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Transit IDEA Program

Evaluation of Transit Vehicle Brake Inspection through Ultrasonic Emissions Analysis

Final Report for
Transit IDEA Project 94

Prepared by:
Brian Hearing, BrakeAudit LLC
Andrew Alden
Kevin Grove, Virginia Tech Transportation Institute

October 2020

TRB TRANSPORTATION RESEARCH BOARD
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IDEA Programs
Transportation Research Board
500 Fifth Street, NW
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Evaluation of Transit Vehicle Brake Inspection through Ultrasonic Emissions Analysis

IDEA Program Final Report

For the period May 2019 through October 2020

TRANSIT-94

Prepared for the IDEA Program

Transportation Research Board

National Academies of Sciences, Engineering, and Medicine

Brian Hearing, BrakeAudit LLC
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Executive Summary

This research project explores a new approach for improving transit safety based on detecting problems with transit vehicle brakes by analyzing sounds emitted by braking events. Vehicle brakes emit acoustic energy as part of the friction process; the spectra of these sounds are highly dependent on the mechanical condition of the brake and can be used to detect problems. Acoustic theory indicates that as brake linings wear the resonant frequency of the shoe or pad increases, potentially enabling the monitoring of lining wear. To test this approach passive acoustic sensors were placed roadside at the exit of a transit bus facility for 9 months. The sensors collected almost 10,000 recordings of a bus fleet of 160 vehicles braking over a variety of conditions. Spectra of buses that had brake work performed during this period were analyzed to compare differences between new and old friction linings. It was found that the spectra changes as friction linings wear, agreeing with acoustic theory, where both the centroid and spread of resonant frequencies increased with wear. The use of this information in predictive maintenance was found to be promising; with a modest increase in the number of brake inspections resulting from the acoustic system the maximum time a problem could go undetected would be significantly shortened versus waiting for the next periodic inspection. The performance of this capability could be significantly improved with additional data.

IDEA Product

A new approach for improving transit safety is based on detecting problems with transit vehicle brakes by analyzing ultrasonic sounds emitted by braking. Vehicle brakes emit ultrasonic energy (acoustic frequencies above what humans can hear) as part of the friction process; the spectra of these sounds are highly dependent on the mechanical condition of the brake and can be used to detect problems. Ultrasonic-based brake monitoring systems consist of non-invasive automated sensors placed roadside near exits of transit vehicle facilities that provide daily analysis of brakes for every vehicle and issues alerts if problems are detected.

Advanced warning of brake problems can lead to benefits in increased transit safety and operating efficiencies. Transit safety will be improved through less accidents and injuries due to brake failures. The ultrasonic-based system issues immediate alerts if critical safety conditions are detected; the bus can be stopped immediately after leaving the maintenance facility. Operating efficiencies will be improved through less roadcalls, mechanical breakdowns, unplanned maintenance, and customer inconvenience. The ultrasonic-based system provides daily updates of brake conditions which can help optimize maintenance schedules

Concept and Innovation

This project proposes a new approach for improving transit safety by analyzing ultrasonic sounds emitted by the brakes to detect problems. Vehicle brakes emit ultrasonic energy (acoustic frequencies above what humans can hear) as part of the friction process; the spectra of these sounds are highly dependent on the mechanical condition of the brake and can be used to detect specific types of problems.

Ultrasonic-based brake monitoring systems consist of non-invasive sensors placed roadside near exits of transit vehicle facilities. The sensors can be automated to provide daily analysis of brakes for every vehicle and issues alerts if problems are detected. The data can be used to optimize maintenance schedules based on the conditions of the brakes.

Investigation

Background

Despite advances in transit vehicle safety technology, vehicle brakes remain a common cause of accidents, injuries, roadcalls, and mechanical breakdowns. In the United States there are over 480,000 truck and bus crashes annually(*1*) with almost 30% of them involving brake failure as a factor*(2).* Every year about 15% of all commercial vehicles, including buses, are placed out of service after inspections because of brake-related violations*(3).* Brake related roadcalls and unplanned maintenance in transit agencies can exceed several per day; for example, in 2010 WMATA averaged 3 brake-related roadcalls per day*(4),*in 2005 Miami-Dade averaged 2 brake-related roadcalls per day*(5),* and in 2013 Montgomery County MD averaged over 1.5 brake-related mechanical failures every week*(6).*

Transit vehicle brakes require invasive and time consuming manual inspection in order to reliably detect issues. This is because many critical components face each other with only millimeter sized gaps, requiring disassembly for visual inspection. Because of this, vehicle brakes are usually not disassembled and fully inspected more than twice a year, long enough for problems to occur without notice between inspections. Existing alternatives to visual inspection methods are available but have limitations such as performance-based brake testers (expensive and time consuming) and infrared imaging (expensive and limited effectiveness). Development of non-invasive method for detecting brake problems that does not require disassembly could save commercial vehicle fleets significant resources and improve roadway safety by facilitating brake maintenance.

Fundamentals of Brake Acoustics

Vehicle brakes emit acoustic energy as a result of the friction conversion of the vehicle's kinetic energy to thermal energy where a small fraction of that energy finds its way to vibrational energy. Profiles of actual contact surfaces are microscopic in size (Figure 1) and have been shown to emit acoustic energy into the ultrasonic realm (Figure 2). Manufacturers measure acoustic emissions of braking systems during the design phase via noise, vibration, and harshness (NVH) analyses where parameters such as pad thickness and structural integrity have been shown to affect acoustic emissions (Figure 3).

