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CHARACTERISTICS OF COMPRESSION BRAKE NOISE

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ABSTRACT
This study examines compression brake noise levels in heavy-duty diesel trucks, using test procedures based on the ISO and EPA driveby acceleration noise tests. The data shows that compression brake noise levels are very high if worn out or open stack exhaust systems are used. Compression brake noise is also audible with OEM exhaust systems and, in at least one case, potentially objectionable. This study also describes the time and frequency domain characteristics of compression brake noise. Brake noise is dominated by strong pressure impulses which repeat at one of the first three harmonics of engine firing frequency. The subjective quality of brake noise is primarily determined by medium and high frequency noise which is produced by the periodic pulses. No useful correlation between brake performance parameters and noise levels is found. Two methods for reducing brake noise are investigated: improved mufflers and the use of an exhaust brake with the compression brake. Both techniques demonstrate a potential for reducing compression brake noise, but an improved muffler is far more cost effective.

INTRODUCTION

Compression brakes on heavy-duty diesel powered trucks have long been recognized as a source of community noise. As a result, local bans on the use of compression brakes are common in several countries, and national bans have been considered in some cases. Manufacturers and operators of trucks have resisted compression brake bans, because reducing a truck's braking capacity can cause a safety problem, particularly in areas with steep hills. Despite the fact that compression brakes were recognized as an important source of community noise, published research on compression brake noise was very limited until recently [1, 2, 3]. The operation of compression brakes is described in a companion paper [4].

In this paper, the results of a survey of compression brake noise are presented. The goal of the survey was to get a representative sample of the noise levels of compression brake types available in production today. Engines from the three leading US manufacturers of heavy-duty diesel engines were included in the survey. In addition to the survey, the time and frequency domain characteristics of compression brake noise were investigated. Here, the goal was to understand the features of compression brake noise which create the characteristic, and sometimes objectionable, brake sound. Next, two brake performance parameters which could influence noise levels were evaluated. Finally, two potential methods of reducing the noise of compression brakes were investigated: the use of improved exhaust mufflers, and the use of an exhaust brake combined with the compression brake. Since market pressure is pushing designers to look for ways of reducing compression brake noise, a thorough understanding of the noise generation mechanisms and sound characteristics of brakes is required in order to find cost effective low-noise solutions.

SURVEY TRUCKS AND ENGINES

Four of the five engines in the survey were tested in identical trucks to reduce any variability introduced by differences in exhaust system or vehicle designs. These identical trucks had identical exhaust systems, except for the piece of pipe which adapts directly to the turbocharger outlet. All of the engines were inline 6 cylinder diesels with turbocharging and air-to-air aftercooling. All of the trucks tested were conventional tractors. The set of identical trucks had a single vertical muffler, while the other truck had dual vertical exhausts. Table 1 below lists the characteristics of the test engines.

Table 1. Engines used for compression brake noise tests.

Eng #	Disp. (L)	RATING HP @ RPM	Hi Idle RPM	Emission Level	Identical Truck?
1	14.0	370 @ 1800	2000	94 EPA	YES
2	14.0	525 @ 2100	2300	94 EPA	YES
3	10.8	370 @ 1800	2000	94 EPA	YES
4	12.7	430 @ 1800	2100	94 EPA	YES
5	14.6	425 @ 2000	2250	91 EPA	NO

Each engine in the survey was equipped with a compression brake manufactured by the Jacobs Vehicle Equipment Company and sold under the "Jake Brake" name. Variations in the brake design are required to tailor the product to each engine, but the basic principle of operation is always the same. Four of the five engines tested have unit injectors, so the Jake Brake uses the injector lobes on the cam to drive the brake. The only exception is engine #5 in Table 1, which uses a jerk pump fuel system. In this engine, exhaust lobes on the cam are used to drive the brake.

SURVEY TEST PROCEDURES

Well established driveby noise test procedures exist for measuring the acceleration noise of trucks at low speeds. The US EPA driveby test is based on SAE J366, while most other countries around the world base their test on ISO 362. Both the EPA and ISO tests are similar in nature. The truck is driven into a test section at a low road speed (typically 20 - 50 km/h) and low to medium engine speed. At the beginning of the test section, full throttle is applied, and the truck accelerates through the test section. Microphones are placed on either side of the test section at the centerline of the acceleration zone. The peak noise level observed as the truck passes the microphones is recorded and reported as the test result. These driveby acceleration tests are intended to simulate the noise a bystander would hear when a truck is accelerating in typical urban driving conditions.

