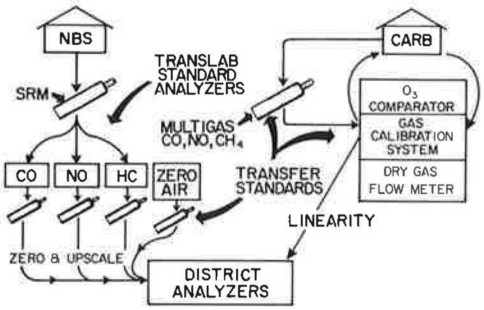
Figure 3. NBS traceability: air quality instruments.



PROGRAM EXPERIENCE

Calibration of noise-measuring equipment, prior to the formal QAP, had been left up to the Caltrans districts. Appropriate intervals had been recommended, but practice varied considerably. There are 41 SLMs, 16 GLRs, 45 microphones, 7 analyzers, and 41 calibrators involved in the program. When the QAP was initiated, it was found that two years had elapsed since some instruments were calibrated. Fortunately, only about 6 percent of the instruments were out of specified tolerances. About 15 percent of the instruments showed problems that needed correction.

The program for air quality measurements interfaced with a previous program carried out by the California Air and Industrial Hygiene Laboratory. This meant that the equipment was in good calibration when the program started. Calibration, however, had been based on one or two upscale points, and it was found that linearity adjustments were necessary for the lower-scale values. Seventeen CO analyzers and eight each for O_3, HC, and NO_x are calibrated in this program. The hydrocarbon analyzers are more troublesome than the rest because of their complexity.

The procedures developed for the program seem adequate. Having the equipment adjusted and put in good repair as part of the calibration process is a great advantage. It is too early to draw conclusions about long-term instrument stability, but as we accumulate calibration history it will be one of the things that will affect calibration frequency.

The need for environmental measurement has diminished along with capital improvements, and Caltrans is doing much less today than a few years ago. As long as any measurements are made, however, a QAP will continue to be a necessary part of our work.

ACKNOWLEDGMENT

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REFERENCES

1. R.D. Smith and M.M. Hatano. Noise Measurements and Quality Assurance. Transportation Laboratory, California Department of Transportation, Sacramento, Rept. FHWA-CA-TL-79-06, 1979.
2. K.O. Pinkerman, R. Bushey, and E.C. Shirley. Air Monitoring Quality Assurance Program. Transportation Laboratory, California Department of Transportation, Sacramento, Rept. FHWA-CA-TL-81-10, 1982.
3. M.M. Hatano and J.A. Pantalone. Water Testing Quality Assurance Program. Transportation Laboratory, California Department of Transportation, Sacramento, Rept. TL 657108, 1976.

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Quick Fix for Washington Metro Brake Squeal

GUMMULURU N. SASTRY AND EDGAR C. GREEN, JR.

When the Washington Metropolitan Area Transit Authority (WMATA) made some changes in the brake system configuration of pads and discs to increase the wear life of the brake system in the fall of 1980, the quality, duration, and frequency of brake squeal increased dramatically, causing citywide complaints and adverse publicity. A quick fix had to be found within a few weeks to mitigate this squeal and avoid further losses of ridership. A test program was designed to find a solution simple enough to incorporate into the system immediately. Several configurations of brake pads were tested and a "quiet pad" that does not generate the annoying squeal was found among those pads made available to WMATA. Abex 1389b pads were retrofitted to the system, and the squeal disappeared.

When the Washington, D.C., Metro system was first opened to the public in 1976, quietness, speed, and comfort were the trademarks of the system and were highly praised by the public. But a letter to the editor of the Washington Post published on January 5, 1981, read as follows: "As a visiting New Yorker, I find the noise levels of arriving Metro trains intolerable. As a worker a year ago in Washington I knew this was not the case. Trains arrived with some quietness....Why has this been allowed to go unchecked? Where are the environmentalists?....Are D.C. travelers so immune to this insane decibel level that they ignore it?"

This rider's observation of the increased noise level in the Washington, D.C., Metro system was one of the more mildly worded of the widespread adverse reactions. Meanwhile, Washington Metropolitan Area Transit Authority (WMATA) environmentalists were aware of this annoying problem and were frantically working to alleviate the noise.

