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ROLLING STOCK BRAKING PERFORMANCE EVALUATION UNDER LOW ADHESION CONDITIONS

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Abstract. *This paper describes the derivation of equations for the evaluation of the effective acceleration/deceleration of a passenger car in support of the evaluation of its complex braking system. The derived equations are applicable in the estimation of braking performance of modern passenger cars in Transit systems, especially under low adhesion conditions.*

The modern braking system of passenger cars employs complex algorithms to control individual axle speeds and brake cylinder pressures to prevent the on-set of wheel sliding which are very likely to occur under low adhesion conditions and at the same time maintain safe braking distances.

The efficiency of the braking system's algorithm depends on the effectiveness of the usage of available adhesion for each axle during its speed reduction by manipulating the respective traction motor speed and the magnitude of the brake cylinder pressures to achieve the prevention of wheel-slide and at the same time to have the ability to stop the car with in the stipulated safe distance.

This paper presents the results of a series of tests conducted on modern transit cars (with latest generation of brake systems), made under low adhesion conditions. The objective of these tests was to evaluate the braking performance, by monitoring individual axle speeds, brake cylinder pressures, longitudinal deceleration of the car and other related parameters. The effective deceleration rate and the corresponding stopping distance from maximum allowable initial speeds are calculated from the derived equations presented in this paper. These computed parameters are compared to the maximum available adhesion to establish the efficiency of complex braking system. This type of testing is essential as a part of the total performance evaluation of new generation of passenger cars introduced in Transit systems.

1 INTRODUCTION

The Rolling Stock tests to check the braking performance tests frequently present the acceleration/deceleration values to vary with the time and with the speed. This occurs mainly in braking tests made under low adhesion condition, where the braking system contains a complex control system to prevent excessive sliding and/or locking of the wheels, through variation of the applied brake effort.

These conditions present a difficult task of the determination of an equivalent acceleration/deceleration that is representative of the actual braking system performance, for a given braking distance and energy dissipated during the test. This determination is needed to evaluate qualitatively and quantitatively the average performance of a complex braking system.

It may be noted that the effective acceleration aef or deceleration is not a simple arithmetic average calculated by the total variation of the velocity with time. This type of calculation is not always the best choice to represent the physics of the energy/work actually performed by the braking system for a given braking distance achieved.

2 DEFINITION OF THE EFFECTIVE ACCELERATION - a_{ef}

Definition: The Effective Acceleration - a_{ef} - is a weighting value of the acceleration based on measured acceleration in the tests – a(t) – that will produce the same braking distance travelled (ΔS) for a observed initial velocity (V_o) and final velocity (V_f), within same energy dissipated (or transformed) during typical braking tests.

The parameters of distance and energy are required in the determination of the available acceleration/deceleration of the braking system, from a safety point of view. Evaluation using the average value of the acceleration/deceleration versus time has no physical significance in order to establish required braking distance by the complex braking system in a passenger vehicle.

3 CASE ANALYSIS

To better understand this concept, Figure 1 shows an example of the velocity change with time during a braking event.

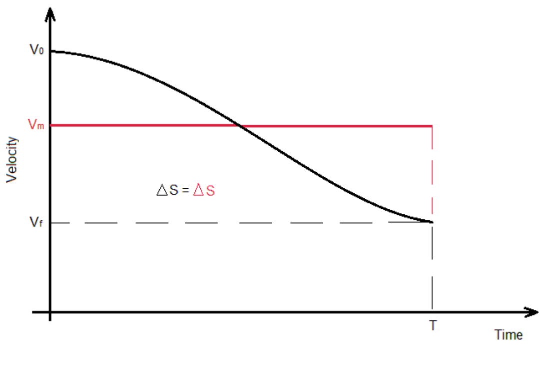

Figure 1 - Example of a Braking Event

In this figure, the brake was applied to reduce the speed with the time, but the acceleration also varies with time being:

$V(t)$ - the instantaneous speed of the body with respect to time (t);

V_0 - initial velocity;

V_f - final velocity;

$a(t)$ - instantaneous value of acceleration at time (t).

The travelled distance (ΔS) is given by the total area of the curve $V(t)$ between time = 0 to time = T.

We can define a trajectory that had a constant average speed V_m so that could also define the same travelled distance (ΔS) at same time T.

4 DETERMINATION OF THE AVERAGE BRAKING SPEED - V_m

$$\Rightarrow \Delta S = \int V(t) \,.\, dt = V_m \,.\, T \qquad (1)$$

Then, $V_m = 1/T \,.\, \int V(t) \,.\, dt$

With measured data digitally in the test we can approximate:

$V_m = (1/T) \,.\, \Sigma\ Vi \,.\, \Delta t$,

Where:

i - index ranging from i = 1 to i = N;

Vi - value of the instantaneous velocity measured digitally;

N - the number of digital measurements made at time T and

Δt - time interval between measurements.

So,

$$T = N \,.\, \Delta t \qquad (2)$$

Then,

$$V_m = (1/N) \,.\, \Sigma\ V_i \ \text{-> for i=1 to N} \qquad (3).$$

5 DETERMINATION OF THE EFFECTIVE BRAKING ACCELERATION a_{ef} /DECLERATION [- a_{ef}] ON TRACK IN "LEVEL" CONDITION WITHOUT SLOPE

By the calculation of the energy dissipated or transformed by the braking system we have:

$E_0 = (M.V_0^2 / 2) + M.g.h_0$ -> initial energy (4)

$E_f = (M.V_f^2 / 2) + M.g.h_f$ -> final energy (5)

Where:

M = Mass of the body;
g = Acceleration due to gravity;
h_0 = Height of the body at the beginning of the event;
hf = Height of the body at the end of the event.

The total work performed during braking (Wr), is given by:

$W_r = \Delta E = E_f - E_0$ =>

$W_r = (M.V_f^2 / 2) - (M.V_0^2 / 2) + M.g.(h_f - h_0)$ (6)

But Wr is also given by:

$Wr = F . \Delta S$ and (7)

F = Braking Force

As defined,

$F = M . a_{ef}$ (8)

Therefore:

$M . a_{ef} . \Delta S = (M.V_f^2 / 2) - (M.V_0^2 / 2) + M.g.(h_f - h_0)$ (9)

and

$a_{ef} = (V_f^2 / (2 . \Delta S)) - (V_0^2 / (2 . \Delta S)) + g.(h_f - h_0) / \Delta S$

Assume braking distance is equal to $S_f - S_0$ and if the braking event is in an inclined plane, of a very small angle α, the variation of h is related to ΔS as:

$\Delta S . \alpha = (\alpha . S_f - \alpha . S_0) = h_f - h_0$ (10)

=> $a_{ef} = (V_f^2 / (2 . \Delta S)) - (V_0^2 / (2 . \Delta S)) + g.\alpha$ (11)

The value of α will be positive for descending slope and negative for the ascending slope.

Conclusion:

In tests on level track ($\alpha = 0$), it is correct to use Torricelli's equation for determination of the a_{ef} where:

$$a_{ef} = (V_f^2 - V_0^2) / (2 \,.\, \Delta S) \qquad (12)$$

6 DETERMINATION OF EFFECTIVE BRAKING ACCELERATION/ DECELERATION a_{ef} IN OPERATIONAL TRACK WHERE SLOPE ≠ 0

For the tests made in Operational Tracks, the Torricelli's formula can no longer be used for the determination of the a_{ef} because $\alpha \neq 0$.

In this case, the determination of a_{ef} can be made from the energy variation of the body during braking. Considering the equations (6), (7), (8) we have:

$$M \,.\, a_{ef} \,.\, \Delta S = \Delta E = E_f - E_0 \qquad (13)$$

As defined, the power dissipated (or transformed) by the braking system, changes the total energy of the body with mass M, from the initial state E_0 to the final state E_f, shown by:

$$\Delta E = \int P(t) \,.\, dt \qquad \text{for } t=0 \text{ until } t=T \qquad (14)$$

Where:

$P(t)$ = Power dissipated (or transformed) by the brakes at time (t)

And

$$P(t) = F(t) \,.\, V(t) = M \,.\, a(t) \,.\, V(t) \qquad (15)$$

Then,

$$\Delta E = \int M \,.\, a(t) \,.\, V(t) \,.\, dt \qquad \text{for } t=0 \text{ until } t=T \qquad (16)$$

In the case of digital measurements, this integral can be approximated for:

$$\Delta E = M \,.\, \sum a_i \,.\, V_i \,.\, \Delta t \qquad \text{for } i=1 \text{ to } i = N$$

and

$\Delta t = T/N$ using the equation (2):

Then,

$$\Delta E = ((M \,.\, T)/N) \,.\, \Sigma\ a_i \,.\, V_i \qquad \text{for } i=1 \text{ to } i = N \tag{17}$$

From the equations (1), (3), (13), and (17) we have:

$$\Delta E = M \,.\, a_{ef} \,.\, \Delta S = ((M \,.\, T)/N) \,.\, \Sigma\ a_i \,.\, V_i \qquad \text{for } i=1 \text{ to } i = N \tag{18}$$

and:

$$a_{ef} \,.\, V_m \,.\, T = (T/N) \,.\, \Sigma\ a_i \,.\, V_i \qquad \text{for } i=1 \text{ to } i = N \tag{19}$$

Therefore:

$$\boxed{\mathbf{a_{ef} = (\textstyle\sum a_i \,.\, V_i) \,/\, (\textstyle\sum V_i)} \qquad \text{for } i=1 \text{ to } i = N \qquad (20)}$$

Conclusion:

Equation (20) can be used in any situation for the calculation of the effective acceleration a_{ef}, even braking under non level situations.

Figures 2 and 3 show plots that represent a typical braking event under low adhesion condition.

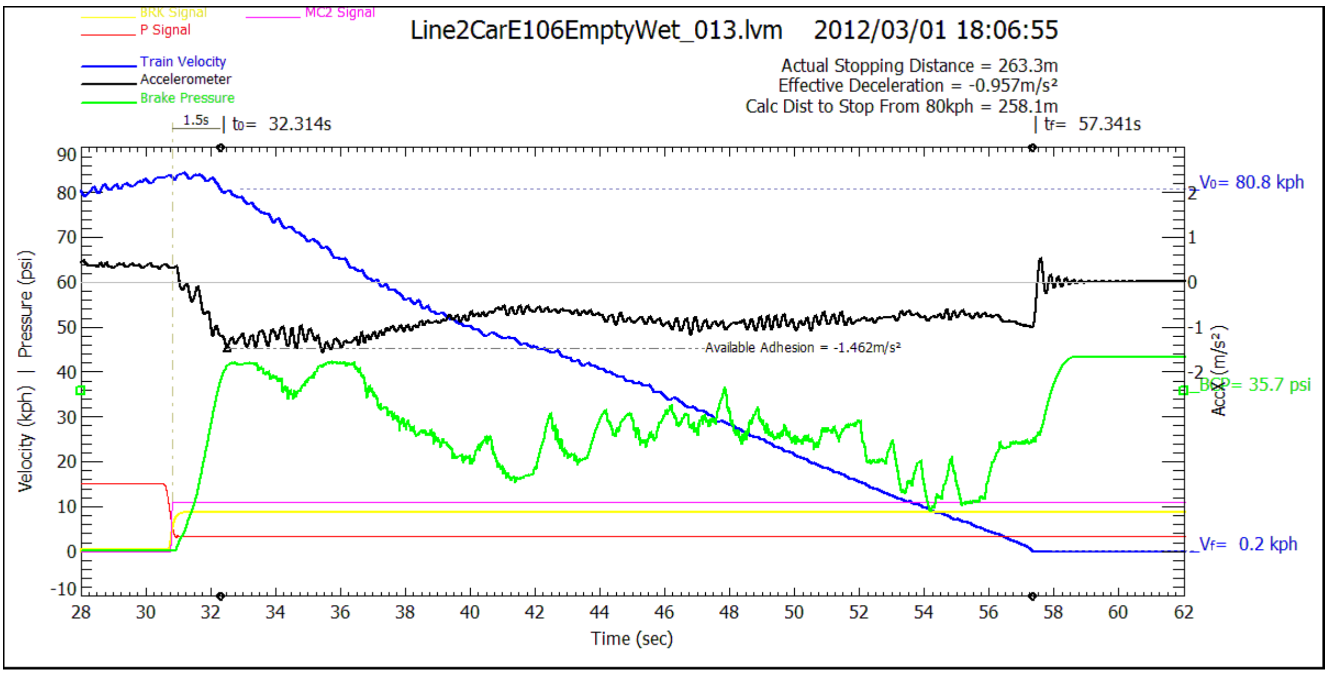

Figure 2. Typical Measured Performance Parameters under wet conditions for a Passenger Train

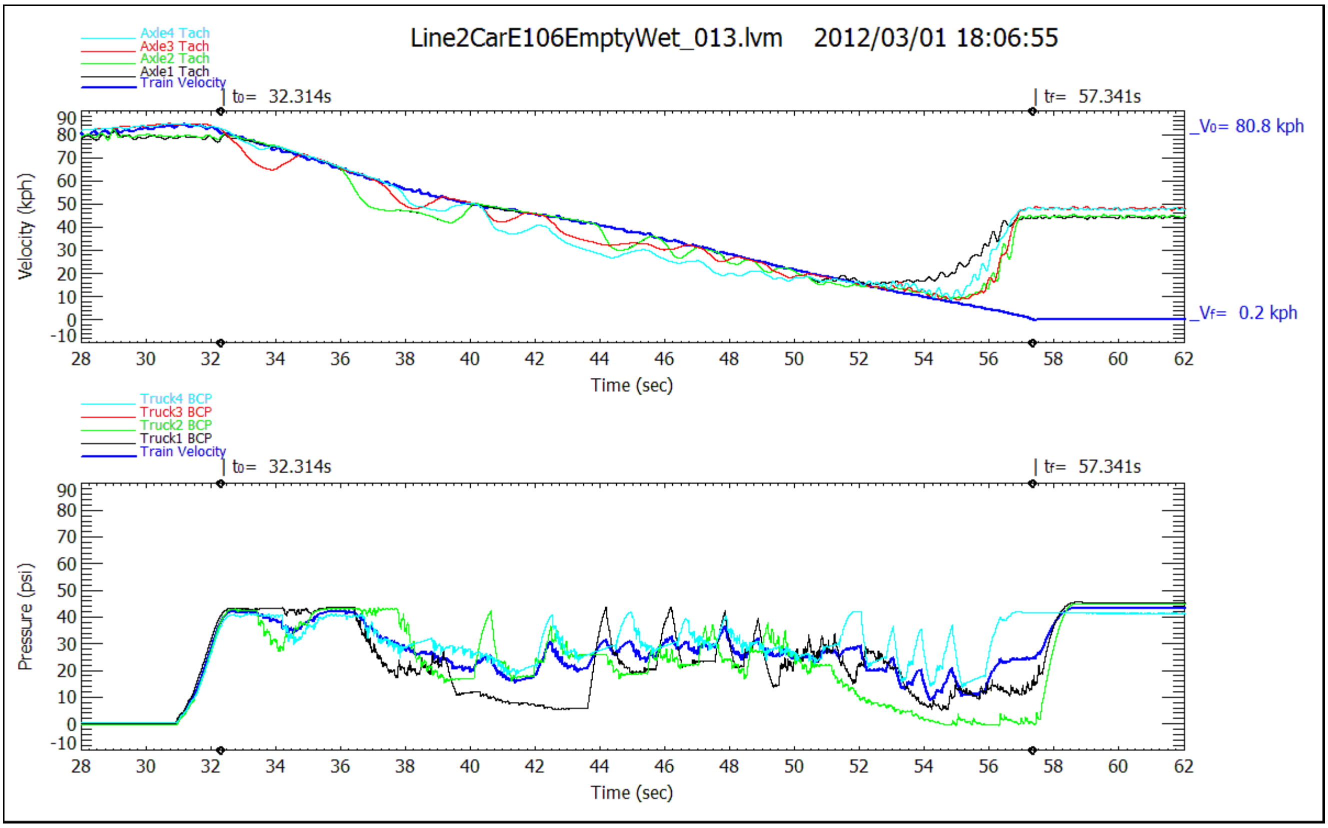

Figure 3. Train speed compared to individual axle speeds (upper graph) and individual brake cylinder pressures for each truck (lower graph) under wet conditions for a passenger train for a typical test run from maximum initial speed

Figure 2 shows the measured braking performance parameters, including train speed, the average of the 4 brake-cylinder pressures, and the measured deceleration. Initiation of braking is indicated by (t_0), beginning 1.5 seconds after the brake command signal (BRK/P-Signal) changes. The velocity at the initiation of braking (V_0) is shown. The train speed is integrated to calculate distance travelled over time, and the actual distance to stop from t_0 until stop (V_f <= 0.1 kph) is calculated by subtracting the distance at t_f from the distance at t_0 and displayed. The effective deceleration is computed using Equation 12 $a_{ef} = (V_f^2 - V_0^2) / (2 . \Delta S)$, which becomes $-a_{ef} = V_0^2 / (2 \text{ Dstop})$. Additionally, the maximum available adhesion is reported by finding the maximum deceleration peak immediately after braking initiation.

Figure 3 shows the measured train speed and individual axle speeds on the upper graph and individual brake cylinder pressures for each truck on the lower graph, as observed during a typical braking test run on wet rail when stopping from maximum track speed. As the brake pressure is increased, the wheels begin to slide, indicated by a sudden drop in individual axle speed. The train's braking control system detects the slide and reduces brake cylinder pressure. Correspondingly, the individual axle speed recovers and approaches the actual train speed again.

Table 1 shows results of typical braking performance evaluation tests under reduced adhesion conditions in a passenger train using Equation (12) developed in this paper. Table 2 shows results of typical braking performance evaluation tests under reduced adhesion conditions in a passenger train using Equation (20) developed in this paper.

Table 1. Braking Performance Under Wet Conditions

	Calculated Distance To Stop From 80 km/h Initial Speed m	**Effective Deceleration Rate from Equation (12) m/s²**
Average Performance for Wet / Emergency	232.3	-1.068
Average Performance for Wet / Full-Service	258.3	-0.957

Table 2. Braking Performance Under Wet Conditions

Friction Condition	**Initial Velocity**	**Final Velocity**	**Time To Reach Final Velocity**	**Distance To Final Velocity**	**Calculated Stopping Distance**	**Effective Deceleration**	**Available Adhesion**	**Braking Efficiency**	**Brake Cylinder Pressure**
	km/h	**km/h**	**s**	**m**	**M**	**m/s²**	**m/s²**		**psi**
Average Performance for Wet / Emergency					**209.7**	**-1.181**		**90.9%**	
Wet	77.1	0.2	22.213	214.7	231.3	-1.068	-1.667	64.1%	37.0
Wet	79.7	0.1	22.487	223.2	224.8	-1.099	-1.776	61.9%	50.5
Wet	80.7	0.1	26.276	265.6	260.8	-0.947	-1.417	66.8%	47.9
Wet	81.2	0.1	20.326	216.4	210.3	-1.174	-1.779	66.0%	47.0
Average Performance for Wet / Full Service					**232.3**	**-1.068**		**65.5%**	
Wet	79.4	0.1	27.623	268.5	272.7	-0.905	-1.622	55.8%	42.9
Wet	80.1	0.1	26.514	267.3	266.5	-0.926	-1.459	63.5%	42.7
Wet	80.8	0.1	24.836	252.4	247.1	-0.999	-1.658	60.3%	42.8
Wet	80.8	0.2	25.027	263.3	258.2	-0.956	-1.462	65.4%	35.7
Wet	81.5	0.1	25.868	258.6	248.9	-0.992	-1.524	65.1%	30.8
Wet	82.1	0.2	23.433	258.5	245.3	-1.006	-1.459	69.0%	31.0

7 ONLINE MONITORING OF COMPLETE TRAIN FOR FOUR MONTHS DURING RAINY SEASON IN SOUTH AMERICA FOR THE ESTABLISHMENT OF AVAILABLE ADHESION/EFFECTIVE DECELERATION RATE

Four specific trains were selected and instrumented for continuous monitoring of adhesion performance under various climatic conditions starting January 2012 to October 2012. Leading and trailing cars of a 6-car train were instrumented with longitudinal accelerometers. The leading car was fully instrumented for monitoring brake cylinder pressure, axle speeds, measurements, etc., as shown in Table 3.

Table 3. Parameters for Instrumented 6-car Train

Ch.	Measurement	Range	Location
0	GPS Speed	0-120 km/h	Lead Car
1	Car speed 1	0-120 km/h	Front, lead car
3	Long. Accel	±0.5g	Mid car body lead car
4	BP1	0-100 psig	Truck 1 brake cylinder
5	BP2	0-100 psig	Truck 2 brake cylinder
6	ABPL1	0-100 psig	Front air bag press left
7	ABPR2	0-100 psig	Front air bag press right
8	ABP3	0-100 psig	Rear air bag press.
9	Axle 1 speed	0-1500 pps	Axle 1
10	Axle 2 speed	0-1500 pps	Axle 2
11	Axle 3 speed	0-1500 pps	Axle 3
12	Axle 4 speed	0-1500 pps	Axle 4
13	GPS time		
14	Latitude		
15	Longitude		

8 LOW ADHESION DATA ANALYSIS

The raw data collected as shown in Table 3 was processed continuously using exploratory data analysis (EDA) and applying statistical data reductions methods. The reduced data was loaded into a large database for statistical analysis and modeling. Braking calculations were performed for selected runs that exhibited low adhesion levels to calculate the effective deceleration rates of the instrumented car by applying the following methodology:

Effective Acceleration Formulas

Flat track (no slope)

$$a_{ef} = (V_f^2 - V_0^2) / (2 . \Delta S) \qquad (12)$$

Any slope

$$a_{ef} = (\Sigma\, a_i . V_i) / (\Sigma\, V_i) \quad \text{for } i=1 \text{ to } i = N \qquad (20)$$

a	acceleration
V	velocity
S	distance traveled

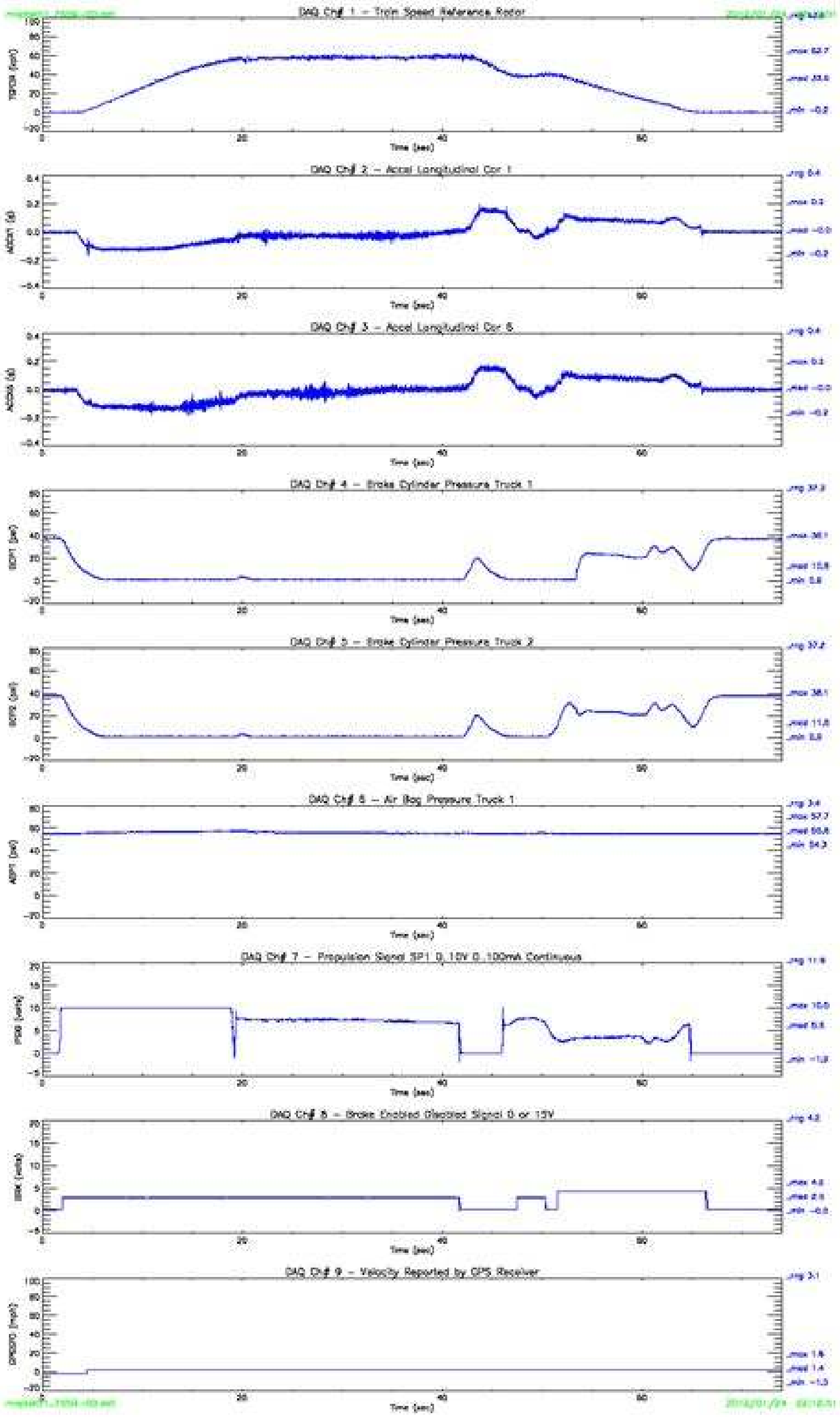

Figure 4. Example Raw Signal Plots from the Instrumented Wagon for a Typical 1-mile run between two metro stations

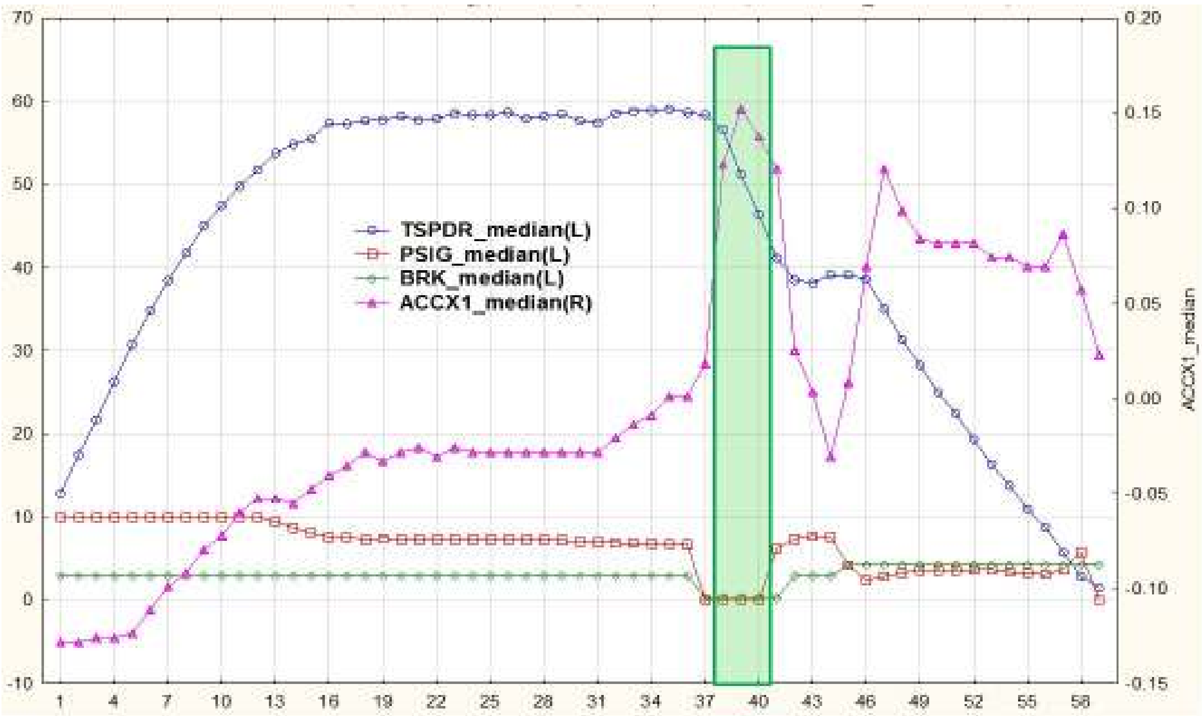

Figure 5. Peak Available Adhesion Determination for a Selected Run

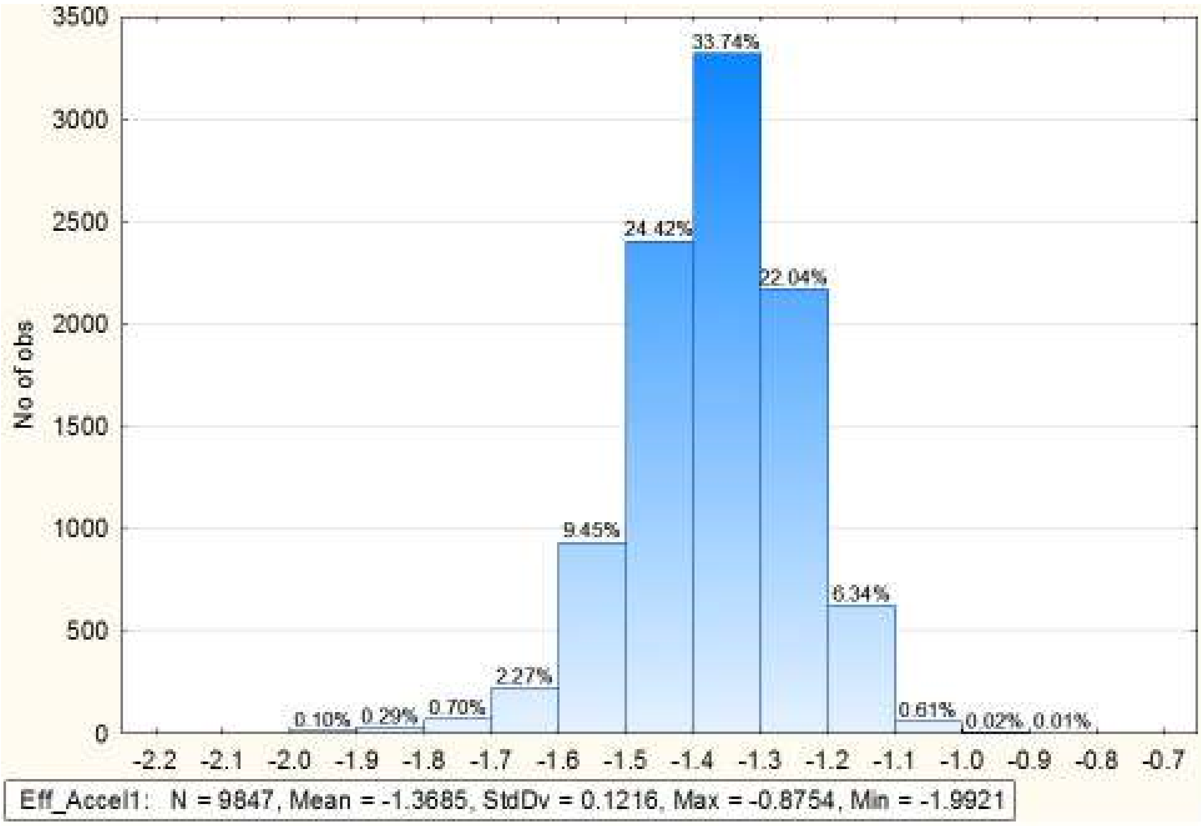

Figure 6. Effective Acceleration Histogram During the Rainy Season

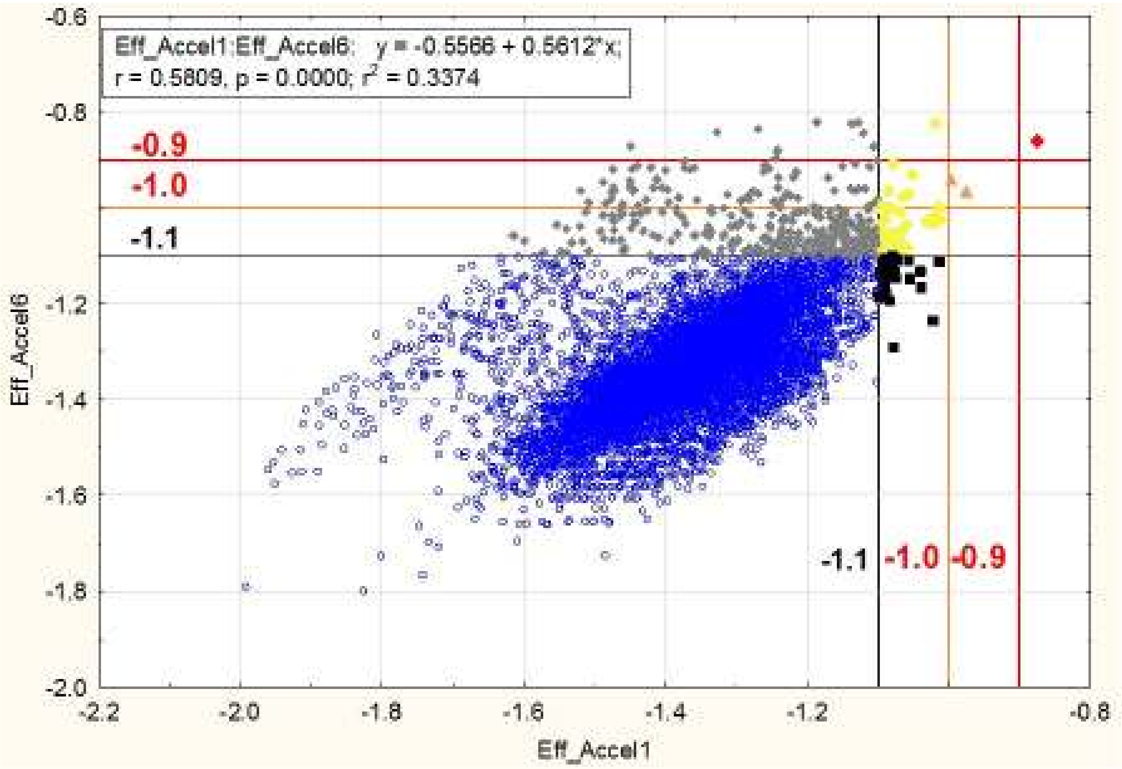

Figure 7. Effective Acceleration Scatterplot between Leading and Trailing Cars During the Rainy Season

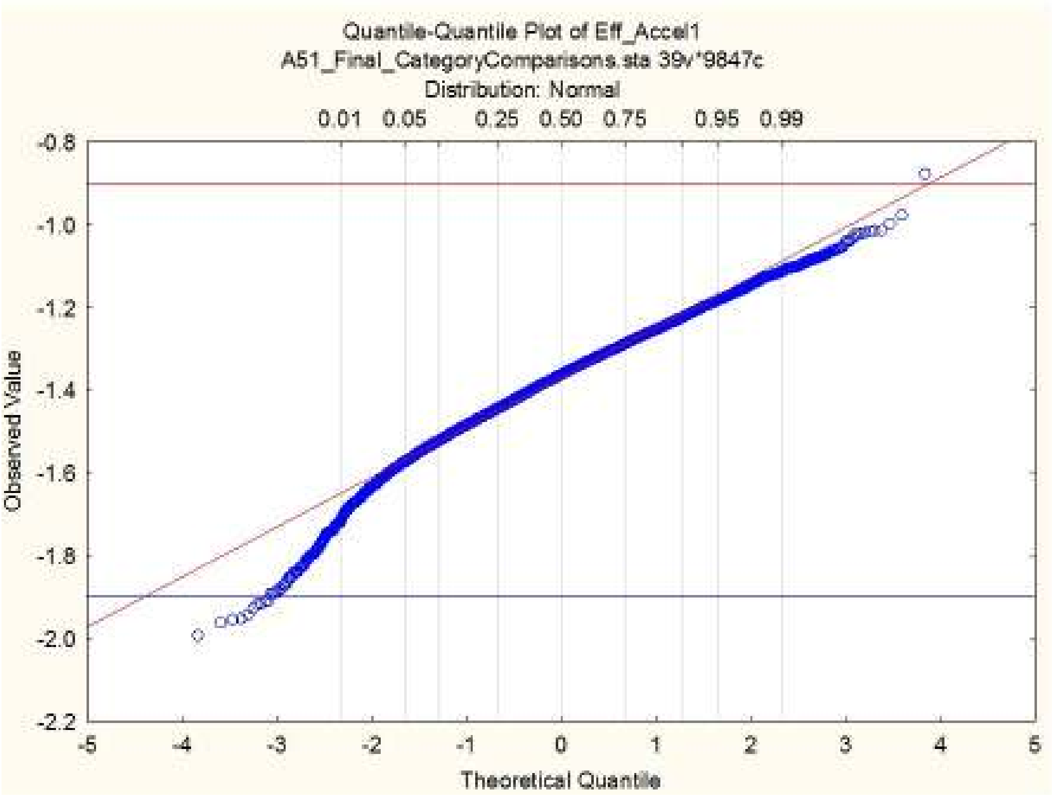

Figure 8. Effective Acceleration Distribution During the Rainy Season

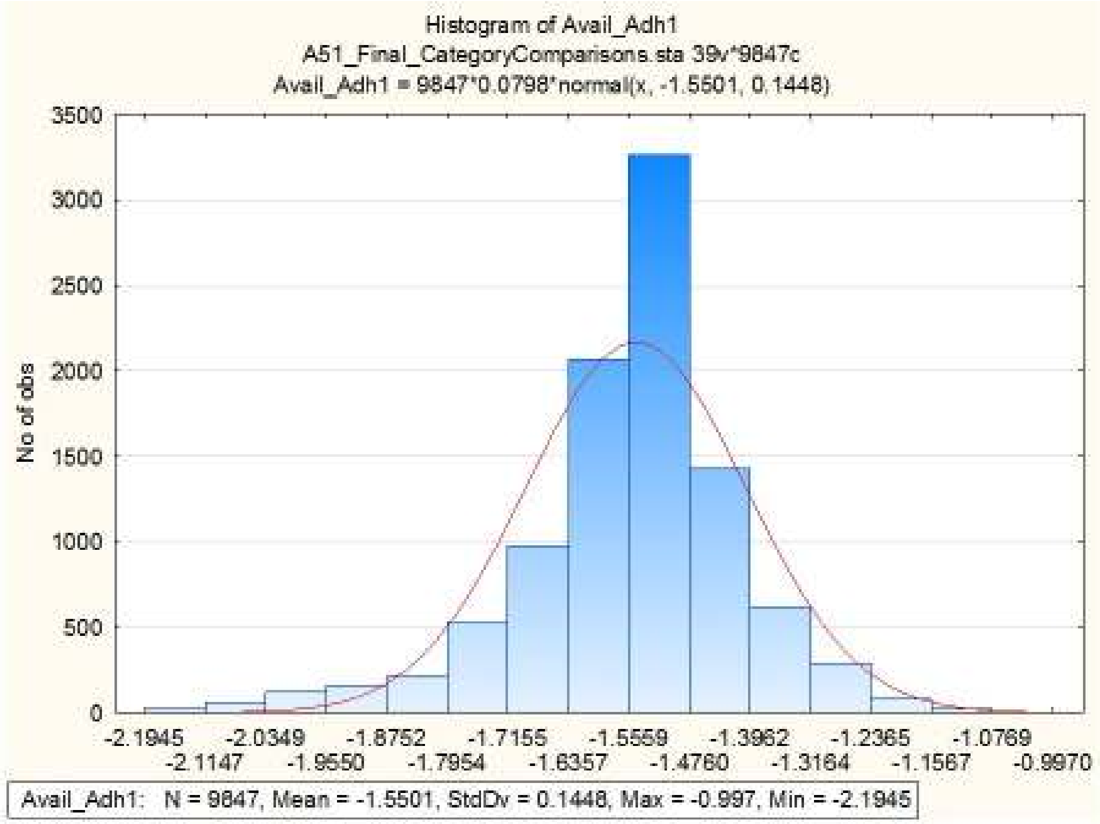

Figure 9. Available Adhesion Histogram for the Entire Rainy Season

9 CONCLUSIONS

Modern rolling stock designs employ very complex algorithms in their braking systems to avoid wheel sliding under low adhesion operating conditions. The performance evaluation of such complex designs requires a systematic approach in the application of fundamental equations of physics in the computerized data analysis techniques. This paper describes a systematic approach of conducting performance evaluation tests on modern transit vehicles that employ sophisticated technologies to provide maximum deceleration rates.