Briefly, the test procedure used here is a "reverse" driveby test, based on the ISO 362 driveby procedure. In the "reverse" test, the truck enters the driveby test track at high idle (maximum achievable engine RPM) in the gear which allows an approach speed of 50 to 55 km/h. The throttle pedal is released at a point chosen to cause the compression brakes to come on when the truck is 5 meters past the start line of the test track. This is half way between the start line and the line through the two measuring microphones. The truck passes the microphones with the compression brake on, at an engine speed just below the maximum possible RPM. References [2] and [4] describe the development of the test procedure, and show that the on-highway noise levels of compression brakes can be very accurately simulated with the low speed, unladen truck test procedure used here.

All tests reported here were conducted on Cummins Engine Company's driveby noise test track in Columbus, Indiana. This track has a smooth concrete surface which meets the requirements for EPA noise test tracks. Results measured on this track will be slightly louder than what would be obtained on the more porous ISO 10844 test surface now used in Europe.

SURVEY TEST RESULTS

All of the engines were tested in two configurations: with the standard OEM exhaust system, and with a straight pipe in place of the standard muffler. The test gear was chosen to achieve an entry speed of 50 – 55 km/h. In addition to the noise level measurements, recordings of every test were made for later subjective evaluation. The jury consisted of six engineers who

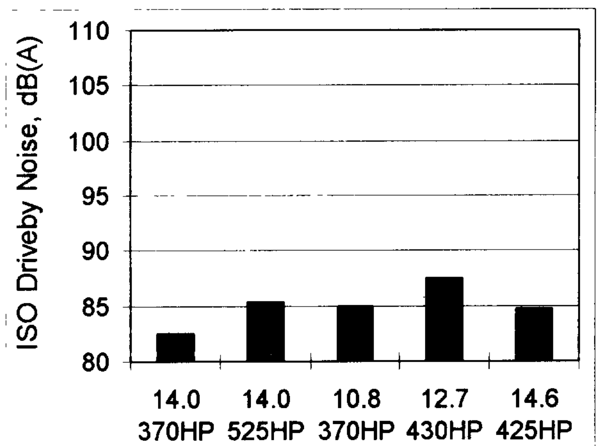

Figure 1. Acceleration driveby noise levels with OEM exhaust systems. The first four bars represent engines tested in identical trucks.

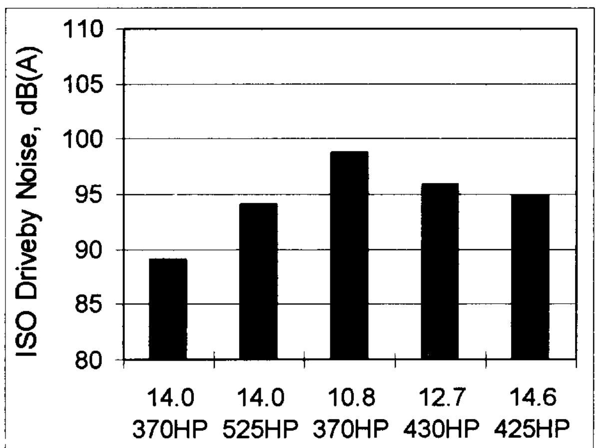

Figure 2. ISO acceleration driveby noise levels with an open stack exhaust system. The first four bars represent engines tested in identical trucks.

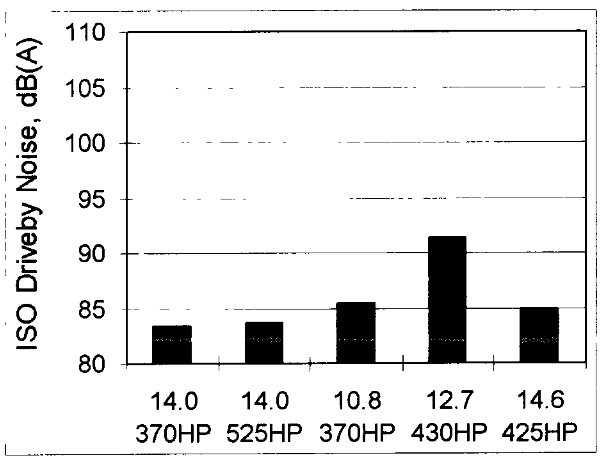

Figure 3. Driveby noise levels under braking with an OEM exhaust system. The first four bars represent engines tested in identical trucks.