WMATA cars were designed with disc brakes as the primary friction braking system. There have been several investigations and tests over the past few years aimed at improving brake pad and disc life and mitigating the noise problem. When WMATA made some changes in the brake system configuration of pads and discs in the fall of 1980 in order to increase brake pad and disc life, the quality, duration, and frequency of the squeal changed dramatically, causing citywide complaints and adverse publicity. This prompted WMATA immediately to look into the brake squeal problem and to adopt a multifaceted approach. De Leuw, Cather and Company, the general engineering consultant to WMATA, was charged to find what was called a "quick fix" to the brake squeal problem. A solution had to be found within three or four weeks through diagnosis and identification of major noise contributors by field surveys and investigations. The solution had to be simple enough to be incorporated immediately into the existing braking system.

APPROACH TO THE PROBLEM

A brief survey of recent literature revealed that there was no simple explanation of the mechanism that produces squeal. Some of the significant factors are pad coefficient of friction, temperature, humidity, mass of brake assembly, and stiffness of brake components. It is also believed that squeal is affected by the geometric relation of the piston, the pad, and the disc, which may be subject to "geometrically induced or kinematic constraint instability" (1). A recent study by Ronk and Staino (2) indicates that "the squeal instability region is largely dependent upon the contact point position of the pad with the disc, disc stiffness normal to its plane of rotation, Young's modulus of pad material caliper system stiffness normal to the disc, and caliper mass."

It was evident from the start that a number of investigations incorporating several parameters were needed to define the Metro squeal problem and develop solutions. Our approach, however, was limited by the following constraints:

1. From the start, the Metro system has shown intermittent brake squeal at low speeds.
2. Squeal duration and frequency changed dramatically when WMATA attempted to prolong the wear life of pads and discs by experimenting with different friction materials.
3. Time constraints prevented major changes to the calipers or discs of the brake assemblies. Therefore, any solution requiring design changes in the braking system was ruled out in the exercise.

To satisfy all of these parameters, the pragmatic approach was to concentrate on the friction pads. The following guidelines were established at the beginning:

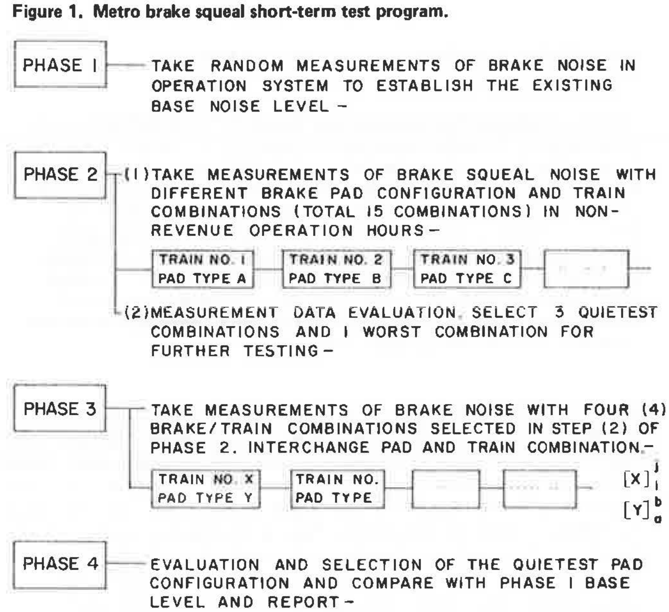
1. Test the effectiveness of a 0.125- or 0.25-in-thick resilient material installed between the pads and back plates and
2. Test various brake pads readily available on the market that met strict WMATA deceleration specifications for crush loads under wet and dry conditions.

The decision to concentrate on the pads alone was based on the theory that the disc and the total brake assembly act much as a bell ringing under the action of a clapper, i.e., the pad. It is known that a bell emits different frequencies when different clappers are used. The aim was to find a pad (the clapper) that produced the least squeal of low frequency because low-frequency squeals are not as objectionable to the human ear as high-frequency pitches. Table 1 identifies the various pads that were tested during the four-phase program (see Figure 1). Phase 1 established a base noise level by measuring the brake squeal of existing six-car trains during normal revenue hours. Phases 2 and 3 involved the testing of several brake pad configurations installed on two-car test trains operated during nonrevenue hours. Pads were ranked according

Table 1. Brake pad configurations and test trains used for brake squeal measurements.