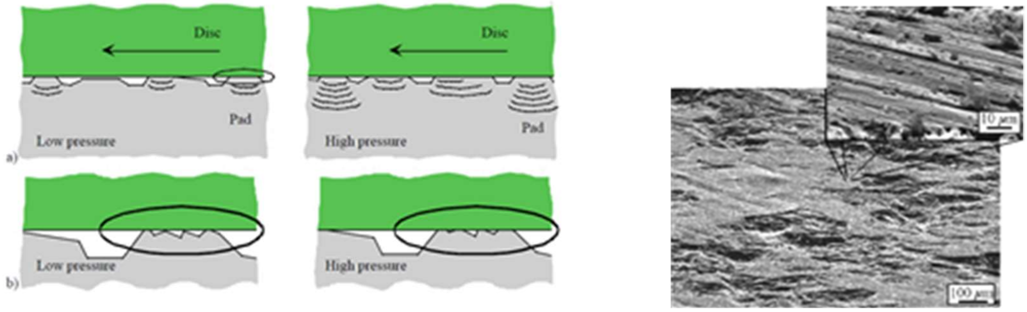

Figure 1: Vehicle brake contact plateaus are microscopic in size (7)

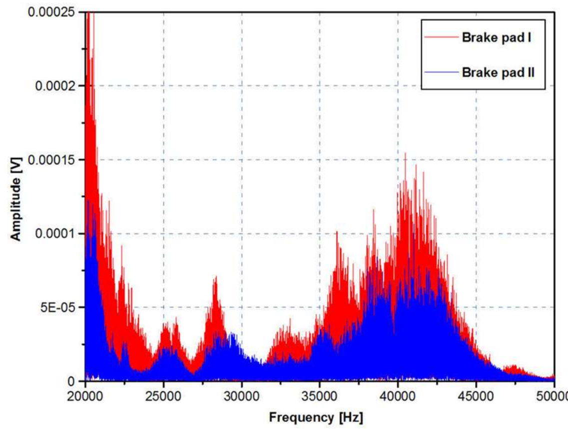

Figure 2: Acoustic energy extending into the ultrasonic realm, as measured in a laboratory environment (8)

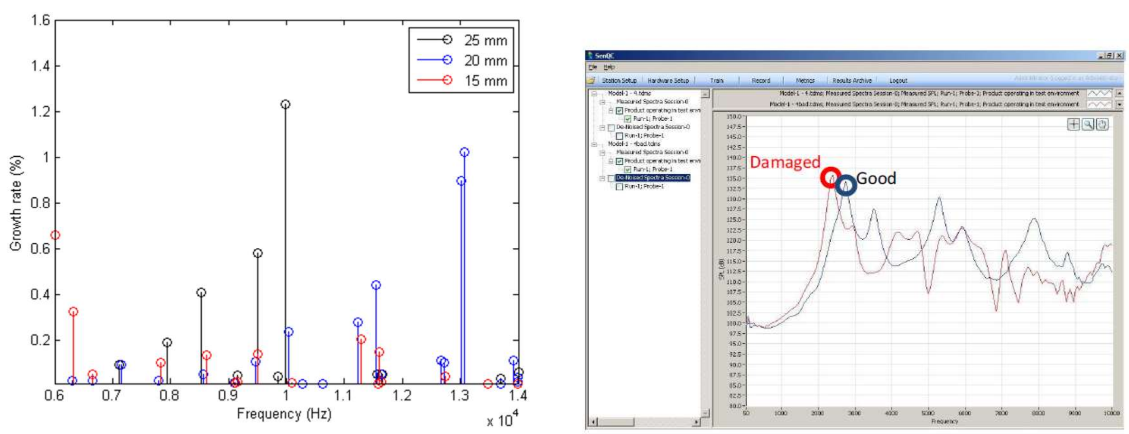

Figure 3: Acoustic spectra are influenced by factors such as pad thickness and structural integrity (8) and (10)

Acoustic Signatures of Brake Problems

Because acoustics are associated with the friction process, the spectra can reveal mechanical characteristics including problems. Most NVH is concerned with human-audible sounds like squeal and groan; however, there is still substantial content in the ultrasonic region. Previous ultrasonic collections of braking events have revealed patterns associated with out-of-round drums, cracks and hot-spots on rotors, and friction material wear, as shown in Figure 4.

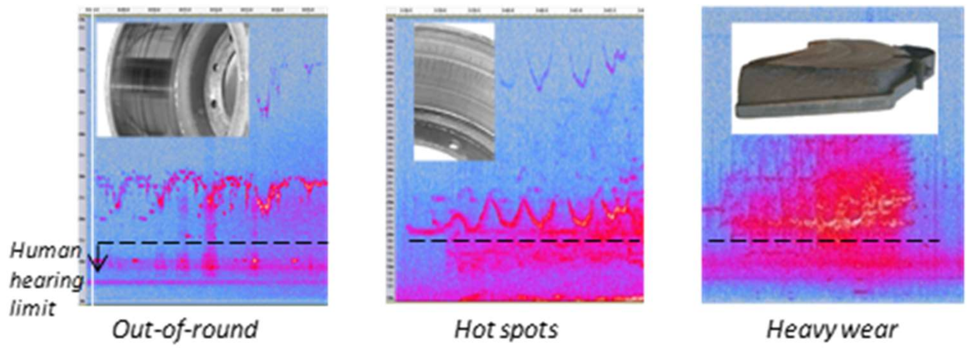

Figure 4: Examples of ultrasonic emissions from brakes with different conditions

Many sources of human perceptible acoustics such as squeal and groan are well known. They typically include brake rotor and drum resonant frequencies for squeal and other suspension component resonances for groan. Passenger car brakes often intentionally include wear indicators that resonate as squeal when brake pads get worn, in order to prompt the driver to take the car in for service. Higher frequency squeals have been shown to be induced when similar modes of resonance occur between the rotor and pad, as illustrated in Figure 5; this is further complicated as the components change temperature.

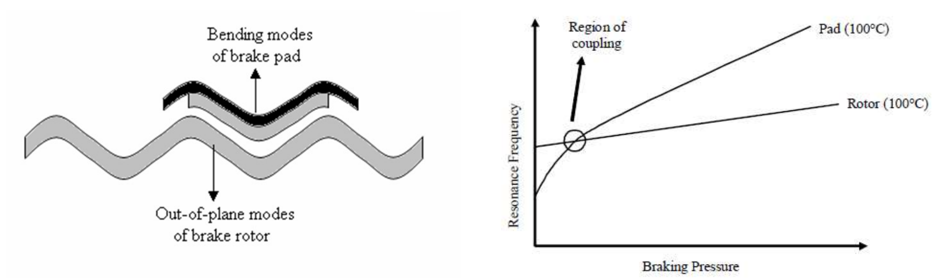

Figure 5: Simple diagram of bending modes of brake pads and how the friction process could drive resonances (left), and how those resonances can come and go depending on temperatures of the components (right) (11)

Analyzing the source of resonances usually involves a detailed finite element model but trends can still be examined through the fundamental frequencies of a brake shoe and pad. Wikipedia describes the fundamental frequency as $f_0 = v/2L$ where v is the speed of the wave in the material and L is the length of the body in which the wave is traveling *(12).* Harmonics of any resonator may also appear at integer multiples of the fundamental frequency.