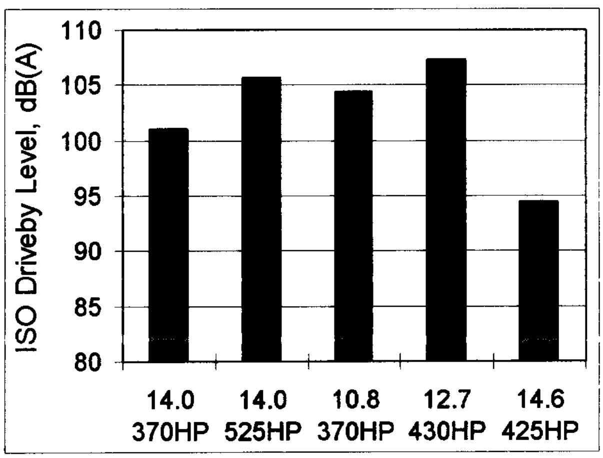

Figure 4. Driveby noise levels under braking with an open stack exhaust system. The first four bars represent engines tested in identical trucks.

normally work on diesel engine noise reduction projects. The survey results are shown in Figures 1 to 4.

The figures show that there are significant noise level differences between the engines tested, even among the four engines which ran in identical trucks. When the OEM exhaust system is used, all the engines but one have acceleration noise levels which are very close to those measured under compression brake operation. The one exception is the 12.7 liter engine, which is 3.9 dB louder under braking than under acceleration. Note that the 12.7 liter engine was also the loudest on the ISO acceleration test. Subjectively, the jury of six noise engineers judged that there is only a modest difference in sound quality between the acceleration and braking recordings, except in the case of the 12.7 liter engine. Even for the 12.7, the jury of engineers concluded that it was unlikely to be a cause of many community complaints, except when operating in residential areas. It should be noted, however, that the jury was able to audibly detect compression brake operation on every engine tested.

When open stack exhaust systems are used, the acceleration noise of all engines increased by 6.5 to 13.9 dB(A). The ranking of overall noise levels fits well with the subjective ranking. Among engines tested in identical trucks, the noise increase caused by compression brake operation with an open stack exhaust was 15.9 to 22.0 dB(A). Subjectively, all the open stack compression brake recordings sound very harsh. The characteristic open stack compression brake sound is a sharp staccato "bark" somewhat like a low pass by a World War Two single engine fighter. All of the open stack brakes were judged to be very objectionable, except for the 14.6 liter 425 HP engine, which was no worse under braking than under acceleration.

BRAKE NOISE CHARACTERISTICS

The time domain characteristics of compression brake noise are unusual. Recordings of sound pressure during brake operation show a series of sharp pressure pulses at the third, sixth, or ninth order of engine rotation. This corresponds to the first three harmonics of the exhaust valve opening frequency (or firing frequency). Figure 5 shows two time histories of exhaust noise for the 10.8-liter engine, measured with an open stack exhaust at different speeds. At around 1420 RPM, the pulses occur primarily at ninth order (three times firing), while at 1000 RPM, the pulses clearly occur at third order. The dominant order changes several times over the engine speed range, for reasons that are not yet understood.

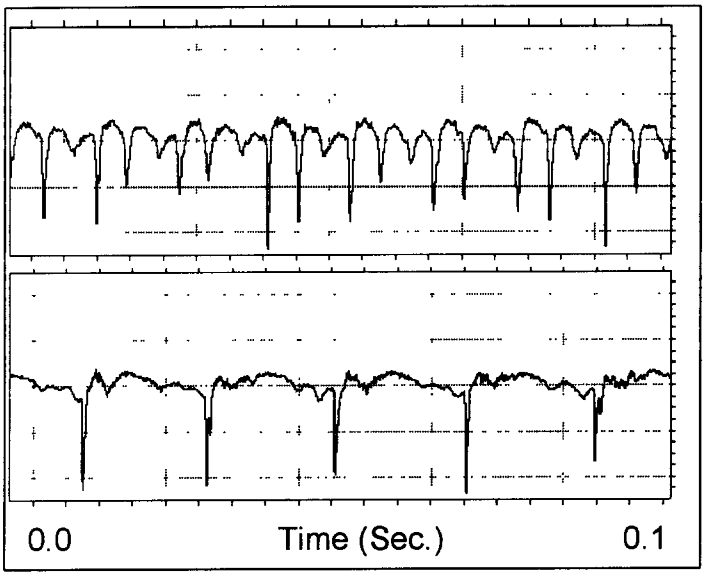

Figure 5. Typical time histories of sound pressure near the exhaust outlet. The upper plot was recorded at 1420 RPM, and the lower plot at 1000 RPM.