Car No.	Brake Pad Configuration
1084/85	Knorr disc; Knorr pad (881)
1046/47	Abex disc; Knorr pad (881), backing plates with FOL 8; bonding 303 IMP
1040/41	Abex disc; Knorr pad (881); B1 dynamic brake
1050/51	Abex disc; Abex pad (45109)
1104/05	
1228/29	
1264/65	Abex disc; Raybestos pad without backing plates
1242/43	Abex disc; Knorr pad (402)
1282/83	Abex disc; Knorr pad (881); factory-bonded noise abatement material
1084/85	Knorr disc; Knorr pad (881); laminated inserts
1026/27	Abex disc; Knorr pad (881) with link isolators
1104/05	Abex disc; Abex pad (45109)
1118/19	Abex disc; Knorr pad (881), eight-segment
1032/33	Abex disc; Knorr pad (881)
1176/77	Knorr disc; Knorr pad (881), used pads cut with additional slot to form eight segments; one-half wear
1118/19	Abex disc; Knorr pad (881), eight-segment, new pads with two-day revenue service
1032/33	Knorr disc; Knorr pad (881)
1118/19	Knorr disc; multisegment (eight) Knorr pad, backing plate standard noise abatement material
1032/33	Abex disc; single-slot Knorr pad (881), backing plate standard noise abatement material
1280/81	Abex disc; outside brake Knorr pad (881), inside brake single-slot Knorr pad (881) (standard)
1286/87	New York Air Brake System
1190/91	Knorr disc; Knorr pad, standard
1168/69	Abex disc; Abex pad 1389b, single-slot
1076/77	Abex disc; Raybestos pad
1068/69	Abex disc; Abex pad 1389b
1076/77	Abex disc; Knorr pad (881-1)
1032/33	Abex disc; Knorr pad (881), single-slot
1076/77	Abex disc; Knorr pad (881-1), three-slot without backing
1150/51	Abex disc; Knorr pad (881-1), one diagonal, three-slot without backing
1122/23	Abex disc; Knorr pad (881-1) with backing plate
1076/77	Abex disc; Knorr (881-1) standard pad, three-slot; crush load
1168/69	Knorr disc; Abex pad 1389b, single-slot
1122/23	Knorr (881) standard pads, outside pad with backing plate (0.125 in)
1192/93	Inside pad Knorr (881) standard, outside pad Abex 1389b
1076/77	Abex disc; Abex pad 1389b; 33 000-lb crush load
1084/85	Knorr disc; Abex pad 1389b
1036/37	Abex disc; Abex pad 1389b with backing plate
1064/65	Abex disc; Abex pad 1389b

Figure 1. Metro brake squeal short-term test program.



to their quietness, and the three quietest pads were selected for further testing. Phase 4 consisted of testing the quietest pads installed on six-car revenue trains and comparing them with the base noise levels established during phase 1.

INSTRUMENTATION AND MEASUREMENT TECHNIQUES

Measurements of Metro brake squeal were conducted at Union Station near the Brentwood Yard on the Red Line. Instruments were installed in the middle of the center platform, about 15 ft from either edge, so that when the test train stopped the middle of the train would be near the microphones.

Two sets of instrumentation were used. The first set consisted of a B&K 4156 0.5-in condenser microphone, a B&K 2619 preamplifier, and a NAGRA IV SJ tape recorder. The microphone, equipped with a wind screen, was mounted on a tripod about 5 ft from the ground and connected to channel 1 of the NAGRA tape recorder through the preamplifier. The channel 1 output in turn was connected to the channel 2 input with an additional 10-dB attenuation set on the front panel of the tape recorder. The reason for 10-dB additional attenuation on channel 2 was to preserve any overshoots on channel 1.

The second set of instruments consisted of a B&K 2209 precision sound-level meter with a B&K 4131 1-in microphone and a B&K 2306 level recorder. The sound-level meter with a wind screen was mounted on a tripod about 5 ft above the ground. The output from the sound-level meter was connected to the level recorder. All of the instruments were calibrated with a B&K 4230, both before and after each set of measurements. A 1-min calibration signal was recorded on each tape. The maximum sound level observed on the sound-level meter for each run was logged by an assistant. A voice commentary describing each run was also recorded on the tape. All instruments functioned satisfactorily throughout the three-week measurement schedule.

The measurement procedure involved the following: A two-car test train was fitted with a selected brake pad and disc configuration. For example, a test train comprising cars 1282 and 1283 was fitted with Abex discs and a Knorr pad 881 with factory-bonded noise abatement material (Table 1). The test train ran from Brentwood Yard and came to a full stop at Union Station in automatic mode, continued to the next station (Judiciary Square), reversed direction, and came to a full stop at Union Station. It returned to Brentwood Yard and then repeated the same run. Each stop at Union Station was considered one run. The tape recorder started recording the run as soon as the train was in sight at the station portal. Approximately 20-30 runs for each test train were recorded to obtain consistent squeal readings. The trains were usually empty, but sev- eral tests were conducted with 33 000-lb ballast loaded on each car (equal to a crush load) for selected brake pad configurations.

The recorded magnetic tapes were sent to Wilson, Ihrig and Associates, Inc., to obtain one-third octave band plots.

RESULTS

In phase 1, brake squeal measurements included the establishment of existing squeal levels during normal revenue service. A total of 79 readings were taken with the B&K 2209 sound-level meter equipped with a B&K 4131 1-in microphone mounted on a tripod 5 ft above ground in Union Station. Of the 79 readings, 18 were discarded because two trains, inbound and outbound, stopped in the station simultaneously. The average squeal level of the remaining 61 readings was 98 ± 3.5 dB(A); the lowest was 88 dB(A) and the highest 104 dB(A). Eighteen readings were exactly 98 dB(A). Average duration of the squeal was found to be 12 s [duration was defined as the length of time a squeal exceeds 80 dB(A)]. This noise level, which a local newspaper compared to the noise of a jackhammer, indicates the severity of the problem.

American Public Transit Association (APTA) Guidelines for Design of Rapid Transit Facilities, published in January 1979 by the Rail Transit Committee, established a level of 80 dB(A) for platform noise produced by trains entering or leaving stations. Although this criterion does not deal specifically with brake squeals, it was considered applicable and was used for the purpose of this paper. Therefore, any brake pad configuration with a squeal lower then 80 dB(A) was considered a "quiet" pad.

It is beyond the scope of this paper to discuss the measurements and analysis of each brake pad configuration. However, Table 2 summarizes a sample of squeal levels recorded during several runs of three different brake pad configurations. Figures 2-4 show the one-third octave band spectra of brake squeal, including the duration of some squeals (shown at bottom left of the figures).

In general, the analysis of the squeal levels and the noise spectra indicated the following:

1. The instantaneous spectrum of squeal shows significant peaks at 375, 500, 2500, 3100, 3800, and 5800 Hz (some of these peaks can be seen in Figure 2).
2. It appears that the squeal generally originates within the frequency range of 350-750 Hz and that the disc subsequently vibrates at its higher modes.
3. The New York Air Brake System brakes generated no significant squeal during the 10 runs conducted; they were tested no further because a separate testing program was planned for this at a later date.
4. The squeals generated by the Abex disc and the Knorr pads were generally in the range of 2800-3000 Hz, although higher modes were also common. The Knorr pads were tested in different configurations; some were slotted at various locations, and others

Table 2. Brake squeals for several runs of three brake pad configurations.

Run No.	Direction	Brake Squeal Level [dB(A)]: Cars 1032/33, Abex Disc and Knorr 881 Pad	Cars 1068/69, Abex Disc and Abex Pad 1389B	Cars 1076/77, Abex Disc and Abex Pad 1389B, Crush Load
1	Inbound	86	76	75
2	Outbound	97	78	77
3	Inbound	81	72	81
4	Outbound	86	79	80
5	Inbound	92	80	79
6	Outbound	92	78	78
7	Inbound	94	77	79
8	Outbound	90	76	76
9	Inbound	88	77	79
10	Outbound	89	75	76
11	Inbound	94	78	78
12	Outbound	90	76	75
13	Inbound	95	78	79
14	Outbound	90	76	77
15	Inbound	94	79	78
16	Outbound	89	75	76
17	Inbound	96	78	78
18	Outbound	90	76	76
19	Inbound	96	78	78
20	Outbound	90	77	76

Figure 2. Test results for cars 1282/83: Abex disc and Knorr pad (881) with factory-bonded noise abatement material.

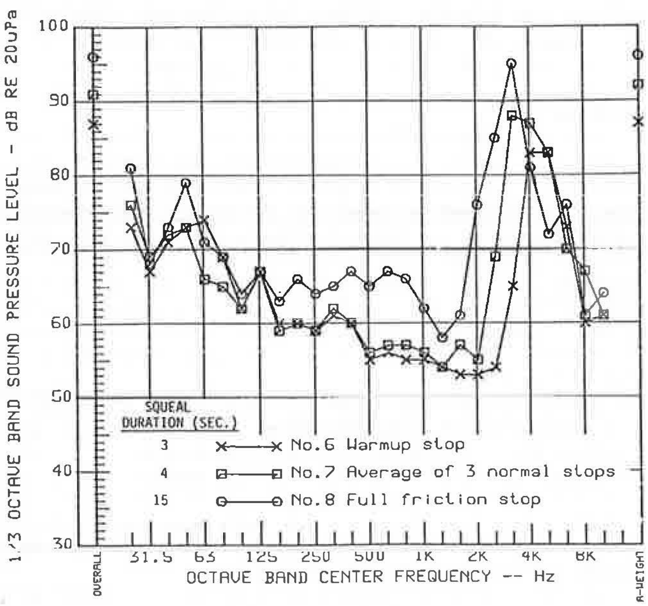
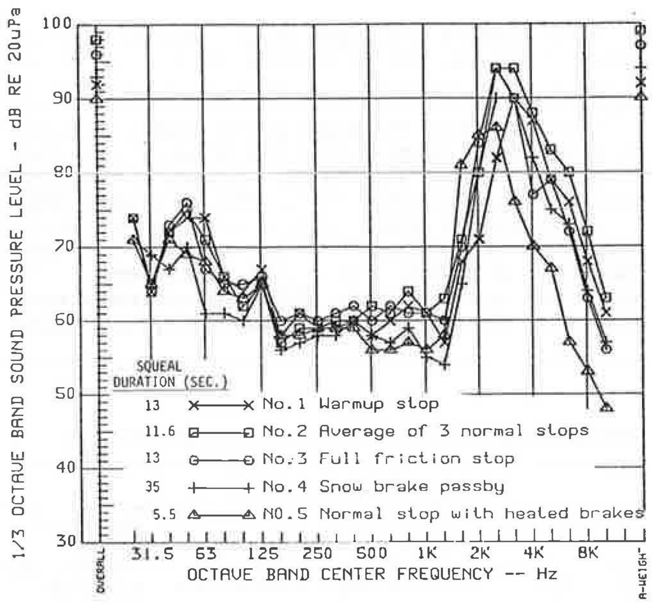


Figure 3. Test results for cars 1084/85: Knorr disc and Knorr pad (881) with laminated insert.

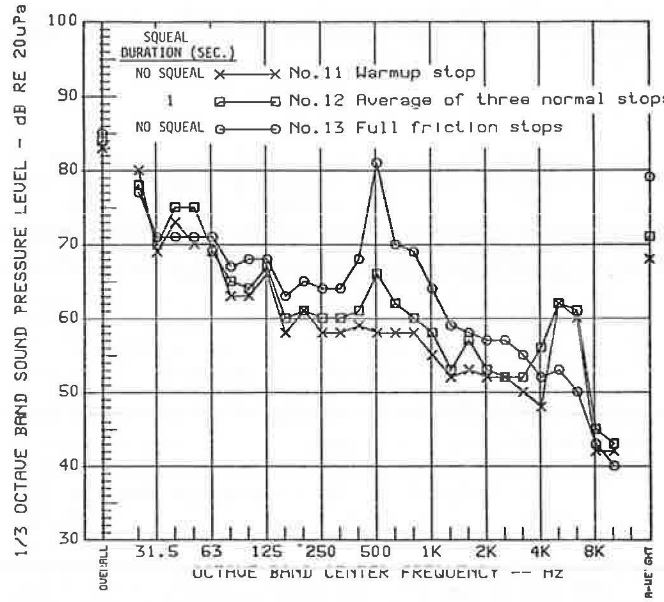


were equipped with special noise abatement plates installed between pad and backing plate. In every case, no significant improvements were recorded.

5. The noise spectrum of the Abex disc and Abex pads generally indicates a squeal peak at 500 Hz. Squeals of higher modes in the spectrum were not evident.

6. Because of procurement difficulties, only the Abex 1389b pads could be tested extensively. Nearly 160 tests were conducted. Various cars were used, empty or crush loaded, equipped with either Abex or Knorr discs but all using Abex 1389b pads. Only 32

Figure 4. Test results for cars 1104/05: Abex disc and Abex pad (45109).



runs generated squeals, and of these only 6 produced squeal exceeding 80 dB(A).

It was concluded that the Abex 1389b pads were suppressing the higher modes of disc vibration, thus eliminating most of the unpleasant squeals. They rarely produced squeals above established acceptance criteria of 80 dB(A) and even then only at frequencies of 500-750 Hz. The duration of the squeals was also very limited (approximately 1 or 2 s).

Thus, the Abex 1389b pad was deemed the candidate most likely to eliminate the annoying brake squeal problem, and all WMATA cars were subsequently retrofitted with these pads. Several follow-up tests conducted during revenue service consistently confirmed the results.

ACKNOWLEDGMENT

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REFERENCES

1. S.W.E. Earles. A Mechanism of Disc Brake Squeal. Society of Automotive Engineers, Warrendale, PA, Paper 770181, 1977.
2. L.A. Ronk and M.A. Staino. Evaluation of Squeal Noise from the WMATA Transit Car Disc Brake System. ORI, Inc., Silver Spring, MD, Tech. Rept. 1734, Nov. 24, 1980.

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