A typical transit drum brake component part number is 4707 and is a 16.5" x 7" drum which takes linings of roughly 17.8cm square and 2.12cm thick. The shoe steel backing ('table') is 3.8mm thick. New linings are 21mm thick and minimum thickness before replacement is 6.4mm.

A typical disc brake pad part number is 04-01-1113 which is 250mm length, 114mm wide, and 29mm thick. The pad consists of two sections roughly 100mm square and the backing steel plate is 9mm thick. Lining thicknesses are 21mm when new and recommended replacement thickness is 2mm.

Brake lining material composition are difficult to define exactly (manufacturers do not specify exact compositions as they are trade secrets). A typical mix may be defined as 30% matrix (phenolic resin), 30% abrasive modifier (graphite), 30% steel fiber, and 10% abrasive (quartz*)(9).* Velocities of sound for these materials are resin (150m/s), graphite (1500m/s), steel (6,000m/s), and quartz (5,800 m/s). The resulting composite velocity of sound in the lining is estimated at 2,800m/s, as shown in Table 1.

Table 1: Estimated friction material components, velocities of sound, and equivalent composite velocity of sound

Component	Velocity	Composition
Matrix (phenoli resin)	150 m/s	30%
Modifier (graphite)	1,500 m/s	30%
Fiber (steel)	6,000 m/s	30%
Abrasive (quartz)	5,800 m/s	10%
Friction material equivalent	2,800 m/s	

Using the relative thicknesses of the different components of the entire shoe and pad the composite velocity of sound in the lining plus steel backing shoe or pad is estimated at: new drum shoe (3,290 m/s), worn drum shoe (4,000 m/s), new disc pad (3,760 m/s), and worn disc pad (5,420 m/s). Dividing this by the length of the component results in fundamental resonant frequencies of new drum shoe (9.2 kHz), worn drum shoe (11.2 kHz), new disc pad (18.8 kHz), and worn disc pad (27.1 kHz), as shown in Table 2.

Table 2: Estimated composite velocities and fundamental frequency for new and worn brake shoes and pads.

Component	Composite velocity	Fundamental frequency
new drum shoe	3,290 m/s	9.2 kHz
worn drum shoe	4,000 m/s	11.2 kHz
change in drums		**21.7%**
new disc pad	3,760 m/s	18.8 kHz
worn disc pad	5,420 m/s	27.1 kHz
change in discs		**44.1%**

Friction linings ususally wear at different rates on different pads and shoes so the resonant frequencies will spread as the overall brake wears. Because there are four linings on each wheel end the spread could be significant if one pad wears faster than others. It should be noted that the frequencies calculated in Table 2 are simple estimates and real-life spectra may be different due to a variety of factors including different friction material properties, varying pad thicknesses, and structural aspects such as the web steel on the back of the brake shoe.

As illustrated in Figure 4 the overall spectra in both frequency and time domain are rich and complicated because different components can resonate at different times during the braking event. Each wheel end can include four friction material linings (two for each pad or shoe, with two shoes or pads on each wheel end). When two axles are in tandem both can resonate at the same time for up to 8 resonances per wheel end. Furthermore, some resonanses can be very loud and be heard across the vehicle; ultimately for a 3 axle coach, for example, there could be 24 different resonanses that can emit at different times during the braking event. Lastly, as the components heat up during the event the spectra can shift or the resonances fall out of synch as shown in Figure 5.

It should be repeated that this analysis is a very simplistic model useful only for analyzing trends in resonances, IE the percent change in frequency as the lining wears. It assumes in-plane resonances only (which have been found to be the source of higher frequency squeal*(10)*) but out-of-plane resonances can also exist. At these higher frequencies resonance modes become more dense so there can be resonant modes very close to each other (meaning the same pad could vibrate at different frequencies under different conditions). Finally, resonances occur at the interaction between the friction lining and surface (rotor or drum), which do not change in frequency as much as the friction lining so the changes in total composite frequency may not be as much as estimated above.

Goals of This Project

This project proposes a new approach for improving transit safety by analyzing ultrasonic sounds emitted by the brakes to detect problems. Vehicle brakes emit ultrasonic energy (acoustic frequencies above what humans can hear) as part of the friction process; the spectra of these sounds are highly dependent on the mechanical condition of the brake and can be used to detect specific types of problems. Ultrasonic-based brake monitoring systems consist of non-invasive sensors placed roadside near exits of transit vehicle facilities. The sensors can be automated to provide daily analysis of brakes for every vehicle and issues alerts if problems are detected. The data can be used to optimize maintenance schedules based on the conditions of the brakes.

Data Collection

Battery operated, wireless ultrasonic sensors were installed at Omniride's facility in Woodbridge Virginia. Two sensors were located on either side of the road near a stop sign as buses exit the facility; sensors were placed at locations where front axles and rear axles would pass during a stop, as shown in Figure 6. A camera sensor was placed to capture the bus number on the front of the bus. Ultrasonic audio recordings were collected for 10 seconds as each bus came to a stop, up to 192kHz.

9,910 ultrasonic recordings of 160 different vehicles were made over a period of 9 months. Each collection consisted of the four ultrasonic recordings of the four different wheel end locations and a still image including the bus number, as shown in Figure 7. It was found that there was a reduction in bus operations for three months during the collection period (March to May) due to COVID-19. Also, because the sensors were battery operated it was limited to collecting buses that passed only in daytime.

Figure 6. Installation location at Omniride facility in Woodbridge, VA showing locations of four ultrasonic sensors and one camera sensor for the vehicle ID number

Figure 7. Ultrasonic sensor (left) and image from visual sensor (right) showing bus ID number

Most braking acoustic recordings would sound quiet to a human but spectrograms reveal significant content in the ultrasonic realm above what humans can hear, as shown by example in Figure 8. The spectrogram in FIgure 8 shows a typical braking event during the first 3 seconds with significant emissions in the ultrasonic region (in this figure, the yellow bands from 25kHz to 35kHz). The short, strong wideband bursts that appear as vertical lines around 2, 4, and 5 seconds are the air brake releasing. Then, from seconds 7 to 10 the bus accelerates and moves on from the stop sign.

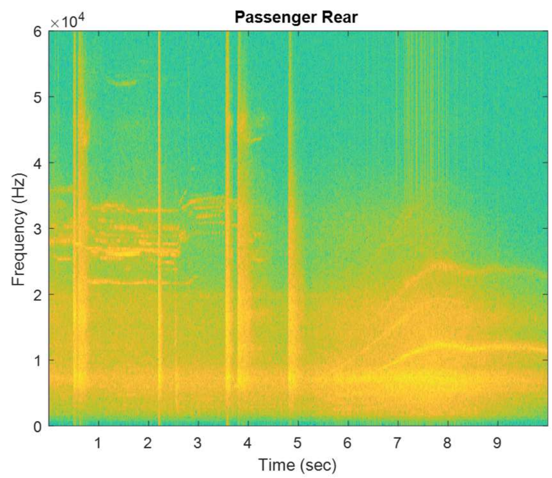

Figure 8. Spectrogram showing ultrasonic emissions of bus 3012 while braking (first 3 seconds); the emissions are all above the human hearing limit (20kHz) and this bus would sound silent to a human standing near it while braking. Note that the ultrasonic tones are within the range estimated above

Maintenance records concerning brake work were also collected from Omniride. It was found that 44 brake jobs were conducted over the 9 months of this study; however, in the three months of January to March there were no brake jobs performed due to COVID-19. This is especially detrimental to this project since this period was right in the middle of the data collection period and would have increased the amount of data with recordings both before and after the brake work. Buses with drum shoes had on average 170,000 miles before replacement and lasted about 4 years and buses with discs had 85,000 miles on pads and lasted a little over 2 years.

Acoustic Processing

Several processing steps were conducted to automate the analysis of acoustic spectra during braking events. First, the braking event had to be identifiable in the acoustic record; IE there had to be enough acoustic content to continue processing that recording. Then, a characteristic spectra of the braking event was chosen by averaging the spectra during the entire event and chosing an actual spectra close to the average. This was done also to filter out spectra where a broadband spike caused by air releasing from the brake was included. Finally, statistics from the spectra were calculated including frequency centroid and spread. Those statistical characteristics were then plotted over time and trends in the data were evaluated for periods before and after the brake work to examine differences between new and worn friction linings.

Some qualitative differences were obvious in some of the data. For example, Figure 9a shows bus 3001 spectra with new and worn pads. It is observed that the spectra with worn pads has significantly more ultrasonic emissions than after; this should be identifiable in frequency centroid and spread. It is theorized that as the pads age they will wear at different rates and thus have different resonant frequencies; new pads should all be similar thickness and perhaps all have the same resonant frequency. Figure 9b shows a cross section of the worn spectra on Figure 9a; it is speculated that the different peaks may correspond to different friction material pads. Figures 9c and d show composite spectra of bus resonances over time, revealing apparent increases in centroid and spread of the resonances as the friciton material wears.

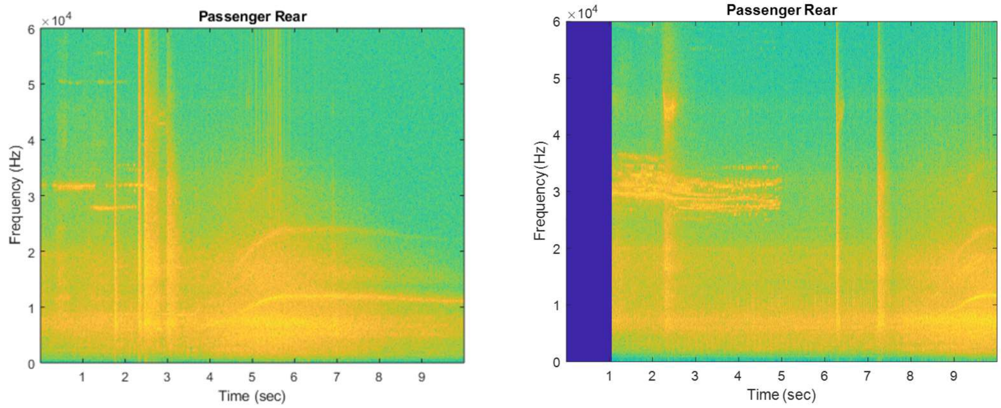

Figure 9a. Example of observable differences from bus 3001 of simple spectra with new pads (left) and complex spectra with worn pads (right)

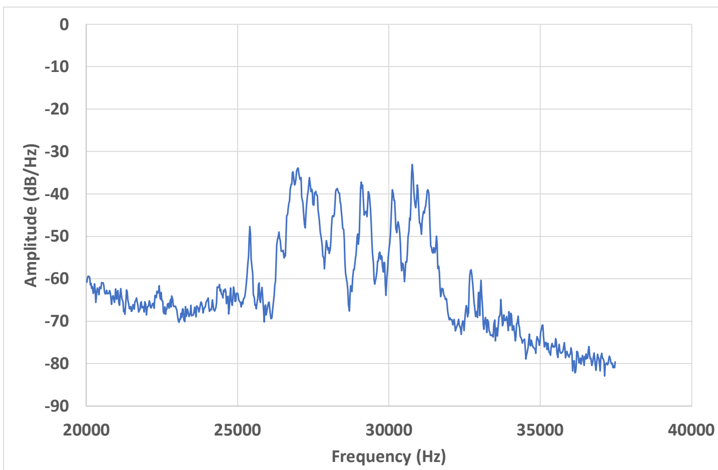

Figure 9b. Closeup of spectrum of braking event shown in Figure 11a on right, with worn pads. Are the peaks resonant frequencies for the 8 pads with different thicknesses in the rear passenger wheel ends?

