Microprocessor Diagnostic System for Heavy-Haul Trains in Actual Operation

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Operation with heavy-haul trains on Brazil's Ferrovia do Aço (Steel Railway) began in March 1989. Although the original project was for a totally electrified railroad using 25 kV, 60 Hz, the initial operation was with diesel-electric locomotives. Because this railroad has many tunnels, the longest one being 8.6 km, diesel-electric locomotive performance inside tunnels and questions such as type of consist, headway, and environmental conditions inside tunnels were intensively discussed. Because the dynamic operation of a heavy-haul train through long and difficult stretches is extremely complicated, and many random variables are involved, such an operation cannot be estimated in a simple mathematical simulation. Therefore, the necessity of preliminary tests in actual operation became a reality before the beginning of traffic activities. A system was developed to gather data from several points of the tunnels and another system to gather data from on board the locomotives. Both systems were computerized, coupled directly to sensors strategically located inside the locomotives and tunnels. The collecting of data both inside the tunnels and that concerned with the locomotive behavior was performed in real time, both systems being synchronized with the computer's built-in timer.

Brazil's Ferrovia do Aço (Steel Railway) is 300 km long and crosses the rugged Mantiqueira Mountains on a maximum gradient of 1 percent, with curves of 900-m minimum radius. The profile of Ferrovia do Aço ascends for about 200 km to a height of 1125 m, in the export direction; it then penetrates the Mantiqueira Mountains, descending on a consistent 1 percent grade for about 100 km. To accomplish this maximum grade and minimum radius curve, the construction required many viaducts and tunnels. There are 91 viaducts and 70 tunnels in all, the longest tunnel being 8.6 km long.

Because it was necessary to begin traffic operation with diesel-electric locomotives, operating conditions inside tunnels were discussed in depth, taking into account the type of train, train consist, headway, and environmental conditions inside tunnels. Theoretical studies were carried out by international consultants, but they were not definitive (*1*). Therefore, the necessity of preliminary studies in actual operation arose before the traffic activities with diesel-electric locomotives could commence.

Before heavy-haul train operation began, the main facts tested and discussed were the behavior of locomotives and the environmental conditions under which the train crew and the maintenance team would have to work when inside the tunnels.

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After operation had begun, other problems appeared and so new tests had to be performed; some are still being carried out so that the failure in some locomotive systems can be solved and ideal conditions for handling trains in these long stretches can be found.

DYNAMIC BEHAVIOR OF HEAVY-HAUL TRAINS INSIDE TUNNELS

The idea of performing dynamic tests with a heavy-haul train inside tunnels arose from the need for studying more deeply the behavior of the train on this new railroad. There was a need to analyze the operational conditions and the demand on the equipment as a function of the general conditions of the train, as well as the traction theoretically dimensioned for the stretch.

The typical consists of iron-ore trains on the Ferrovia do Aço were initially four locomotives (3,000 HP) and 86 wagons (120 t). The first tests were performed with this consist. After 1 year of operation the consist changed to five locomotives and 108 wagons. Therefore, the necessity of other tests arose. The principal objectives were as follows:

- Dynamic behavior of locomotives inside tunnels.
- Data collecting while locomotives are inside tunnels and after they leave them,
- Analysis and diagnosis of the behavior of variables concerning tunnels and locomotives, and
- Operating feasibility of iron-ore trains hauled by diesel-electric locomotives inside tunnels of the Ferrovia do Aço (*2*).

Two systems, one capable of collecting data in several points inside the tunnels and the other capable of gathering data from on board the locomotives, were developed. The systems were computerized, directly coupled to sensors placed at several points in the locomotives and tunnels. Thus, it was possible to gather data both inside the tunnels and on the locomotives in real time, synchronized with the computer's built-in timer. The data sampling was about one datum per second. Thus, a more accurate analysis of trains' behavior inside the tunnels was possible.

Monitored Signals

The following signals were monitored inside the locomotive and in other parts of the train:

- Main generator voltage,
- Traction motor current,
- Train speed,
- Traveled distance,
- Brake cylinder pressure,
- External temperature,
- Air-intake temperature,
- Lubricant oil temperature,
- Cooling water temperature,
- Tractive effort,
- Acceleration notch, and
- Performance of the protection relays.

Description of Instruments

Temperature sensor—The thermocouple produces a small, variable voltage according to the temperature to which it is subjected. This voltage is amplified and read by the computer.

Speed sensor—The speed sensor consists of a pulse generator coupled to the wagon wheel. This gives a signal in a certain frequency, a signal that is converted into voltage and read by the computer.

Tractive effort sensor—This is based on a bridge of resistors that varies according to the effort to which it is subjected. This bridge nullifies the torque effort, registering only the movements of compression and expansion. These sensors are called strain gages and are connected to a coupler. The resulting signal passes through a conditioner equipped with a filter and an amplifier. This signal then enters a computer as voltage. Negative voltage means a compression; positive voltage, an expansion.

Brake cylinder pressure sensor—To measure the brake pressure, a sensor with a membrane connected to a strain gage is used. Pressure acts upon the membrane and a voltage proportional to its intensity is produced. The resultant signal is read directly by the computer.

Generator voltage sensor—This is based upon the Hall Effect. For the output voltage to be measured, a resistor was connected with a previously calculated value so that a current of a wanted value can be made to flow. The current flows through the shunt hall, and at its output, provides a proportional current with a reduced amperage. Finally, this output current flows through another resistor, which gives a voltage to be read by the computer. The scale of this signal is determined by the resistor's value.

Traction motor current sensor—To measure the traction motor current, a Hall Effect transducer was inserted at the armature terminal cables of the traction motor. The signal from this transducer passes through a condition-amplifier and then enters the computer as voltage.

Acceleration notch—The acceleration notches were monitored by installing a potentiometric transducer on the main lever of the leading locomotive. The signal from the sensor goes to the signal conditioner, which is an operational amplifier. From there, it can be read by the computer.

Data Acquisition System

A digital computer cannot store or process directly an analogical input signal. The computer does not understand something such as "5 V" as input data. It is necessary to transform this voltage into a digital representation that can be stored in a physical media, such as a disk. This transformation of an analogical input signal is performed by an analogical/digital (A/D) converter chip. As the input signals are all analogical, we use a board with an A/D converter that is able to read directly 16 input signals when connected to a microcomputer. To control this board, a program was developed in a scientific language. This program reads and stores information for subsequent use, and it also prints out reports and graphs.

The acquisition system of the locomotive has 32 analogical inputs in the range of −10 V to +10 V and a 17 ms-12 bit A/D converter. It also has 16 digital inputs for the locomotive protection signal indications, for relay devices, or for frequency signals. The signal multiplexing is performed by four 8-input multiplexers selected by a 6-bit word. These bits are directly transferred by the computer bus.

All the signals are isolated for 1,000 V, with a programmable gain via computer, of 1, 10, 100, and 1,000 times. This characteristic allows for a wide range of different indications, such as for thermocouples, strain-gage bridges, millivolts originated from resistor shunt, and so on.

A low-pass filter with a maximum range of 20 kHz and 3 dB is responsible for the high reading efficiency of the signals without noise interference due to the electric machines of the locomotive. The system can be said to be a board for a microcomputer slot that can be easily adapted and installed.

The software used has internal and external interrupt routines for acquisition data. During the test, the information appears on the screen, in windows, in the form of plotted color graph curves, during the test. Thus, a better analysis of the information is provided for immediate use.

The sampling rate can be programmed during the test. Tables and graphs can be consulted as well as the last 3 hr of the test without cutting off the signal acquirement. There are also alarm routines, such as loss of power in one of the locomotives, slipping, or operation of any locomotive protection system.

Some measures for protection were taken to nullify problems such as high vibration, temperature, and humidity. The worst of these problems is vibration. This was solved by creating a pseudo-driver for the operating system. At the end of each testing stage, the information is transferred from this pseudo-driver to the real driver where it is stored.

The system also has the track profile, which includes stretches of about 200 km mapped in memory in order to provide orientation during the tests. It shows the position of yards and important points, such as viaducts, bridges, and tunnels.

At the end of each test, the data are transferred to a work station where they will be analyzed, and graphs and reports will be produced.

Analysis of Test Results

The tests were performed using two types of locomotives, trying basically to keep all the operating characteristics, without involving any specific procedures. To accomplish so many specific studies, several tests were made inside tunnels to observe the behavior of trains while passing through them. These studies showed that the greatest problem was found in the Cabritos Tunnel (T-0601). This tunnel is 908 m long with a grade of 1 percent for loaded trains and has the smallest cross section.

Two alternatives were proposed for an 86-wagon train, when loaded: (a) four locomotives with no helper and (b) four locomotives with a helper at the end. Figure 1 shows the performance of the hot engine protection during the passage of an 86-loaded-wagon train hauled by four locomotives without a helper through the Cabritos Tunnel. Analyzing these graphs, one can evaluate the performance of the protection device, examining several parameters such as external temperature, traction motor current, and speed.

One can see that the protection device was operated when the water temperature reached 90°C. Due to this fact, both traction motor current and speed decreased. The problems were not greater because the protection device was operated just before the end of the tunnel.

Figure 2 shows the operation, at the same time, of the three locomotives' sprays and hot engine protection devices. The test was carried out inside T-0601 with four locomotives and no helper at the train end.

Because of the progressive heating of the locomotives from the first to the fourth one, the relays operation should have happened in the same order. This did not occur, however, probably owing to an error of adjustment, particularly for the spray of the second locomotive.

Figure 3 shows the test carried out inside Tunnel T-0601 and the comparative graph curves for the fourth locomotive external temperature and operation of several devices, but in this case the train had a helper at its end.

In this test, the sprays were operated for a shorter time, compared with the test without helper. Moreover, the engine protection did not actuate. Once again, the spray of the second locomotive showed it to be incorrectly adjusted, because the logical sequence would be to operate after the third locomotive spray operated, turning itself off before the third

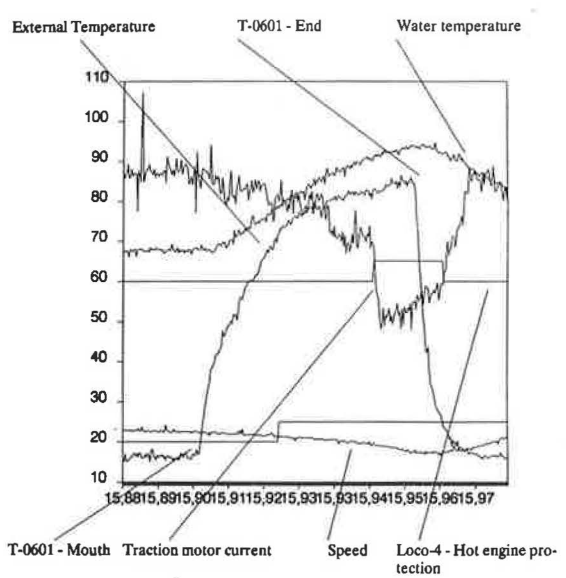

FIGURE 1 Hot engine protection (4 locomotives, 86 wagons, no helper) versus decimal time [external temperature (°C), water temperature (°C), traction motor current ($A \times 10$), speed (km/hr)].

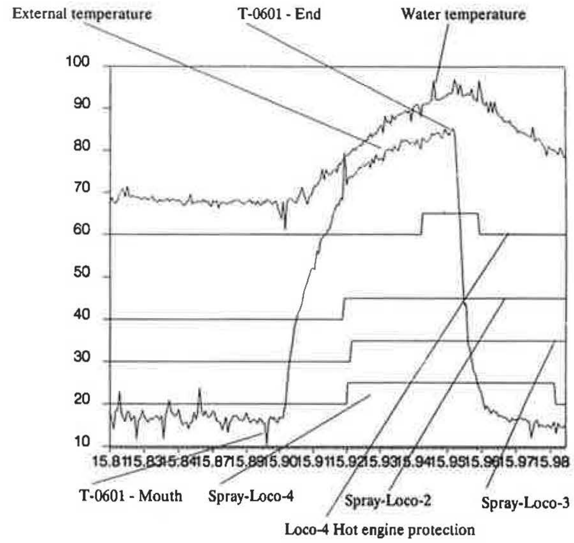

FIGURE 2 Hot engine protection (Locomotive 4) and spray (Locomotives 2, 3, and 4) (4 locomotives, 86 wagons, without helper) versus decimal time [external temperature (°C), water temperature (°C)].

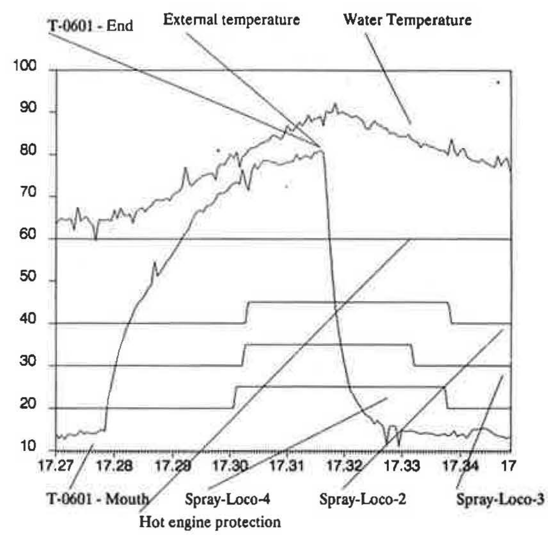

FIGURE 3 Hot engine protection (Locomotive 4) and spray (Locomotives 2, 3, and 4) (4 locomotives, 86 wagons, with helper) versus decimal time [external temperature (°C), water temperature (°C)].

locomotive did (because its temperature is lower as it receives hot air only from the first locomotive).

Figure 4 shows that speed was higher than the one for the experiment without a helper, and those problems that occurred with the previous experiment—when the hot engine protection almost shut down the fourth locomotive—did not happen this time.

Also, in all of the tests performed, it can be noted that, when the locomotive enters the tunnel, its power decreases and starts increasing only after leaving the tunnel. Such a fact explains the decrease in speed inside the tunnel.

Figure 5 was plotted from data collected during the passage of a train made up of four locomotives and 86 loaded wagons and no helper. A very fast increase in the external temper-

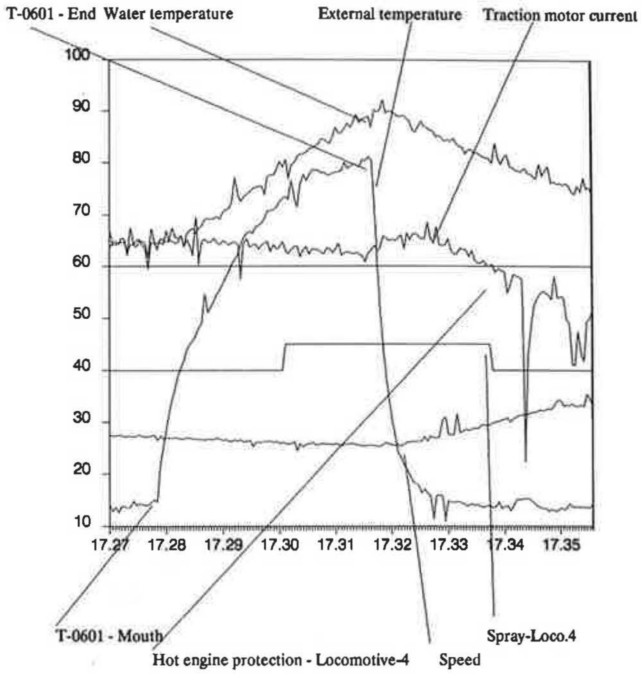

FIGURE 4 Hot engine protection (Locomotive 4) and spray (Locomotive 4) (4 locomotives, 86 wagons, with helper) versus decimal time [water temperature (°C), external temperature (°C), traction motor current ($A \times 10$), speed (km/hr)].

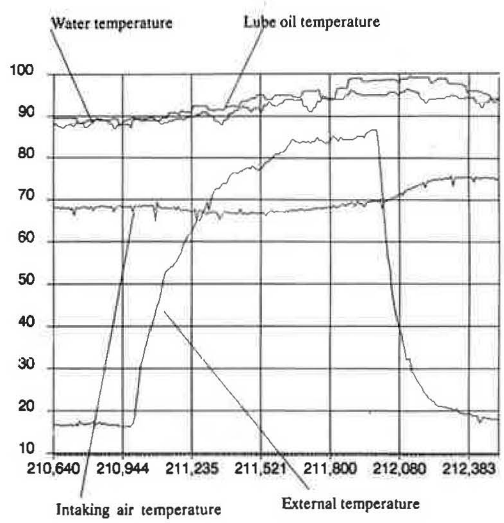

FIGURE 5 Data collected during passage of train (4 locomotives, 86 wagons, no helper): lubricant oil temperature (°C), water temperature (°C), external temperature (°C), and intake air temperature (°C) versus distance traveled (km).

ature inside the tunnel can be noted, reaching more than 80°C. A sudden temperature drop can also be seen as soon as the train leaves the tunnel. This graph also shows the temperature values for the air intake (monitored before it enters the combustion chamber), the lube oil, and the cooling water. The train speed when entering the tunnel is 16.5 km/hr, but inside the tunnel it drops to 14.5 km/hr.

ENVIRONMENTAL ASPECTS INSIDE TUNNELS

Vehicles fueled by diesel oil contribute to environmental pollution by burning this fuel owing to a set of chemical reactions that takes place simultaneously. These reactions happen because the diesel oil is composed of hydrocarbon (the boiling point of which varies from 170°C to 325°C) and gives out byproducts, that is, molecules with fewer carbon atoms, such as carbon dioxide, carbon monoxide, sulfur, and nitrogen compounds and water.

Carbon monoxide is extremely poisonous and can block the breathing process of living beings whose blood contains hemoglobin. Carbon monoxide competes with oxygen, and it is the first to reach the hemoglobin, forming a stronger bond, causing loss of vision and even death. As to the performance of vehicles, there is an alteration due to the decrease of oxygen percentage necessary for fuel combustion.

The principal objectives were as follows:

- Analysis of all components: SO_2, NO_2, NO, CO, CO_2, and fuliginosity in the air sampling inside the tunnels of the Ferrovia do Aço, and
- Analysis of the working conditions inside the tunnels for the locomotive crew and maintenance team.

Gases and particle samples were collected by selective monitors for specific analysis, according to the required technique, in the middle of the tunnel and at both ends, before, during, and after the passage of the train.

Then the following procedure assessed the concentrations of gases and particles found inside the tunnels and cabs:

Particles—The samples from which the particle concentration was to be determined were collected by passing a flow of air through a filter.

Gases—The measurement of gas concentrations was through direct reading using colorimetric reaction tubes equipped with electrochemical sensors.

This equipment was placed at several points along the tunnel and the sensors at different heights.

The study of the locomotive engineer's exposure to chemical agents inside the locomotive cabs was also carried out. The measurements were performed at the height of the breathing zone in normal conditions.

Monitored Parameters

- Direction and air speed,
- Air temperature,
- Carbon monoxide level,
- Oxygen level,
- Nitrous gases, and
- Other poisonous gases.

Data Acquisition System

The measurements of air speed, air direction, air temperature, and an analogical signal from 0 V to 5 V that comes from gas sensors of CO_2, NO_x, CO, and O_2 were usually registered in EPROMs (erasable programmable read-only memory) from a data-acquisition system developed by the Universidade Federal de Juiz de Fora (UFJF) jointly with the Rede Ferroviária Federal S/A (RFFSA), according to the test operational conditions.

The portable device for collecting data inside the tunnels is a simple, small EPROM recorder for 32 kilobytes coupled to an 8-bit A/D converter multiplexed to three signals with sampling and recording performed by a real-time timer.

At the beginning of the tests, the timers were set in all the equipment in order to have the start-up synchronized. The boxes were distributed inside the tunnel, mainly inside the one that is 8640 m long. Normally, the sampling rate was of 1 sec. The storage capacity of the EPROM and the life span of the batteries permitted the system to record 6 hr of gas activity inside the tunnel, before, during, and after the passage of diesel-electric consist and wagon through it.

After each test, the EPROMs were taken from the boxes and input to a computer in which the information was analyzed. The previously mentioned information was also analyzed together with the data from the locomotive internal system. Because both signals were synchronized against the same timer, the results were easier to interpret.

Analysis of Test Results

Several tests were performed taking into account the results obtained for Tunnel T-0717, the longest one, which is 8.6 km long. Sample collection equipment was installed in three points along the tunnel (P1-17, P2-17, P3-17). The natural direction of air displacement inside the tunnel was the same as that of the train. The air speed at the checking points before the train passage was of about 0.5 m/s. Due to the movement of the train, it increased to 1.2 m/s and kept steady for 10 min at the P3-17 check point, 3 min at P2-17, and 4 min at P1-17 after the train had passed. Afterwards, the air speed kept constant around 1.0 m/s.

CO concentration can be seen in Table 1. The lowest dispersion time for the gas was reached at the P3-17 check point. This is the case because the air and train movements are in opposite directions.

The highest time for gas dispersion was at the P2-17 check point (20 min higher than the time found for P3-17). This was because there was less time for the "Piston Effect" to act on the air speed at this point and because a higher volume of contaminated air was displaced. The same factors were determined for the nondispersion of gas at check point P1-17.

TABLE 1 CO CONCENTRATIONS INSIDE TUNNEL

	Concentration of CO (ppm) by Train Passage					
	Before		Inside	After		
Check Points	Max	Min	Tunnel	Max	Min	Dispersion Time (min)
P3-17	1	1	15	24	0	40
P2-17	2	1	18	22	2	60
P1-17	3	0	19	23	15	—

At the P1-17 check point during 80 min after train passage, no significant dispersion of the gas was observed.

DOWNGRADE OPERATION

Requirements

In handling freight trains, downgrades of any significant length require observance of the following items:

- Balancing the grade, or holding speed steady at safe and practical values,
- Maintaining ample safety margin, or keeping speed within a value that will allow stopping the train anywhere on the grade within signal spacing or other prescribed limitations, and
- Balancing the use of dynamic brakes and air brakes, avoiding the overheating of the wagons' wheels.

Aiming at the improvement of this type of operation and the standardization of its procedure, the previously described data acquisition system was used to monitor the following parameters:

- Train speed,
- Traveled distance,
- Traction motor current,
- Position of the dynamic brake handle, and
- Brake cylinder air pressure.

Analysis of Test Results

Several tests were made in a 1 percent downgrade stretch of 100 km. The train under test had three locomotives and 86 wagons.

Figure 6 illustrates a type of operation in which the dynamic brake is kept in a fixed position and the speed control is performed by using the air brake several times. One can see the great speed variation over the distance traveled. Figure

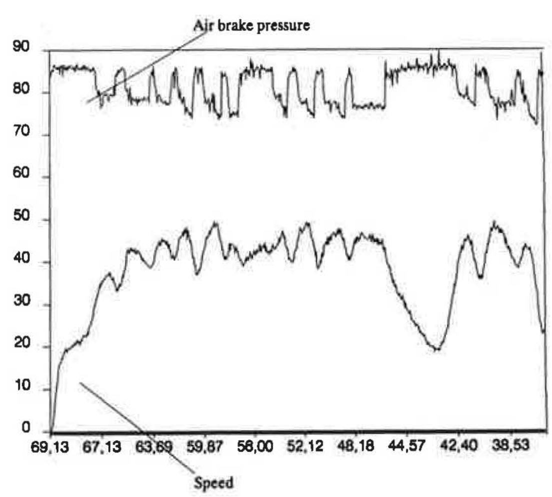

FIGURE 6 Air brake pressure (psi) and speed (km/hr) versus distance traveled in downgrade operation.

7 shows the graphic curve for traction motor current. The travel time was 50 min.

Another test was performed in this same stretch with the same type of train, but with a different train crew. The braking was carried out by using a minimum application of the air brake and using the dynamic brake to control the speed. It was noticed that the speed was kept within a smaller range variation, 45 km/hr on average.

The same distance was covered in 40 min, and the dynamic brake was used more than the air brake.

UPGRADE OPERATION

The data acquisition system was used to diagnose the problems in a 10-km stretch with an upgrade of 0.9 percent and in a 900-m tunnel at the top of the upgrade. The train type was four locomotives and 86 wagons.

Monitored Parameters

The following parameters were monitored in this test:

- Main generator voltage,
- Traction motor current,
- Acceleration notch,
- Speed,
- Brake cylinder air pressure, and
- Tractive effort.

Analysis of Test Results

The graphs of Figure 8 show not only the tractive effort curves, but also the speed and acceleration notch curves. In the tractive effort curve, two maximum values can be seen. The first occurred when the engine driver used notch 8 to accelerate just before entering the tunnel. The second occurred after the hot engine protection of the third locomotive was operated inside the tunnel.

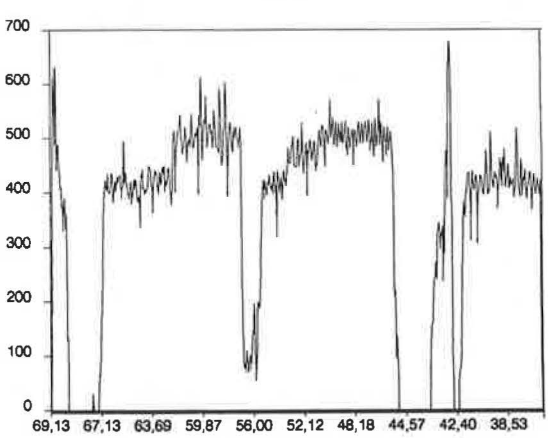

FIGURE 7 Traction motor current in dynamic braking (*A*) versus distance traveled in downgrade operation.

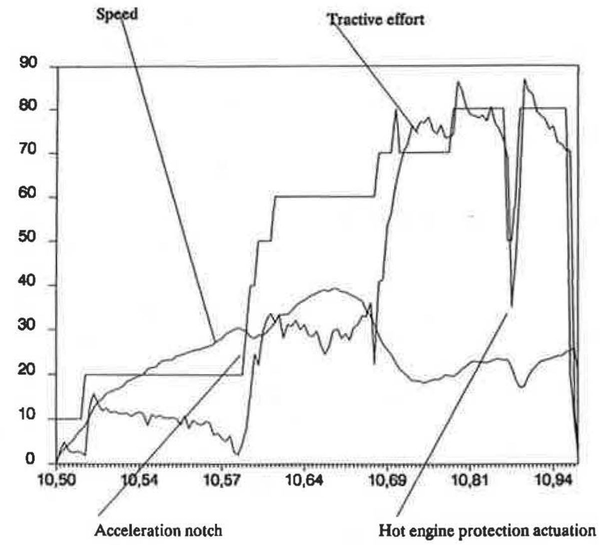

FIGURE 8 Tractive effort (kgf × 1,000), speed (km/hr), and acceleration notch versus decimal time.

As to the acceleration notch, it was observed that when the train started going up the grade the engine driver was using notch 6 and changed to notch 7; but notch 8 was only used when the train was approaching the tunnel. So the train speed, when entering the tunnel, was 22 km/hr. It dropped to 17 km/hr after the power decreased (hot engine protection operation).

To analyze the second test performed with the same stretch and locomotives, the same train type, one has to examine Figures 9 and 10.

The curves for tractive effort, speed, and acceleration notch are plotted in Figure 9. The tractive effort curve shows an irregular section due to slipping of the third locomotive (the test took place on a rainy night). As regards speed, it can be observed that the train entered the tunnel at 27 km/hr, owing to the different way of handling it by another engine driver. The train started up grade in notch 8.

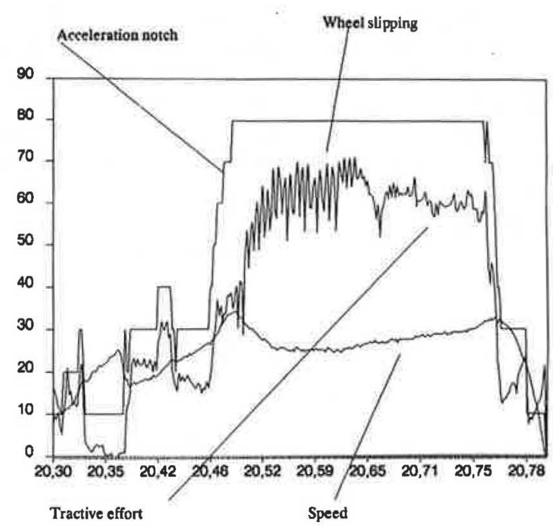

FIGURE 9 Tractive effort (kgf × 1,000), speed (km/hr), and acceleration notch versus decimal time: second test.

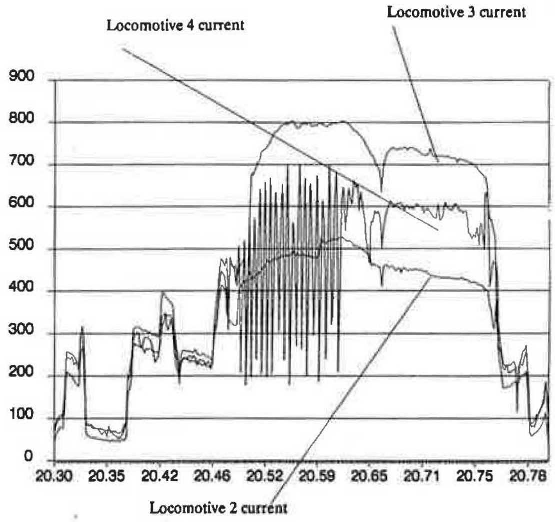

FIGURE 10 Traction motor current, Locomotives 2, 3, and 4, versus decimal time: second test.

Figure 10 shows the curve for the traction motor current. The slipping effect of the third locomotive can be seen.

TURBOCHARGERS OVER SPEED

In several tests performed to monitor the dynamic behavior of the locomotives when hauling heavy trains, the power decrease inside the tunnel was very evident. Some doubts about the locomotive turbochargers were raised. So, some tests with trains made up of 108 wagons and five locomotives were performed. The turbocharger of the fifth locomotive was instrumented, so that the actual operating conditions inside the tunnels could be registered.

Monitored Parameters

The following parameters were monitored:

- External temperature,
- Air-intake temperature,
- Turbocharger rotational speed,
- Turbocharger pressure,
- Traction motor current,
- Main generator voltage, and
- Speed.

Analysis of Test Results

Once again the previously mentioned data acquisition system was used. Figure 11 shows the following curves: external temperature, air-intake temperature, turbocharger rotational speed, and turbocharger pressure. This test was made in a 1 percent upgrade with a 900-m-long tunnel. The curve section relating to a sudden increase of the external temperature concerns the fifth locomotive when inside the tunnel.

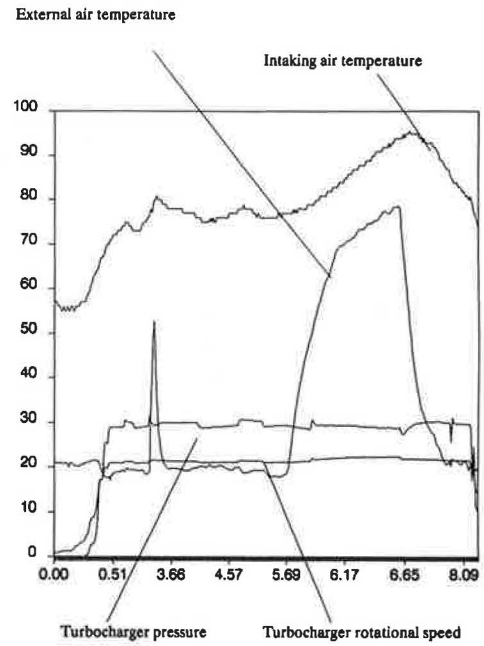

FIGURE 11 Turbocharger test on 1° upgrade and through 900-m tunnel external temperature (°C), intake air temperature (°C), and turbocharger rotational speed (rpm × 1,000)].

For a better analysis of the turbocharger behavior, Figure 12 shows a "zoom" of the curves of rotational speed and pressure when the locomotive is going through the tunnel. It is noted that there is a tendency for a pressure decrease, and the rotational speed increases by more than 1,000 rpm, compared with the reading registered before entering the tunnel.

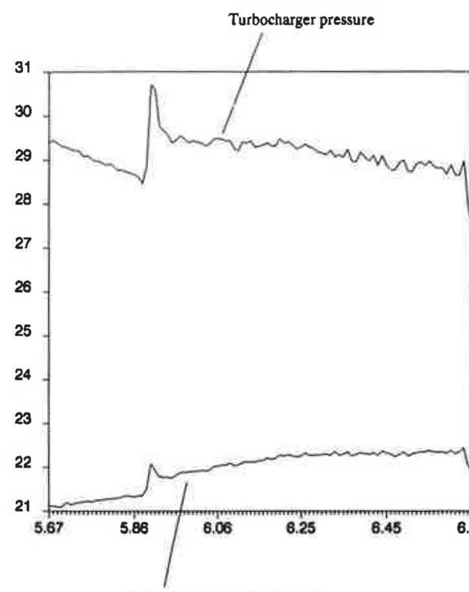

FIGURE 12 Turbocharger pressure (psi) and rotational speed (rpm × 1,000) versus traveled distance inside tunnel T-06-01.

CONCLUSION

The data acquisition system previously described in this paper has in its multiple applications the basis for a precise and appropriate diagnosis for the actual operating conditions of heavy trains. Some of the applications have already been mentioned.

The analysis of the data registered in each test provides a reliable diagnosis that make it easier to find a solution for problems relating to railroad transportation.

A deeper knowledge can be gained by passing from the academic research stage to actual dynamic operation tests; that is, we should not restrict our experience only to laboratory testing. Such knowledge is fundamental so that a definition of company investment priorities, based on the existing resources, can be achieved to increase transportation through lower costs and better quality.

ACKNOWLEDGMENTS

The authors are grateful for the support received from the Executive Board of their company, which believed in the serious development of this subject. Also, the continuous support and contributions from the Universidade Federal de Juiz de Fora (UFJF), the Centro Tecnologico de Minas Gerais (CETEC), and the Fundaçäo Jorge Duprat Figueiredo de Segurança e Medicina do Trabalho (FUNDACENTRO) are gratefully acknowledged.

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