The data taken in Figure 5 was measured with a microphone mounted on the truck near the exhaust outlet. Data measured at the normal driveby microphone location shows the same characteristics. This strongly indicates that compression brake noise is primarily emitted from the exhaust outlet. When an OEM muffler is added, the pressure pulses in the exhaust noise are greatly reduced and often eliminated. Sometimes, the muffler produces "blossoms" in the exhaust noise signal, which indicate a resonant response to the impulse excitation. When these "blossoms" are visible in the exhaust noise trace, the sound quality of the brake noise recording is judged poor. The straight pipe pulses or OEM muffler 'blossoms" introduce a large high frequency component to the compression brake noise, which in turn causes poor sound quality.

A jury test was run to determine the frequencies which contribute most to the characteristic compression brake "bark" seen with an open stack exhaust. First, the original signal was played, and then filtered signals were compared to the original. Filtering out the 0 – 370 Hz range eliminates at least the first nine engine orders, and thus the frequencies at which the pressure pulses occur. However, the filtered signals still have a clearly audible compression brake "bark". Filtering out data over 2 kHz made the brake sound more "mellow", without dramatically changing the brake noise. Listening to recordings with everything except the 370 Hz to 2 kHz data filtered out still gave the impression of typical compression brake "bark".

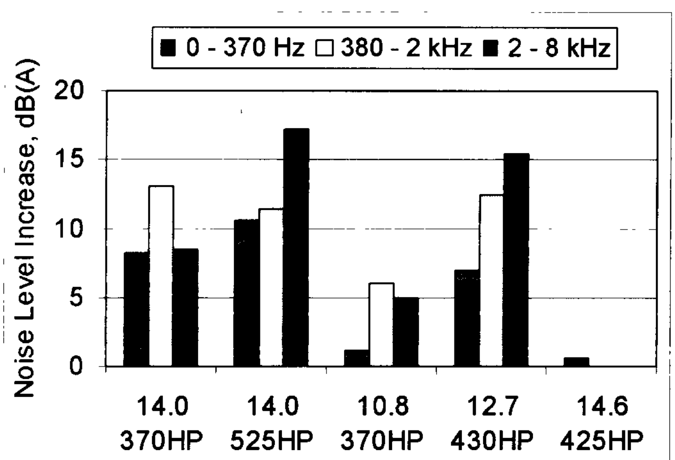

Figure 6. Noise increase of compression brakes over acceleration with an open stack exhaust. Increases are compared for three frequency ranges.

Open stack noise under acceleration is much worse than with an OEM muffler. However, in all but one of the trucks tested, open stack braking was dramatically louder than open stack acceleration, and the sound quality under braking was also considerably worse than under acceleration. Figure 6 shows the difference in levels between open stack acceleration and braking for all five trucks. The data was recorded at the ISO driveby track microphone positions and compared at the instant of highest overall noise level. For every truck but one, there was a greater increase in medium and high frequency noise than in low frequency noise. The lone exception was the engine with the quietest compression brakes. This finding fits with the subjective conclusion that medium frequency noise is most important to the creation of the characteristic brake "bark".

CAUSES OF COMPRESSION BRAKE NOISE

Because of the wide variety of noise levels and sound quality found in the survey engines, it would be useful to know what design parameters control the level of compression brake noise. An understanding of these parameters would allow designers to make intelligent tradeoffs between noise, performance, and other characteristics. In Reference [3], two parameters were studied which could be controlling factors in compression brake noise: braking power and high idle RPM. Since compression brakes absorb power by dumping compressed air into the exhaust system, braking power is maximized by opening the exhaust valve quickly when the cylinder pressure is at its highest. One would expect that both higher braking power and higher noise levels would result from increased cylinder pressure at the time when the exhaust valve opens, or from more rapid exhaust valve opening. Thus, there is a potential relationship between braking power and noise level. Braking power also increases rapidly as engine speed increases. This creates a potential relationship between an engine's maximum speed and brake noise levels.

However, for engines tested with an OEM exhaust system, data presented in Reference [3] shows no correlation between braking power and noise level. In open stack form, on the other hand, there is a strong relationship between noise level and braking power. Open stack noise levels increase with braking power. The data presented in [3] also does not show a relationship between the engine's high idle speed and braking noise level. This is true for both the OEM exhaust and open stack exhaust test cases. However, when two of the engines were tested over a range of entry speeds, approximately a 1.5 dB increase in brake noise was found for every 200 RPM increase in test speed. While brake noise is thus related to engine entry speed, the results in [3] show that engine speed is only a secondary factor in determining compression brake noise levels.

COMPRESSION BRAKE NOISE REDUCTION

The results presented so far show that compression brake noise is a severe problem with open stack exhaust systems. However, the jury was able to detect compression brake operation in all engines with an OEM exhaust system, and the noise of one engine (the 12.7 liter) was judged potentially objectionable even with an OEM exhaust system. In residential areas, all of the brakes could be considered objectionable. This result led to further work aimed at making compression brake operation inaudible. Two of the engines used in the survey were chosen for further investigation: the 10.8-liter 370 HP, and the 14.0-liter 525 HP. However, this work was done with different samples of these engines and in different trucks than the survey work. Details of the tests are available in Reference [3].

Compression brakes make noise by releasing pressure pulses into the exhaust. It is not obvious how the pressure pulses released to the exhaust system could be substantially reduced without having a negative effect on brake performance. Therefore, we looked at noise reduction methods which could be applied downstream of the compression brake, in the exhaust system. Two basic approaches were evaluated: improved mufflers and the use of an exhaust brake.

To evaluate the potential benefit of an improved muffler, an "overkill" muffler was tested. The "overkill" muffler combines two high quality standard truck mufflers in series within a single, very large housing. This silencer offers roughly twice the noise attenuation of the standard OEM muffler, but with the penalties of higher backpressure and very large size. The "overkill" muffler uses only reactive elements (no absorption material). The "overkill" muffler test was also intended to answer another key question. It was assumed that compression brake noise comes through the exhaust system, rather than being directly radiated by the engine or by other system components. The "overkill" muffler test checked this assumption.

The second approach for reducing compression brake noise which was investigated is the use of an exhaust brake. Exhaust brakes are less common than compression brakes on US trucks, but they are widely used in many parts of the world. Exhaust brakes are less expensive, less complex, but also less powerful than compression brakes. An exhaust brake is basically a valve which closes off most of the area of the exhaust pipe between the turbo and the muffler. Because exhaust brakes provide a high degree of restriction in the exhaust pipe, they have the potential to serve as a form of silencer for compression brakes. Tests in Australia on a 12.7-liter engine [6] showed that a significant objective and subjective improvement in compression brake noise could be achieved with an exhaust brake. However, since exhaust brakes bleed exhaust under pressure into the muffler, they also have the potential to be a significant source of flow noise themselves.

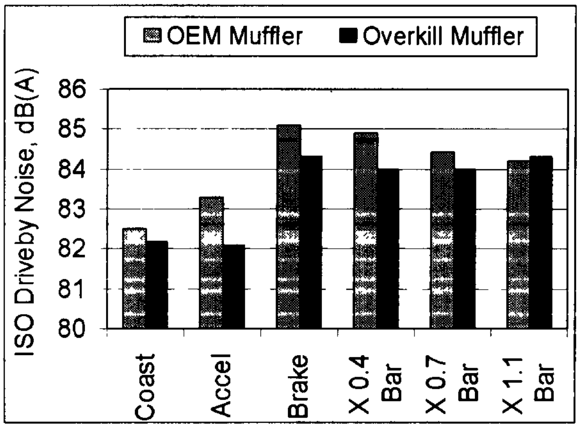

Figure 7. 14-L engine driveby noise levels under coasting, acceleration, braking, and braking with an exhaust brake at several back pressures.

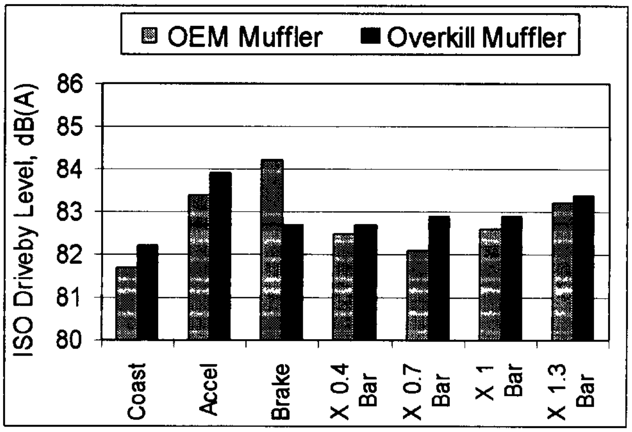

Figure 8. 10.8-L engine driveby noise levels under coasting, acceleration, braking, and braking with an exhaust brake at several back pressures.

The 10.8-liter 370 HP and 14-liter 525 HP engines were tested with both the OEM muffler and the "overkill" muffler. Both exhaust systems were tested under several operating conditions: coasting, acceleration (the standard driveby test), compression brake operation, and compression brake in combination with exhaust brake at various levels of backpressure. The coasting test was run just like the compression brake test, except without brake operation. For the coasting test, the truck entered the test section at high idle, and then the throttle was released to allow the truck to coast. Engine speed remained high during the coasting test.

Figures 7 and 8 show that for both engines, the differences between OEM and "overkill" mufflers under coasting conditions are within the range of experimental repeatability [6]. The "overkill" muffler provides no benefit to the 10.8-liter engine under acceleration, but it does reduce acceleration noise of the 14-liter engine by over 1 dB. Under compression brake operation, the "overkill" muffler provides a significant reduction for both engines: 1.5 dB for the 10.8-liter and 0.8 dB for the 14-liter. When the exhaust brake is combined with the compression brake, the noise performance with the OEM muffler is improved. However, the exhaust brake does not help the performance of the "overkill" muffler, and no combination of exhaust brake and muffler is significantly better than the "overkill" muffler alone.

In evaluating recordings of the 10.8-liter engine, the jury judged that the OEM muffler with no exhaust brake suffered from a modest amount of distinctive compression brake "bark". The jury also found that with the "overkill" muffler or with the exhaust brake at 0.4 bar, the distinctive "bark" was barely detectable. Higher levels of exhaust brake backpressure than 0.4 bar produce a distinct hissing sound which is typical of exhaust brakes.

Subjectively, both the "overkill" muffler and the exhaust brake are only modestly effective on the 14-liter engine, although the exhaust brake's hissing noise at higher backpressures does become significant. It is worth noting that the "bark" of this particular 14-liter engine is subjectively very mild with only the OEM exhaust. In fact, the range of measured braking noise levels on the 14-liter engine was only 1 dB from the best case to the worst.

CONCLUSIONS

1. With an OEM exhaust system, compression brake noise levels are often similar to acceleration noise levels. The one exception was the 12.7-liter engine, where compression brake noise levels were significantly higher than acceleration levels.

2. With an OEM exhaust system, compression brake noise was subjectively detectable on all engines and was considered potentially objectionable on the 12.7-liter engine.
3. With a straight stack exhaust system, acceleration noise increases by a substantial 6.5 to 13.9 dB(A), compared to levels with the OEM exhaust system. Compression brake noise increases by an even more dramatic 9.6 to 22 dB(A).
4. With an open stack exhaust system, compression brakes produce strong impulse sounds at one or more of the first three harmonics of engine firing frequency. To eliminate the objectionable "bark", a muffler must suppress the medium and high frequency components of these impulses.
5. The use of an "overkill" muffler reduced compression brake noise to the limit of detectability on the two engines tested. This demonstrates that brake noise comes almost entirely from the exhaust outlet, and that improved mufflers can reduce brake noise. Because brakes produce high levels of sound at higher frequencies, it might be useful to add absorption material to improve muffler performance.
6. The combination of an exhaust brake with the OEM muffler is also effective in reducing compression brake noise. However, an exhaust brake is very expensive compared to a muffler, and the exhaust brake degrades the braking performance of the compression brake, so an improved muffler would be the preferred solution.
7. It was not possible to demonstrate a strong relationship between compression brake performance and noise levels with OEM mufflers.
8. To reduce community exposure to compression brake noise, enforcement of rules requiring an effective exhaust muffler is essential. The simplest approach to achieving noise reduction beyond current production levels is to develop mufflers for greater brake noise attenuation.
9. Much remains to be learned about how compression brakes produce noise, why some brake designs are louder than others, and how best to reduce brake noise. An analytical model of the gas flow through the engine and exhaust system under braking conditions could yield greater insight into the parameters which control the level of compression brake noise.

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