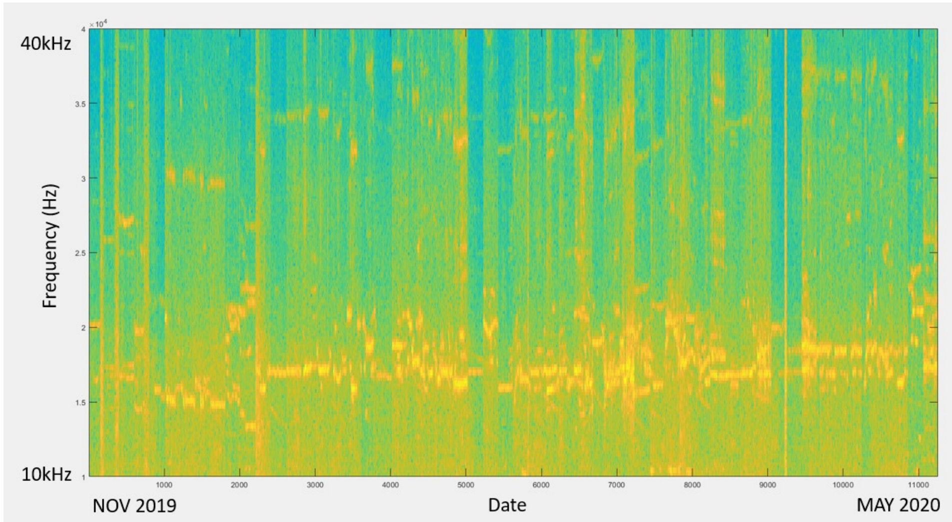

Figure 9c. Composite clips of 56 recordings of Bus 294 with drum brakes from November 2019 to May 2020. It is shown that distinct resonances persist across the length of observation and slightly increase over time

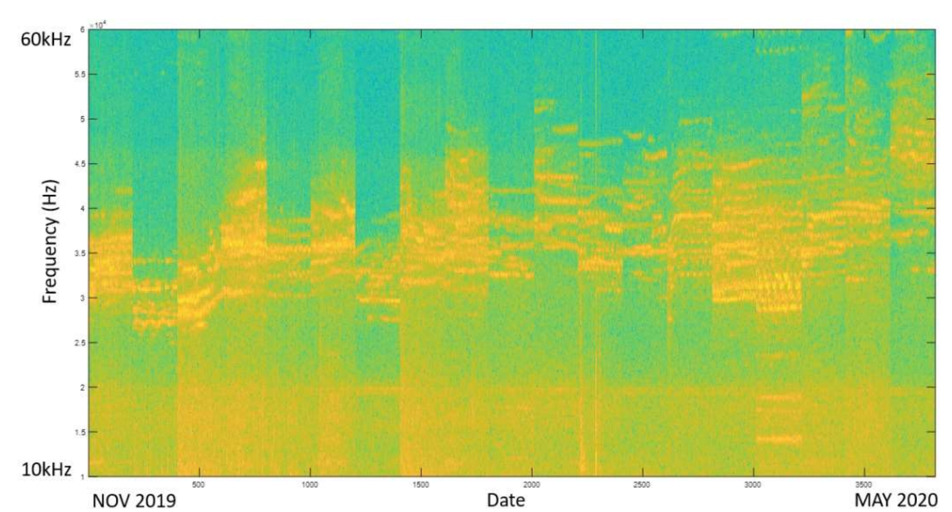

Figure 9d. Composite clips of 19 recordings of Bus 3001 with disc brakes from November 2019 to May 2020. The increase in resonances over time is more apparent and the multitude of persistant resonances could be the 8 friction linings on the wheel ends closest to this sensor

New versus Worn Friction Linings

Spectra of buses that had brake work performed were analyzed to examine the difference in acoustic spectra between new and worn linings. Both drum and disc brakes were examined.

Drum Brakes

Records for eight buses with drum brakes that were replaced during the course of this study were processed. Of these, five had sufficient records to establish trends before the brake work and four had sufficient records to establish trends after brake work. Composite spectra of braking resonances for these buses are shown in Figure 10.

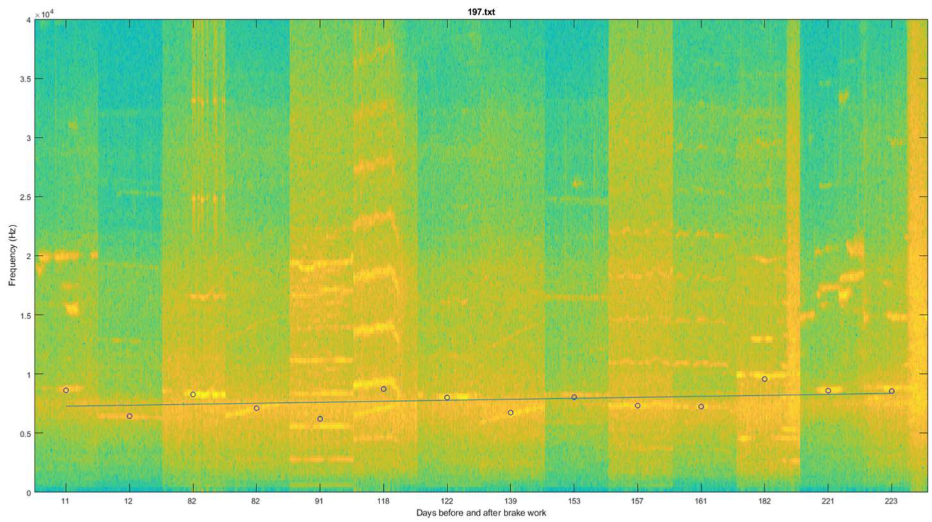

Figure 10a. Records for bus 197, which were recorded after the brake work

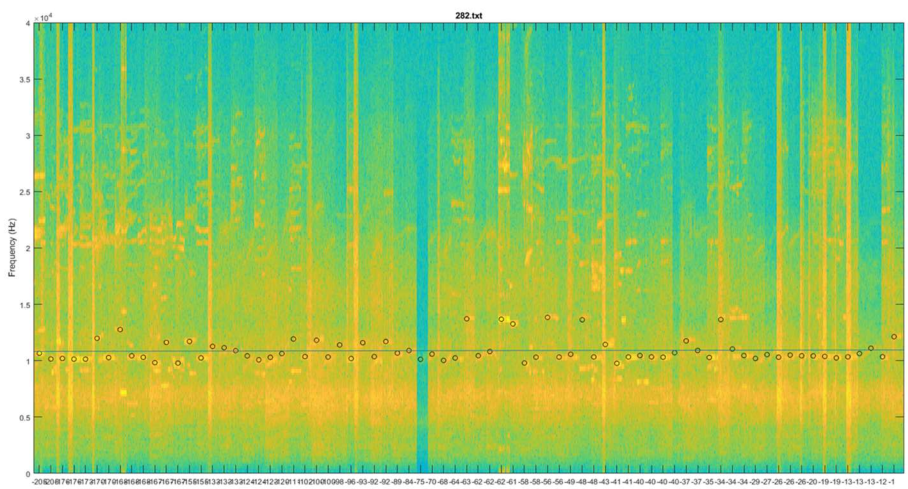

Figure 10b. Braking resonances for bus 282 before brake work. Background noise appears higher because the rear brakes are closer to the engine

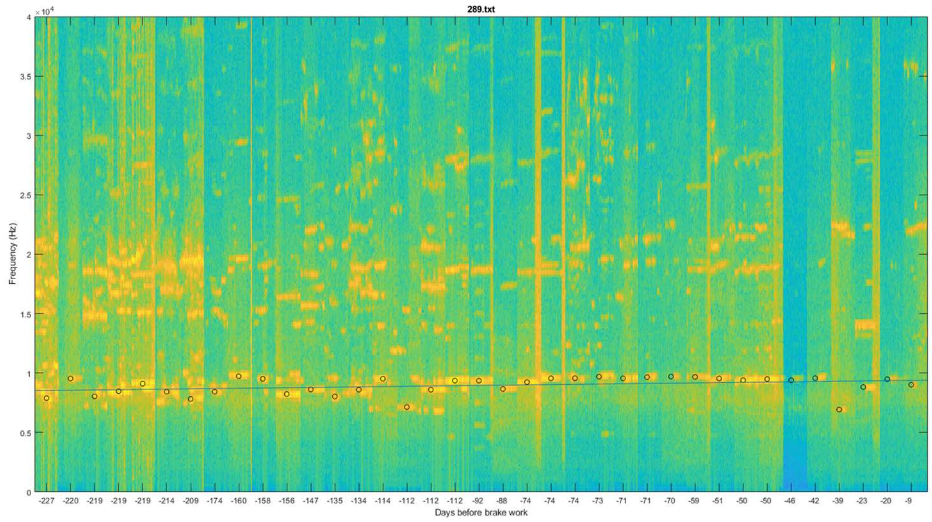

Figure 10c. Resonances for bus 289 before brake work. Here and all subsequent buses had front brakes replaced, away from engine noise

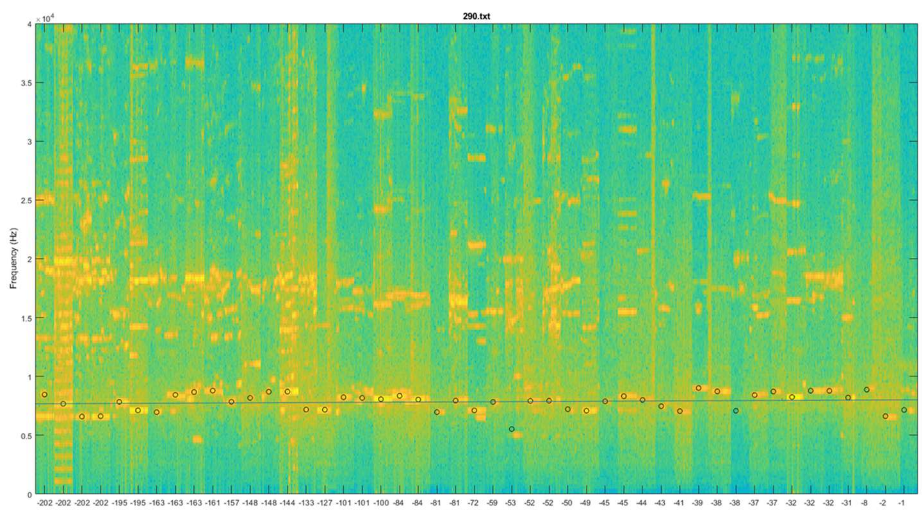

Figure 10d. Resonances for bus 290 before brake work

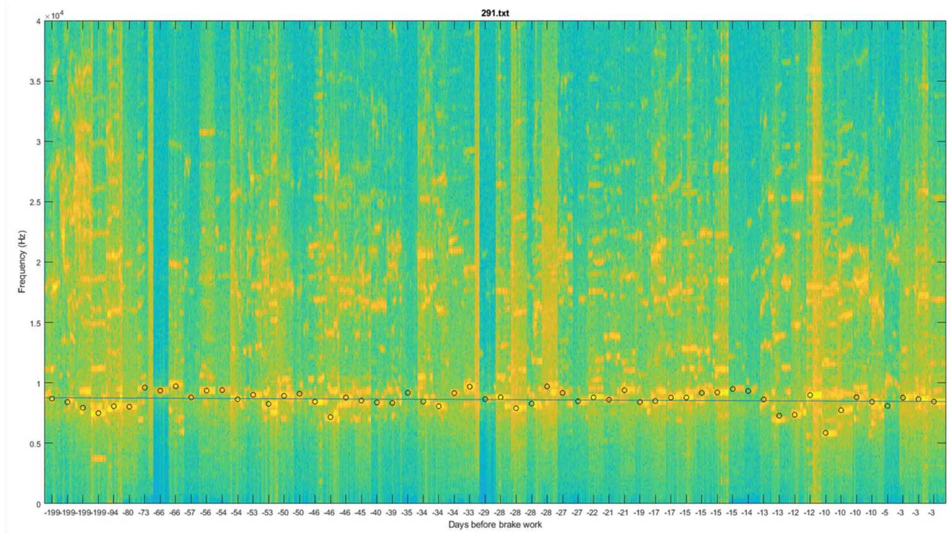

Figure 10e. Resonances for bus 291 before brake work

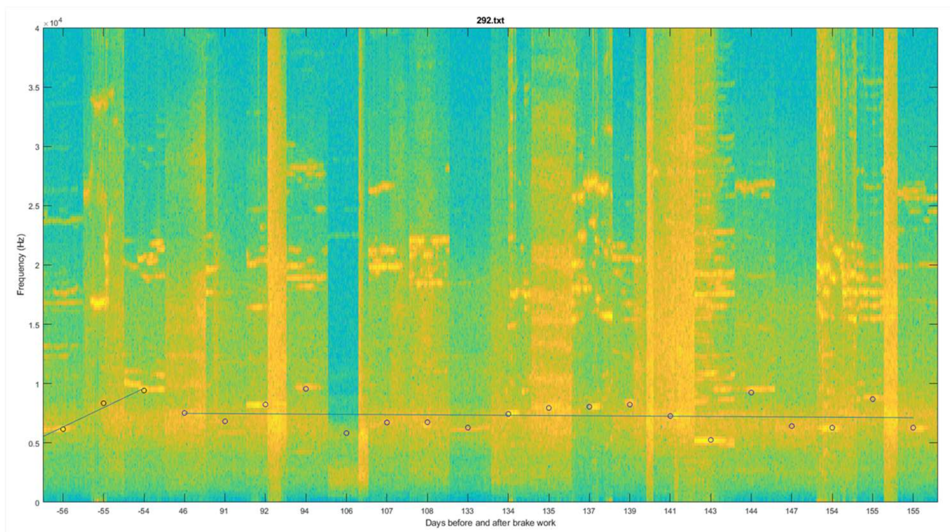

Figure 10f. Bus 292 before and after brake work

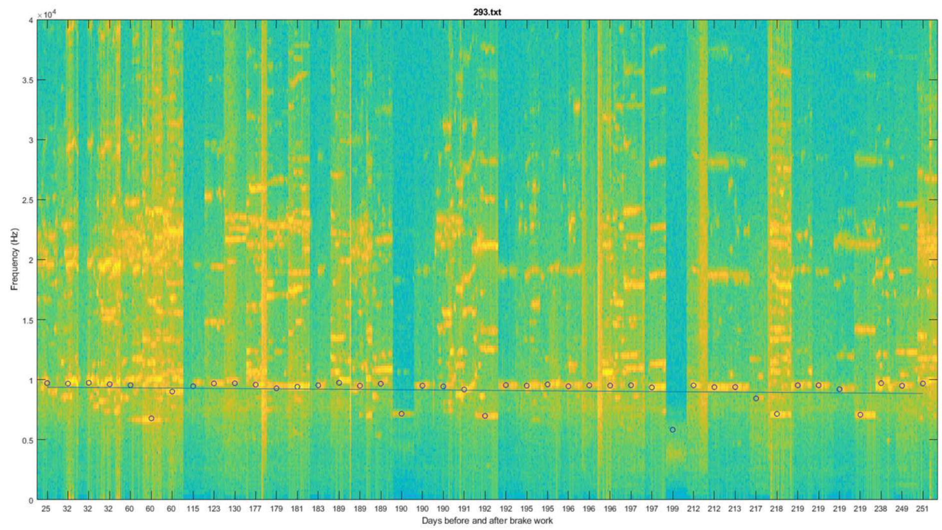

Figure 10g. Bus 293 after brake work

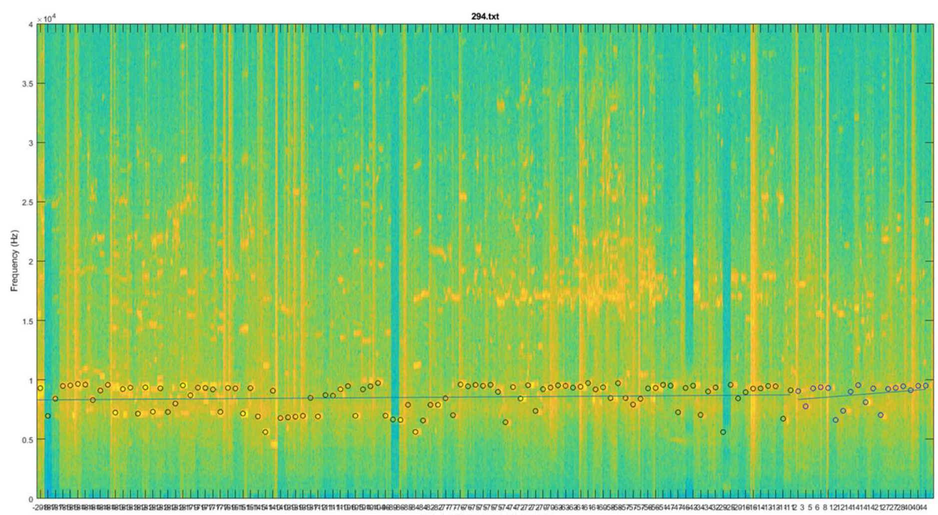

Figure 10h. Resonances for bus 294 before and after the brake work

Disc Brakes

Records for six buses with disc brakes that had work done during the course of this study was processed. All six had sufficient data before the work was performed but only two had sufficient data after the work was performed to establish trends. Composite spectra of braking resonances for these buses are shown in Figure 11.

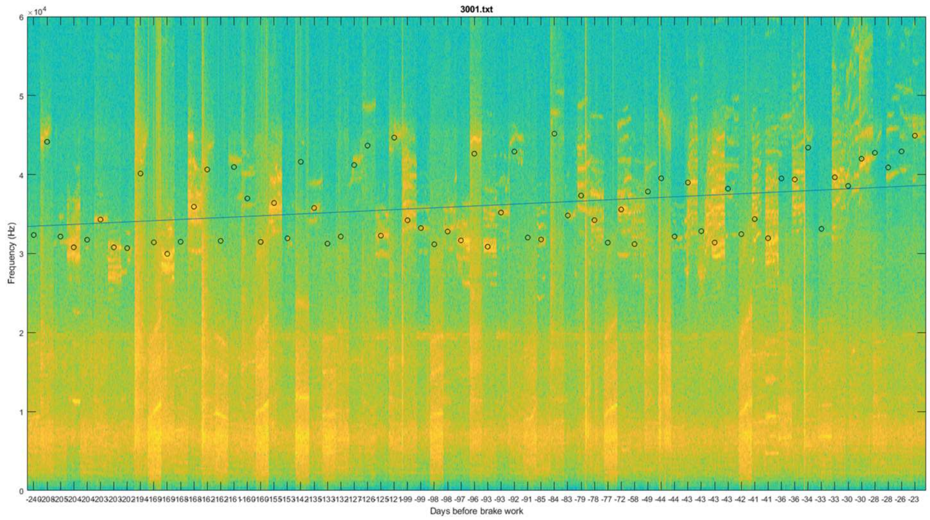

Figure11a. Resonant frequency for Bus 3001 over 6 months before brake work

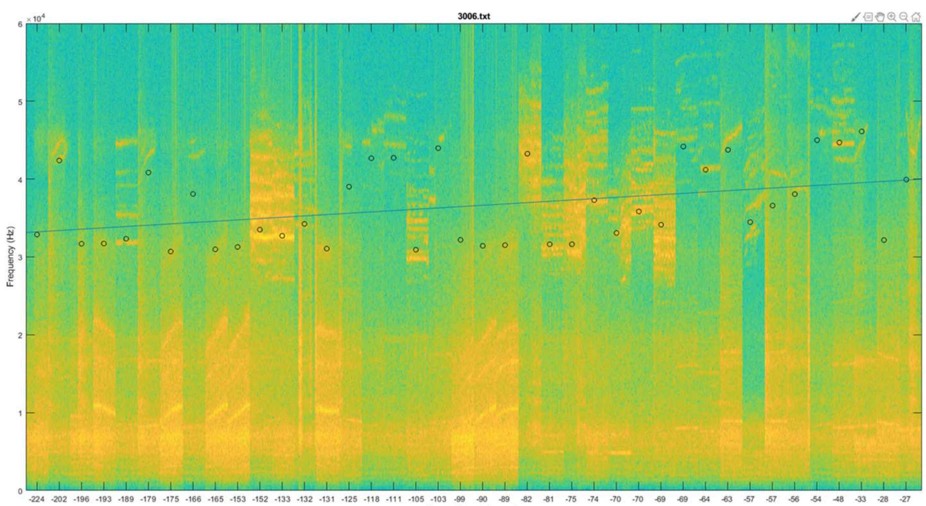

Figure 11b. Bus 3006 before brake work

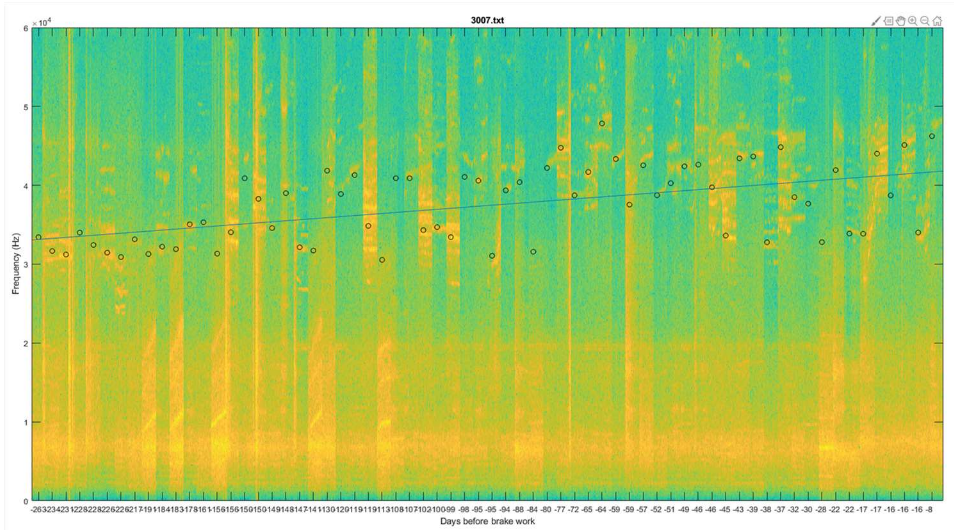

Figure 11c. Bus 3007 before brake work

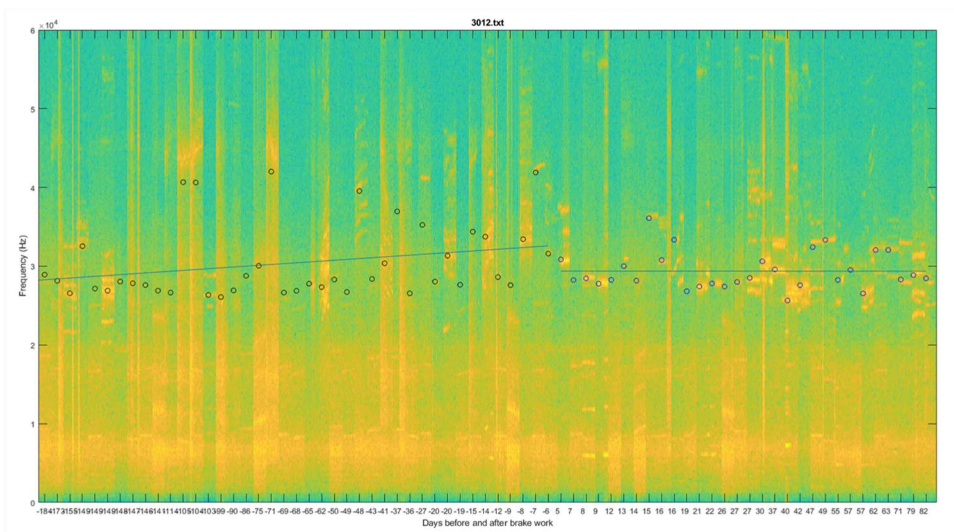

Figure 11d. Bus 3012 before and after brake work

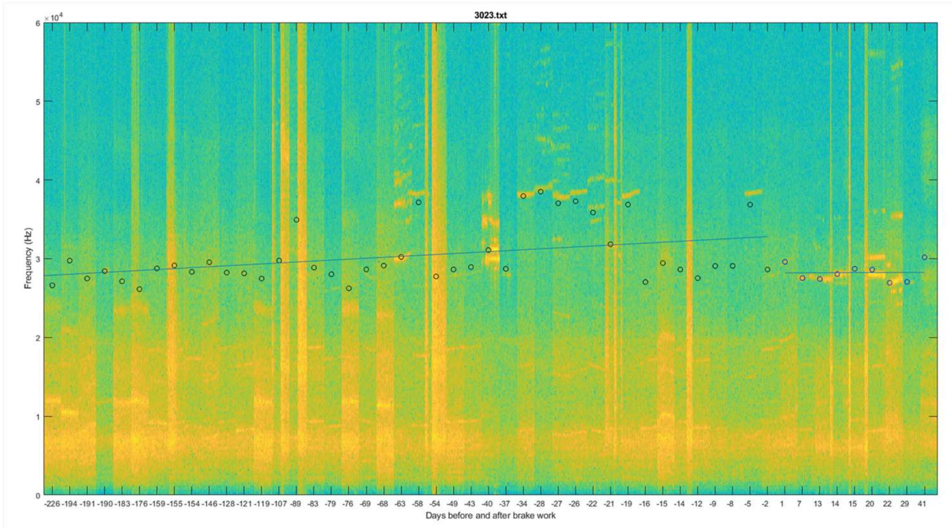

Figure 11e. