n}\sum_{i=1}^{n}\frac{(X_i-M_x)(Y_i-M_y)}{\sigma_x\sigma_y}$$

M_x = thc mean of random variable X

M_y = the mean of random variable Y

σ_x = the standard deviation of X

σ_y = the standard deviation of Y

ANOVA - Analysis of Variance - statistical procedure.

F - denotes the "F" ratio, a statistical test for significant difference in the mean among categories.

α - significance level, the probability of observing computed value of pertinent statistic, given hypothesis is true.

A1 - train line running south from Lake Merritt to Fremont station.

A2 - train line running north from Fremont to Lake Merritt station.

C1 - train line running west to east from Lake Merritt to Concord station.

C2 - train line running east to west from Concord to Lake Merritt station.

INTRODUCTION

The Bay Area Rapid Transit District (BARTD), during the past two years, has conducted a major full-scale test program to accurately determine train braking performance under conditions of limited wheel-rail adhesion (e.g., wet or rainy conditions). This experimentation has been aimed at the problem of determining adequate safety margins for separation of high-speed revenue trains, allowing maximum system throughput. (i.e., in more conventional terms, the problem of railroad "signalling.") The unique concept of Automatic Train Control (ATC), first implemented by this transit district, utilizes complex electronic circuitry and computer control for the daily operation of passenger trains. The primary control system is designed so that normal acceleration and deceleration of vehicles is accomplished in a fully automated manner through transmittal of binary encoded speed commands from "wayside" track transmitters to onboard train receivers. Assuming a high degree of electronic hardware reliability, the most critical technical problem is the allocation of adequate stopping distances between trains. Computation of these stopping margins must adequately take into account measurements of train braking performance under a wide variety of rail conditions.

The original designers of BART based their stopping distance calculations on a 2.7 mph/s* minimum brake rate assumption. This early decision was based on extremely limited non-revenue testing performed mainly under dry and simulated adverse track conditions and was largely influenced by the desire to maintain high operating speeds with minimum 90 sec headways between trains. The builders of BART then proceeded on this assumption and "hard-wired" the entire system for 2.7 mph/s design brake rate.

During an early testing period prior to opening for public service, it was revealed that under "wet" or natural adverse rail conditions, brake rates substantially below 2.7 mph/s could occur due to severe reductions in the coefficient of wheel-rail adhesion. The safety implication of this fact on the proposed "close headway" mode of operation was immediately realized. For example, assuming a brake rate of 2.7 mph/s, a train travelling at 80 mph would require 1,738 ft, after initiation of braking, to come to a complete stop. With a brake rate of only 1.7 mph/sec, the required stopping distance is 2,761 ft or an additional 1,023 ft.

As a result of this finding, BART first opened to the public in September of 1972, with a primitive two-station separation of trains. This restriction was later relaxed to single-station separation and was subsequently enforced automatically through a computer system known as the "Computer Augmented Block System" (CABS). Furthermore, BART was required to run with a full twenty-five percent speed reduction penalty (called "impeded mode") under "wet" track conditions. The above restrictions have, at times, caused a well-publicized throughput problem for the BART system, including prolonged waiting times at stations.

Therefore, it is correct to state that BART has never run according to its initial design plans and that the system's original promise of "close headway" operation during peak revenue hours could not be delivered to the public without further comprehensive study and extensive hardware modifications (CABS headways average from six to twenty minutes depending on location and time-of-day). Moreover, because headway restrictions were also imposed on traffic through the transbay tube connecting San Francisco and the East Bay, BART has also not been able to provide direct passenger service to San Francisco from all suburban locations as originally planned.

As a first step towards solution of the BART brake rate problem and achievement of satisfactory signalling for the railroad, additional brake rate tests were conducted during the winter of 1975. A total of over 3,000 train braking events were recorded. A statistical analysis of the data was subsequently performed and a minimum 1.29 mph/sec BART brake rate was observed. Based on these results, a BART stopping distance algorithm was developed assuming a 1.2 mph/sec brake rate and other pessimistic braking system response assumptions. The results of the 1975 analysis also made possible the identification of several operational variables having a direct impact on train braking performance. Among those originally identified were initial train velocity (v_o) and total train length (LAM).

Although the 1975 data was eventually proven accurate and informative after much controversy, firm conclusions regarding safe stopping distances could not be reached due to a lack of prior experimental design in the data acquisition program. For example, the 1975 data base consisted mainly of spontaneously recorded partial brake applications. Thus, train deceleration rates were, in most cases, measured over comparatively small speed changes. Based on multivariate statistical methods, it was predicted that the full stop braking performance of BART trains would prove superior. In order to confirm this and a number of other important operational assumptions, a major full scale test program was conducted during the winter of 1977/78 utilizing some basic concepts from the statistical theory of experimental design. The main results and conclusions of this study, recommending safe and efficient "close headway" operation for BART, are presented below. First, a description of the instrumentation used for obtaining BART brake rate data in both test programs is presented.

Instrumentation and Data Acquisition Program

The 1975 test data was obtained by placing three instrumented cars in different revenue trains operating throughout all main line tracks. Instrumentation within each of the lead cars included a Systron-Donner linear accelerometer* with output voltage directly proportional to train acceleration. Train velocity was measured by one of the pulse tachometers in the A car's propulsion system. Both analog signals; i.e., the accelerometer output and the D.C. voltage derived from integration of the tachometer pulse train, were recorded on a Brush 220 two-channel strip chart

*2.70 mph/s = 4.35 km/hr-sec

*Systron-Donner accelerometer, model 4310 F-1-A (Serial No. 19249).

recorder. In addition, the onset and termination of braking were recorded by event markers within the recorder. Calibration of the accelerometer was performed on a daily basis via a 13.2° wedge designed to give a 5 mph/s output signal. Further details on the 1975 test program are documented in Reference 1.

The 1977/78 test data was obtained by placing a single instrumented car (Car 164) in different experimental trains operating on two main lines of operation. A major innovation was the use of a Minneapolis Honeywell 5600B seven-channel tape recorder for recording required acceleration and velocity data as well as other important experimental parameters. An automatic calibration switch was available for both the accelerometer and velocity measurements. The seven recording channels on analog tape consisted of a timing reference (0.1 Hz), velocity, accelerometer reading, brake line (BRK 3), 100 Hz frequency reference, and two slip-spin indicator channels FSS1 and FSS2. In addition, a single audio channel was available for annotative purposes. Another major innovation was the development of AS^+, a recording of the maximum value of the four-wheel tachometers. As described in Reference 1, a single-wheel tachometer loses accuracy due to wheel-rail slip-spin activity under low adhesion conditions. In order to improve accuracy, the highest reading of four-wheel tachometers of a car is adopted under the principle that slip will not occur simultaneously in each wheel. A simple voter circuit performs the selection and reduces error from 16% to approximately 2%.

Figure 1 presents a block diagram of the complete BART brake rate test instrumentation package. The main components indicated are as follows: 16 KHz oscillator, frequency divider, accelerometer, tachometers, and interfacing circuitry between tape recorder and instrumentation. A detailed description

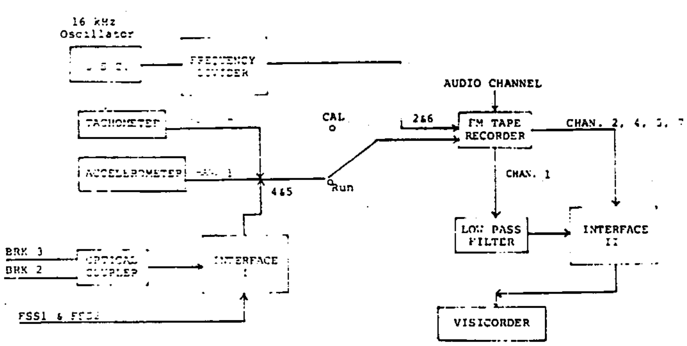

Figure 1. Block Diagram for Brake Rate Test Instrumentation

of each major block is presented in Reference 2.

Specific instrumentation and recording procedures followed by BART personnel in conducting the testing are documented in Reference 3.

The winter 1977/78 data reduction program consisted of the following steps:

1) manual offloading of onboard analog FM data tapes from test train,
2) filtering of analog data through use of an Ithaco 2.5 Hz filter,
3) analog/digital conversion of tapes and production of magnetic computer tape, and
4) data processing of digital braking events via "Brakes" software and calculation of equivalent brake rate (BRK). The latter provides a useful mathematical summary of each braking event and is defined precisely as that constant rate of deceleration which results in the same change in velocity over the same distance travelled; i.e.,

$$BRK = (v_o^2 - v_f^2)/2S_T$$

v_o = initial train velocity

v_f = final train velocity

S_T = total distance travelled.

A number of test runs were initially performed in order to check the accuracy of the entire instrumentation, recording, and data reduction process. Outputs from both the accelerometer and tachometer were recorded in analog form on FM tape and corresponding visicorder traces produced for each event. A series of cross-checks were then performed utilizing standard statistical procedures of error analysis. The results demonstrated that BART's onboard instrumentation and recording medium could provide values of equivalent brake rate (BRK) within an acceptable 2% margin of error.

The 1975 BART brake rate test program. The 1975 test data consisted of 3,000 braking events collected by BART in an ad hoc manner under "dry" track conditions and another 313 "wet" events. The actual data collection procedure consisted of logically and simply recording traces from the onboard accelerometer instrumentation on a brush strip recorder. As previously described, deceleration profiles were recorded over a wide range of braking intervals and in most cases consisted of train decelerations measured over relatively small speed changes.

From an examination of descriptive statistics on relevant variables (see Table 1), it is quite clear that the 1975 testing was not specifically designed to determine the effect of operational variables on train braking performance. For example, the overall spread of initial train velocities is narrow with a mean initial velocity of 68.29 mph and a sigma of merely 9.07 mph. The data base also does not provide much variation in train length. Approximately 11.6% of all test trains were of length four, 80.5% were of length five, and only 7.9% were of length nine. The 1975 data base contained no information on the short 3-car train category. Of special importance is the fact that the mean speed change for the 1975 data was only 29.57 mph with a sigma of 9.94 mph. Examination of a scatter diagram of brake rate (BRK) with total speed change (ΔV) reveals a significant increasing trend in train braking performance with increasing changes in speed. Figure 2 presents the scatter-diagram of brake rate (BRK) with speed change (ΔV), for the five car, high-velocity ($v_o > 75$ mph) low braking ($BRK < 2.0$ mph/s) category. The calculated value of the correlation coefficient is 0.56, and the correlation coefficient has over 99% significance. Based on this statistical result, it was predicted that full-stop braking performance would be better on the average than braking measured over relatively smaller speed changes. As will be demonstrated in subsequent sections, statistical analysis of the 1977/78 data base confirms this assumption.

Table 1. Descriptive Statistics - Brake Rate Operational Variables (1975 Data Base, "Wet" Track Conditions)

Variable / Statistic	Brake Rate (mph/s)	Initial Velocity (mph)	Train Length (cars)	Braking Interval (secs)	Speed Change (mph)
Mean	2.456	68.29	5.28	13.96	29.57
Std. Dev.	0.536	9.07	1.18	4.96	9.94
Variance	0.287	82.27	1.39	24.61	98.74
Kurtosis*	-1.236	2.72	5.85	-0.15	-0.55
Skewness**	0.001	-1.25	2.66	0.83	0.40
Minimum	1.276	29.15	4.00	6.71	10.03
Maximum	3.512	79.84	9.00	28.26	57.14
Sample Size	219	219	219	219	219

$$\text{*Kurtosis} = \frac{\sum_{i=1}^{N} (x_i - \bar{x})/\sigma^4}{N} - 3,$$ a measure of the "peakedness" of the histogram in relation to the normal distribution.

$$\text{**Skewness} = \frac{\sum_{i=1}^{N} (x_i - \bar{x})/\sigma^3}{N},$$ a measure of the degree of asymmetry about the mean.

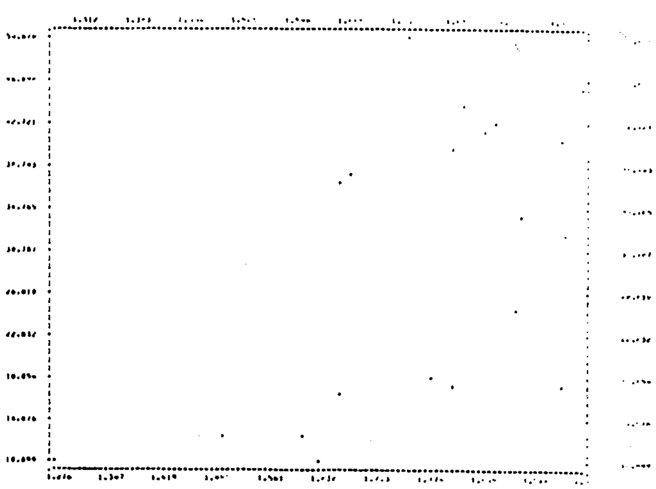

Figure 2. Scatter Diagram of Brake Rate (BRK) with Speed Change (ΔV) ("Wet" track conditions, LAM=5 cars, $V_o > 75$ mph, BRK < 2.0 mph/s)

The winter 1977/78 BART brake rate test program (a statistical design of experiments). An important feature of the 1977/78 test program was exercise of experimental control over all designated test variables as well as the use of basic concepts from the statistical theory of experimental design. The 1975 data base made possible an identification of important variables influencing brake rate. In the 1977/78 test program, all variables were controlled and adjusted to block out random experimental noise and yield greatly improved statistical confidence levels in the results. (The field of statistical design is a highly developed one and the reader is referred to References 8 and 9 for an exposition of the subject. The subject further makes possible prior estimates of required sample sizes for obtaining statistically significant results.) Specific experimental designs used for investigating the influence of identified variables on brake rate are described in appropriate subsections.

Trains of lengths 3, 5, 6, and 7, were utilized in the testing. A large quantity of data was collected in the 3-car category because of the special significance of short trains to close headway operation (close headway operation utilizing 3-car trains during peak passenger hours provides optimum passenger service). All station stops included in the test plan are listed in Table 2. Counting north and south bound lanes of traffic separately, a total of 23 unique station stops were utilized on two main lines of traffic ("A" and "C" lines).

Table 2. Experimental Control - Station Stops ("Wet" Track Conditions)

Station	Absolute Freq	Relative Freq (PCT)	Cum Freq (PCT)
Bay Fair	113	12.7	12.7
Coliseum	75	8.4	21.1
Concord	20	2.2	23.3
Fremont	31	3.5	26.8
Fruitvale	46	5.2	31.9
Hayward	98	11.0	42.9
Lafayette	65	7.3	50.2
Lake Mer	22	2.5	52.6
Orinda	36	4.0	56.7
Pleasant	60	6.7	63.4
Rockridge	8	.9	64.3
San Leandro	109	12.2	76.5
So Hayward	93	10.4	86.9
Union City	66	7.4	94.3
Walnut Creek	51	5.7	100.0
Total	893	100.0	

Other relevant problems addressed by the test plan included investigation of possible significant differences in brake rate based on location, as well as potential date or time of day effects. Since wheel-rail adhesion is believed to be adversely affected by the buildup of filament or particulate matter on the rails, it was conjectured that early morning brake rates, collected when the system has gone relatively unused for hours, might tend to be lower than those observed in the later part of the day. Thus, 1977/78 testing was conducted at all hours of the day including non-revenue hours (i.e., 12:00 AM to 6:00 AM). The influence of temperature on brake rate was also investigated by recording ambient temperatures for each braking event. Finally, investigation of mechanical braking factors was facilitated by a careful recording of individual car numbers for each test train utilized in the program.

Detailed comparison of data bases (1975 versus 1977/78 data). The 1977/78 data base consists of a total of 1,179 braking events recorded under a wide variety of rail conditions. The three main track condition indicators recorded were: "wet," indicating that rain was in progress throughout the braking event, "damp," indicating that rain had occurred prior to the event or that rail moisture was evident, and "dry," indicating that there clearly was no evidence of rail moisture immediately before or during the event. In all cases, track conditions were manually recorded by the test train operator.*

Figure 3 is a computer-generated histogram of the composite winter 1977/78 data base (n=1,179). To begin the analysis a total of 138 "dry" events were selected. The computed mean for this "dry" sample is 3.032 mph/sec with a sigma of 0.311 mph/sec. Hence, approximately 86% of all dry brake applications exceed the original 2.7 mph/sec design assumption. This result clearly substantiates the claim that BART's original designers focused on "dry" track conditions in making their stopping profile calculations.

```
DECEL

 CODE
        I
   7    ** (      5)
        I  1.65 TO 1.8
        I
   8    ** (     10)
        I  1.8 TO 1.95
        I
   9    ***** (     37)
        I  1.95 TO 2.1
        I
  10    ******* (     60)
        I  2.1 TO 2.25
        I
  11    ********** (     87)
        I  2.25 TO 2.4
        I
  12    ********** (     86)
        I  2.4 TO 2.55
        I
  13    *********** (    100)
        I  2.55 TO 2.7
        I
  14    ****************** (    171)
        I  2.7 TO 2.85
        I
  15    *********************** (    221)
        I  2.85 TO 3.0
        I
  16    ******************** (    188)
        I  3.0 TO 3.15
        I
  17    ************** (    134)
        I  3.15 TO 3.3
        I
  18    ****** (     45)
        I  3.3 TO 3.45
        I
  19    *** (     17)
        I  3.45 TO 3.6
        I
  20    *** (     15)
        I  3.6 TO 3.75
        I
  21    * (      3)
        I  3.75 TO 3.9
        I
        I.........I.........I.........I.........I.........I
        0        100       200       300       400       500
        FREQUENCY
```

Figure 3. Computer-Generated Histogram - Composite 1977/78 Data Base

In order to make a meaningful comparison of data bases, only those braking events clearly labelled "wet" were selected for further analysis. Table 3 presents comparative descriptive statistics on brake rate for the two data bases. First, note a substantial difference in computed mean values, with the 1977/78 data having a mean of 2.764 mph/sec and the 1975 data having a much lower mean of 2.456 mph/sec. Next, note that the minimum brake rate for the 1977/78 data is 1.73 mph/sec, while the 1975 minimum is 1.276 mph/sec. Figure 4 presents a comparison of histograms of brake rate under "wet" track conditions for the 1975 and 1977/78 data bases. First note that the 1977/78 distribution, unlike the 1975 bimodal distribution, is unimodal. It is common statistical practice, given the occurrence of a unimodal distribution, to test for normality of the data. However, in this case, it is quite clear from the large and significant skewness and kurtosis coefficients that BART brake rate (BRK) is not a Gaussian phenomenon. It is also important to note a significant difference in the tail structure of the two distributions. For the 1977/78 data, a total of four data points occur in the 1.65 to 1.80 mph/sec interval; specifically: 1.73, 1.73, 1.74, and 1.78 mph/sec. It is demonstrated in a later section that these observed differences in brake rate results may be explained by full-stop braking as opposed to partial brake applications.

*Reference 2 documents experimental recording procedures

Table 3. Comparison of Descriptive Statistics on Brake Rate (BRK) ("Wet" Track Conditions)

Statistics	1975 "Wet" Data	1977/78 "Wet" Data
Mean	2.456	2.755
Std. Dev.	0.536	0.376
Variance	0.287	0.141
Kurtosis	-1.236	-0.599
Skewness	0.001	-0.330
Minimum	1.276	1.730
Maximum	3.512	3.710
Sample Size	N=219	N=893

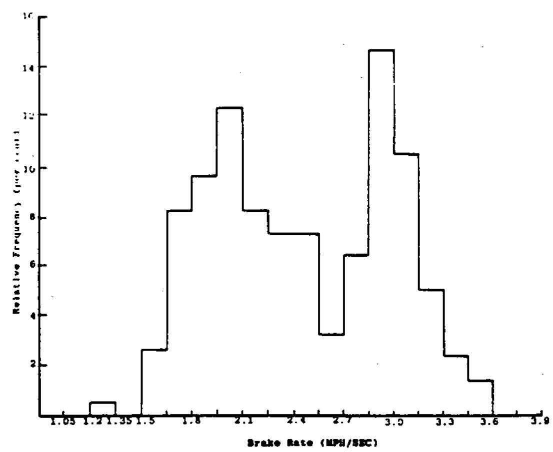

Figure 4A. 1975 Histogram ("Wet" Track Conditions)

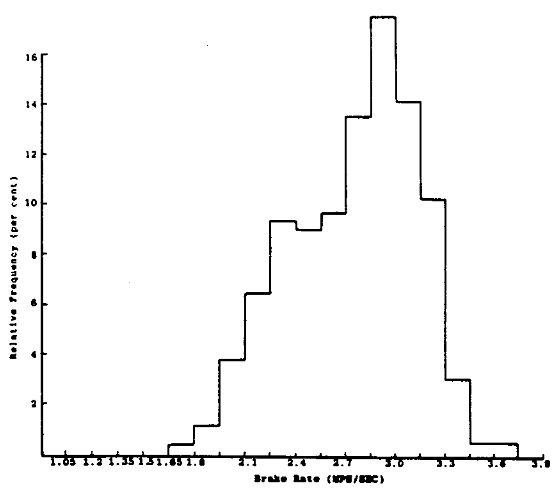

Figure 4B. 1977/78 Histogram ("Wet" Track Conditions)

1977/78 Data Analysis Results (Operating Mode Effects)

The sections below describe the data analysis results pertaining to each individual operational variable. Since a major objective of the 1977/78 test program was precise determination of the influence of each variable on BART brake rates, the specific prior experimental design utilized is appropriately described in each subsection.

Brake rate (BRK) velocity dependency. Train velocity (V_o) prior to initiation of braking was identified as a significant variable in the 1975 data analysis. Consequently, a total of twenty-three distinct station stops from 70- and 80-mph commanded speeds were included in the winter 1977/78 test plan.

A random blocking technique from the theory of statistical design was utilized whereby lower speed command trials (i.e., 27 and 36 mph) were interspersed between stations. The method of approach paralleled the classical agricultural experiments from the theory of experimental design whereby the relative yield of a number of different seed varieties is tested via random block assignment (c.f., References 8, 9).

Table 4 presents the results of a bivariate linear regression of the variable Brake Rate (BRK) on Initial Velocity (V_o). Separate regressions were run for each train length category in order to control for the effect of the latter on brake rate. The results demonstrate that brake rate is velocity dependent. Note that all computed regression coefficients are significant to the 99% confidence level. The correlation coefficient, which intuitively represents the amount of variance in brake rate (BRK) "explained" by the initial velocity variable (V_o), ranges from a low of 11.1% to a high of 48.3% in the six-car category.

Table 4. Regression Results
Brake Rate (BRK) vs. Initial Velocity (V_o)
("Wet" Track Conditions)

Train Length Category	Sample Size	Correlation Coeff. R^2 (BRK/V_o)	Regression* Coeff. (V_o)
3	431	0.150	-0.06 mph/s per 10 mph
5	331	0.111	-0.10 mph/s per 10 mph
6	91	0.483	-0.10 mph/s per 10 mph
7	40	0.142	-0.04 mph/s per 10 mph

*All coefficients are significant to 99% confidence level.

Figure 5 is a sample scatter diagram of acceleration (in mph/sec) versus initial velocity (in mph) for the three-car category. Note that the four main levels of velocity utilized (i.e., 80, 70, 36, and 27 mph) appear in "clusters" due to a variable speed offset from commanded velocity as well as the different performance levels normally applied to modify speed commands during train operations. In all cases, true train speed is somewhat below commanded velocity. For example, a range of speeds from approximately 73 to 79 mph corresponds to the standard 80-mph speed command.

Train length influences on brake rate (BRK). Analysis of the 1975 data clearly indicated that train braking performance varies with train length. Thus, a number of different train length categories were used in the 1977/78 test program (i.e., 3, 5, 6, and 7 car trains). As was previously noted, three-car trains are of special significance to "close headway" operation. The remaining train lengths represent the most frequently occurring categories in current revenue

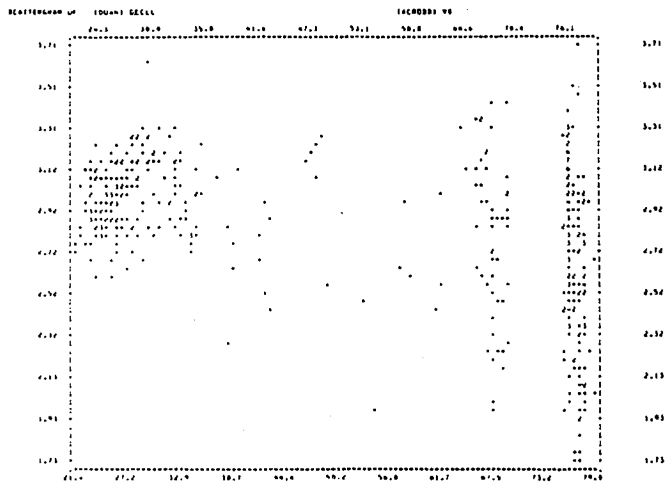

Figure 5. Scatter Diagram Brake Rate (BRK) Versus Initial Velocity (V_o) (3 car consist)

operations. Table 5 presents a complete set of descriptive statistics for brake rate broken down by individual train length categories. It is important to note that trains of length three performed better on the average than all other types, in particular trains of length five. This significant difference may be explainable in terms of aerodynamic considerations. The two main aerodynamic forces on a moving body are so-called "form drag" and "skin friction." Form drag is a function of the shape of the moving vehicle, in this case rectangular. Since there is little difference between a three-car and a five-car train in this respect, the total amount of form drag should be about equal. By calculating the amount of drag on a per-car basis, it is revealed that three-car trains have a distinct aerodynamic advantage over five-car trains in this respect. Skin friction, in

Table 5. Descriptive Statistics
Brake Rate (BRK) Versus Train Length (LAM)
("Wet" Track Conditions, $v_o > 75$ mph)
Train Length

Statistics	3	5	6	7
Mean	2.705	2.631	2.431	2.580
Std. Dev.	0.413	0.365	0.283	0.286
Variance	0.170	0.133	0.080	0.082
Kurtosis	-0.541	-0.627	0.749	-0.034
Skewness	-0.261	0.217	0.571	0.748
Minimum	1.730	1.880	1.900	2.250
Maximum	3.710	3.640	3.280	3.280
Sample Size	171	186	48	18

contrast, is a function of body surface area alone and can be expected to increase with increased train length. However, in both cases, the overall contribution of skin friction to total train resistance is relatively minor making form drag the dominant aerodynamic force in performing train length comparisons.

Note that the minimum observed brake rate for three-car trains is 1.73 mph/sec, in contrast to the 1.88 mph/sec minimum for the five-car trains. Therefore, it appears that although three-car trains perform better on the average than five, the lowest measured brake rates are contained in the three-car category. The so-called "rail cleansing" and "rail gripping" phenomenon may explain these results. A "rail cleansing" phenomenon refers to the fact that lead cars tend to "cleanse" the rails creating higher adjesion surfaces for trailing cars. A "rail gripping" phenomenon refers to the fact that long trains afford a greater degree of wheel-rail contact, and since the coefficient of friction is not constant along the rails, cars braking over portions of relatively higher adjesion tend to pull remaining parts of the consist. Thus, when adhesion is low, short trains may not respond as well as long trains due to these factors. The observed increase in mean brake rate occurring from the six- to seven-car category may represent a crossover point whereby rail cleansing and gripping effects begin to dominate over aerodynamic factors. In Reference 1, based on the 1975 data, brake rate was observed to be an increasing function of train length. This inference was based on data consisting of mainly five-, six-, and nine-car trains. Note that the steady increase in minimum brake rate over the entire range of train lengths is consistent with this explanation.

<u>Influence of mechanical braking factors on brake rate (BRK)</u>. In order to obtain a highly representative sample of train braking performance data, randomized consists, rather than a fixed test train, were utilized in the 1977/78 test program. Potential differences in performance among the individual test trains were investigated by performing a standard analysis of variance (ANOVA). (BRAKE RATE [BRK] VERSUS CONSIST.) Table 6 presents ANOVA results for the high speed, five-car train category. A total of thirteen distinct trains comprised these experiments. The lead car (Car 164), containing the previously described measuring and recording instrumentation, remained the same for all test trains. The computed value of the F-statistic is 5.353, indicating significant differences among the mean values within categories. Unfortunately, due to practical constraints on the execution of the test plan, individual test trains were in most cases operated on different days and therefore, in

Table 6. ANOVA: Brake Rate (BRK) Versus Consist ($V_o > 75$ mph, LAM = 5 Cars, "Wet" Track Conditions)

Consist ID Sequence	Mean	Std. Dev.	Variance	N
164-503-626-502-199	2.589	0.143	.0203	10
-505-513-584-246	2.810	0.344	.1183	15
-557-707-666-234	2.560	0.363	.1315	33
-640-752-711-216	2.667	0.348	.1210	10
-646-630-706-124	2.274	0.282	.0797	10
-646-702-660-196	2.416	0.425	.1806	16
-654-534-702-101	2.756	0.292	.0855	10
-713-550-602-177	2.465	0.176	.0310	16
-716-662-722-208	2.673	0.360	.1297	19
-724-598-606-223	3.340	-	-	1
-751-650-646-180	3.041	0.221	.0490	12
-755-769-522-198	2.674	0.353	.1247	33
Total	2.629	0.365	0.1345	185

$F = 5.3530$; $\alpha = 0.000$

principle, under different track conditions. Consequently, the conclusion that observed differences may be due to mechanical rather than environmental factors may not be warranted due to a lack of adequate experimental design in this one area. Further investigations were conducted by generating histograms for the lowest performing trains within each train length category. Figure 6 presents the brake rate distribution for train I.D. number 164-564-132. Once again, initial velocity and track conditions were controlled in generating these results. A comparison of this historgram with the composite three-car histogram proves interesting. Based on this comparison, it becomes apparent that individual low performers exhibit the same degree of wide variation as their parent group, providing evidence that observed differences among individual test trains are due to wide variations in the coefficient of adhesion, rather than degraded mechanical performance. This is further substantiated by generating a time series plot on test train I.D. number 164-564-132 (Figure 7). The recorded braking history for this test train shows no evidence of degraded braking performance as time progresses.

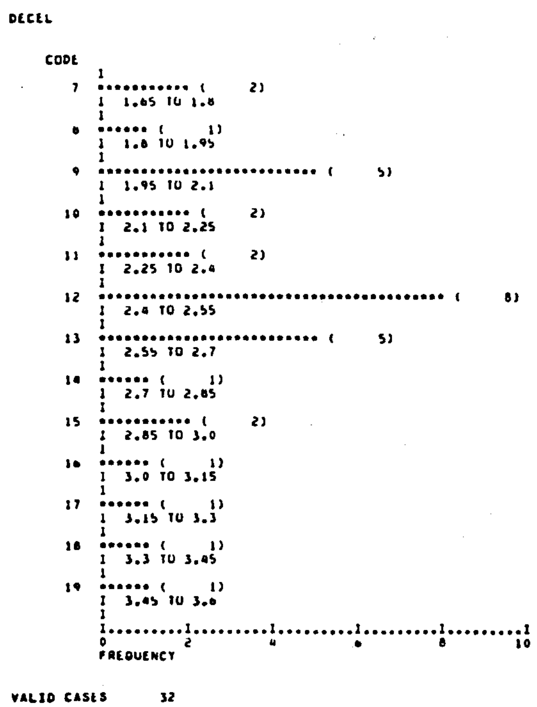

Figure 6. Computer-Generated Histogram - Brake Rate (BRK) for Train ID 164-564-132 ("Wet" Track Conditions, $V_o > 75$ mph)

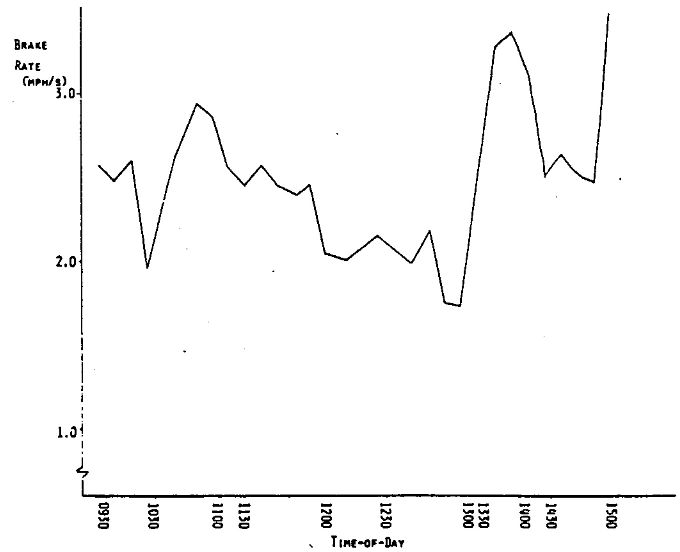

Figure 7. Time Series Plot: Brake Rate - Train ID Number 164-564-132

Influence of other variables on brake rate (BRK).

Time-of-day. Table 7 presents the results of an analysis of variance performed on BRAKE RATE (BRK) versus TIME OF DAY. Contrary to predictions, both the mean and minimum brake rate are higher for early morning test runs, although not significantly so.

Table 7. ANOVA: BRAKE RATE (BRK) vs TIME OF DAY ("Wet" Track Conditions, $v_o > 75$ mph, LAM = 3 cars)

Time Category	Sample Size	Mean	Std. Dev.
6 - 10 am	18	2.820	0.425
10 - 4 pm	55	2.686	0.459
4 - 7 pm	19	2.716	0.314
7 - 6 am	79	2.689	0.400
Total	171	2.705	0.413

$F = 0.545$; $\alpha = 0.652$

Temperature and location. Table 8 presents a brief summary of results pertaining to the temperature and location variables. It is of interest to note that although significant differences among stations were not detected, a rather significant correlation between brake rate (BRK) and train line was discovered. For example, along the "A" line connecting Fremont to Lake Merritt station, trains running northbound (on line A2) performed consistently better than those running southbound (on line A1). An attempt to explain this block effect in terms of readily identifiable factors such as grade, test date, etc., proved unsuccessful.

Table 8. ANOVA: BRAKE RATE (BRK) Versus TRAIN LINE/STATION/TEMPERATURE. (Summary of Results)

Variable	F Ratio	Significance Level α
Train Line (A2,C1,C2,A1)	4.164	0.006
Station (Union City, etc.)	1.458	0.129
Temperature (°C)	0.581	0.560

The influence of temperature was then investigated. The mean recorded temperature for the winter 1977/78 test program was 13.8°C (56.98°F) with a mininum recorded temperature of 6.0°C (42.8°F) and a maximum of 27.0°C (80.6°F). The computed F ratio for brake rate (BRK) broken down by temperature blocks of 3°C is 0.581, indicating that no significant evidence that the coefficient of adhesion is temperature dependent has been found over the range of observed temperatures. Examination of scatter diagrams for deceleration versus temperature (see Figure 8) further substantiates this.

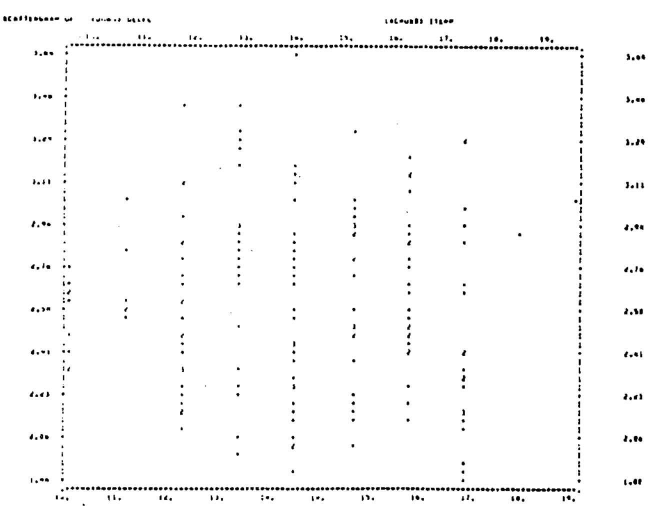

Figure 8. Scatter Diagram: Brake Rate (BRK) Versus Temperature (°C) (5 Car Trains, "Wet" Track Conditions)

Complete multivariate brake rate model. For further confirmation of the previous results, a complete multiple regression model for brake rate was developed utilizing all previously defined variables recorded in the data base. Since the variable train length was discovered to influence brake rate in a nonlinear manner, separate regression runs were performed within each train length category. Table 9 displays multiple regression results for three-car trains.

First, it is important to note that the estimated regression coefficient for initial velocity (V_o) equals that obtained in the previous bivariate regression analysis. This result lends a great deal of credibility to the specific value previously computed.

Next note that large significant differences in mean brake rate have been detected on certain individual test days, indicating that the coefficient of adhesion appears to vary significantly due to

Table 9. Multiple Regression Results, LAM = 3 cars ("Wet" Track Conditions)

Significant Variables	Regression Coefficient	95% Confidence Interval
Initial Velocity (V_o)	-0.06 mph/s per 10 mph	(-0.07, -0.05)
Date 1 (2/6/78)	0.38 mph/s	(0.08, 0.67)
Date 2 (2/8/78)	0.29 mph/s	(0.20, 0.37)
Date 3 (3/1/78)	0.15 mph/s	(0.04, 0.25)
Date 4 (3/2/78)	0.12 mph/s	(0.04, 0.20)
Date 5 (3/3/78)	0.25 mph/s	(0.13, 0.37)
Date 6 (3/4/78)	0.14 mph/s	(0.05, 0.22)
Fremont (A1)	0.23 mph/s	(0.17, 0.29)
Concord (C2)	0.14 mph/s	(0.05, 0.22)
Constant	2.94	

$R = 0.56$
$R^2 = 0.31$
Mean Brake Rate (BRK) = 2.85 mph/sec

environmental changes. Furthermore, relevant changes in brake rate appear to occur in clusters; i.e., patterns of low or high adhesion can persist for several days. For example, note the positive regression coefficients of comparable magnitude obtained from March 1-4, 1978.

The previously discovered block effect for train line also appears as highly significant in the multiple regression. Once again, no physical explanation is offered for this definite effect. Moreover, consistent with previous results, the variables temperature and time-of-day appear to lack significance in explaining brake rate performance.

Comparable regression results for the five-, six-, and seven-car categories were generated and consistency of results obtained. Reference 2 contains the complete set of multivariate results.

Speed change (ΔV) analysis - A comparison of the truncated 1977/78 data base with the 1975 data. Figure 9 displays the histogram for speed change (ΔV) for the 1975 data. Note a mean speed change of 29.57 mph with a sigma of 9.94 mph, with approximately 82.6 percent of all recorded speed changes less than 40 mph. Further, note that approximately 5% of all speed changes were, in fact, under 15 mph. In order to perform a more meaningful data base comparison, a speed change truncation of the 1977/78 data was performed. For a given ΔV, the truncation process is performed by terminating the corresponding deceleration profile of a braking event after a decrease in initial velocity of ΔV mph occurs. Equivalent deceleration is then calculated over the remaining initial portion of the trace in the same manner described earlier. This truncation process utilized the exact 1975 ΔV histogram with random assignment of speed changes to individual 1977/78 braking events. Figure 10 displays histograms for the 1977/78 data before and after speed change truncation. First, note that after truncation the 1977/78 distribution acquires the same characteristic bimodal shape observed in the 1975 data. Further note that the mean has been significantly reduced from 2.63 mph/sec to 2.34 mph/sec and that relatively little change in sigma has occurred. Most importantly, a significant number of relatively low brake rates (i.e., less than 2.0 mph/sec) have been manufactured through the truncation process.

A comparison of the truncated 1977/78 and 1975 histograms proves highly informative (see Figure 11). Examination of these results clearly reveals that the winter 1977/78 testing, had it been performed with the same proportion of small speed changes occurring in 1975, would have, in fact, led to more pessimistic results than the 1975 data, with a higher percentage of brake rates in the 1.2 to 1.35 mph/sec category. Figure 12 displays the same results in cumulative distribution function form.

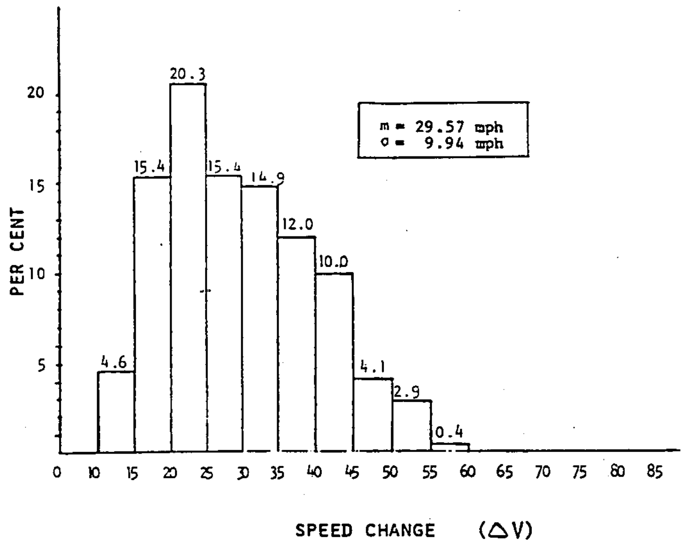

Figure 9. Histogram for Speed Change (ΔV) - 1975 Data ("Wet" Track Conditions, N = 242)

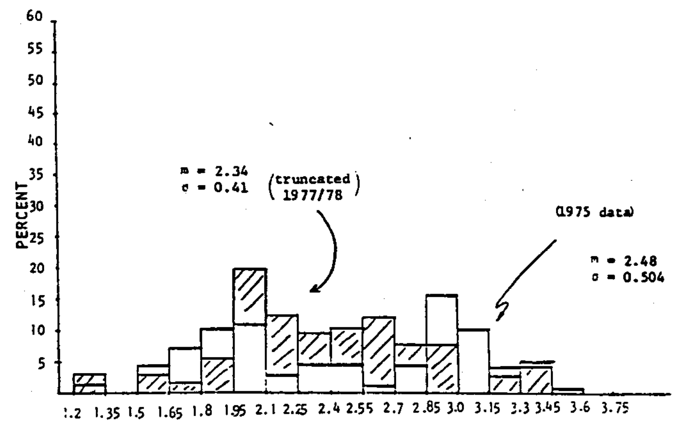

Figure 11. Histogram 1975 Versus Truncated 1977/78 Data (Initial Velocity V_o > 75 mph, Train Length LAM = 5 Cars)

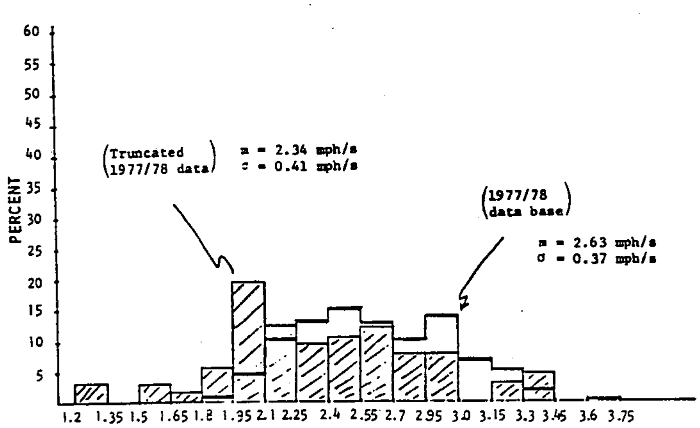

Figure 10. Truncation Effect: 1977/78 Data Base (Initial Velocity V_o > 75 mph, Train Length LAM = 5 Cars)

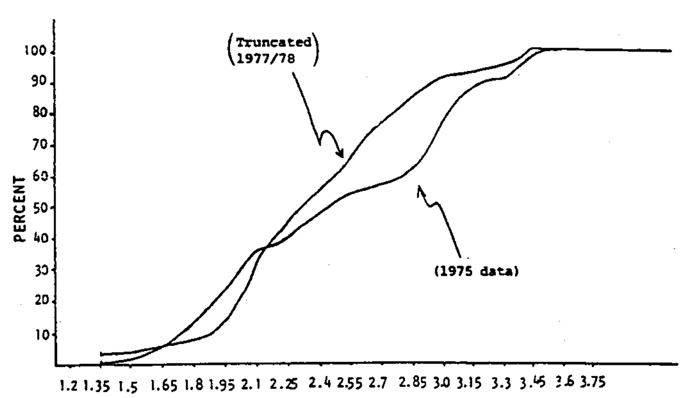

Figure 12. Cumulative Distribution Function Versus Truncated 1977/78 Data (Initial Velocity V_o > 75 mph, Train Length LAM = 5 Cars)

MAIN CONCLUSIONS AND RECOMMENDATIONS

The influence of various operational variables (e.g., train velocity, length, etc.) on BART braking performance has been confirmed through an elaborate test program designed and conducted over the winter months of 1977/78. Extensive testing made possible derivation of all results with high statistical confidence levels. For example, based on a regression analysis of the 1975 data, it was predicted that BART full-stop braking performance would prove considerably better than braking measured over relatively small speed changes. This important assumption was confirmed with a high degree of confidence through analysis of the 1977/78 data. Furthermore, via a speed change-truncation exercise performed with the 1977/78 data apparent differences between the two data bases could be explained and a remarkable consistency in results demonstrated. This result strongly supports the case of "representativeness" of the accumulated data base.

Based on the above results, it appears that BART resignalling for a 1.2 mph/sec brake rate provides an adequate safety margin to the public for normal revenue operations. This 1.2 mph/s resignalling translates into minimum three minute train headways. The results further suggest that a velocity-dependent approach to railroad signalling may be warranted for future consideration since train braking performance appears to be a strong function of train velocity. Thus, required stopping margins may even be reduced over regions of the system with relatively low commanded speeds, yielding a significant increase in throughput without degrading system safety performance. Furthermore, based on analysis of the 1977/78 data, there appears to be no safety-related reason to impose a speed reduction penalty under "wet" conditions for normally operating trains, provided the entire system (i.e., all exposed track) is resignalled based on the 1.2 mph/sec design brake rate assumption.* Recall that BART's past winter operations have required a full 25% speed reduction penalty (commonly called "impeded mode") under wet conditions.

The influence of individual cut-out cars or spontaneous brake failures on total train braking performance was not explored in the previous test series. The term "cut-out car" refers to the fact that each individual car in a BART train has its own hydraulic braking system. Under current operational procedures, if some prior indication of trouble received (e.g., low hydraulic pressure), the entire braking system of that car is intentionally disabled. A spontaneous brake failure refers, of course, to an immediate unanticipated loss of braking in any individual car. Principles of basic mechanics would predict that for a train of length N, loss of braking in any one car would degrade overall braking performance by a factor of (N-1)/N. An immediate implication is that a three-car train with a single brake failure would require a coefficient of adhesion of at least 0.082** to stop adequately, given the 1.2 mph/sec resignalling.*** However, if all brake failures are properly annunciated, appropriate remedial action is always available in the form of an immediate speed reduction penalty application. Current BART operational procedures require 50% speed reduction for trains with cut-out cars. These trains, commonly referred to as "half-speeders," can cause a serious blockage of normal traffic flow and reduced total system throughput. It was, therefore, recommended that a full-scale test program be conducted to precisely determine cut-out car effects. Consequently, current experimentation utilizing onboard instrumentation is being performed at BART with cut-out car operation under adhesion-limited conditions. It is hoped that this testing will yield substantial system benefits by demonstrating a lack of need for severe speed reduction penalties. On the other hand, if a significant speed penalty is found to be necessary to assure safe operation, an investigation into braking efficiency may be conducted. An examination of individual braking profiles for low adhesion events demonstrates that a substantial drop-off, followed by a gradual rebound of the deceleration trace, occurs after the point of peak deceleration (see Figure 13). A sensitive electronic slip-spin device should be capable of making fine adjustments in braking for a given coefficient of wheel-rail adhesion and theoretically prevent the drop-off/rebound effect altogether. Figure 14 presents a hypothetical deceleration trace assuming perfect slip-spin efficiency. The illustrations indicate that a reduction in programmed "brake call" may prove beneficial under low adhesion conditions. This fact could possibly be exploited to improve the braking performance of trains with cut-out cars. It is interesting to note the results of a preliminary analysis of cut-out car operational effects previously performed using a small sample of simulated low adhesion BART braking events. These events, collected during the summer months prior to the 1977/78 test program preparation, demonstrated the need for the kind of experimental design utilized in the winter testing. Because of a large amount of

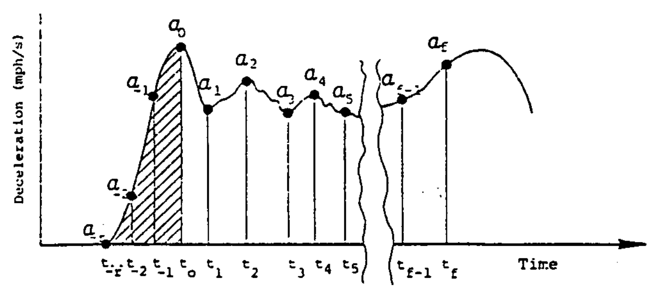

Figure 13. BART Deceleration Trace - Adhesion-Limited Conditions

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*Brumberger, N.A., Reference 4, contains complete documentation on the BART resignalling.

$$**0.082 = \frac{3}{2} \times 1.2 \text{ mph/sec} \div g, \; g = 21.9 \text{ mph/sec.}$$

***This statement turns out to be not quite correct, since BART currently uses a number of other pessimistic assumptions in addition to the 1.2 mph/sec brake rate in computing their stopping distances. Thus, the true effective brake rate is considerably less than this number. Reference 4 provides technical details.

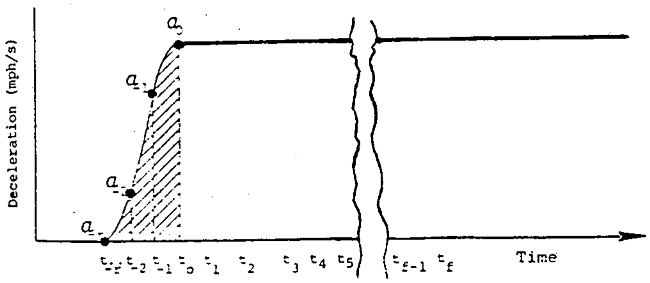

Figure 14. Hypothetical BART Deceleration Trace - Improved Slip-Spin Efficiency

random environmental noise and inadequate variable control, no significant conclusions regarding cut-outs can be inferred from this data. Hence, brake rate testing involving cut-out car operation is currently applying the same basic precepts used in planning and conducting the 1977/78 test program.

As a final note, it is felt that the results and conclusions of this study are of general interest to the transit industry at large, since the problem of railroad signalling is one common to all rail transit systems. It seems clear that the past experiences of the Bay Area Rapid Transit District (BARTD) stress the importance of applying a systematic approach to the problem based on prior planning and experimental design with a view towards public safety as well as system efficiency.

REFERENCES

1. Leon, G.B., et al., "Probabilistic Safety Analysis for Bay Area Rapid Transit (BART) Operational Modes," prepared for BART by SAI, October 1977.

2. _______, Bhatnagar, N., and Tan, W., "Close Headway Operation for Bay Area Rapid Transit (BART)," prepared for BART by SAI, October 1978.

3. Ganstwig, M., "Program Plan Brake Rate Testing of BART Consists," Report No. BA-ENG-78-V16, January 25, 1978.

4. Brumberger, N.A., and Deeble, T.R., "A Comparison of Nominal and Worst-Case Stopping Distances for the BART System," BART Engineering Document, May 13, 1977.

5. Brumberger, N.A., "BART Brake Rate Data Reduction," BART Engineering Document, June 13, 1977.

6. Ames, E.W., Brake Rate Test in Revenue Service, BART Engineering Staff Report, April 28, 1975.

7. _______, "New Accel. Mount Installation and Calibration Check," BART Engineering Memo.

8. Cochran, W.G., and Cox, G.M., Experimental Designs, Second Edition, John Wiley and Sons, New York, 1957.

9. John, P.W., Statistical Design and Analysis of Experiments, The Macmillan Company, New York, 1971.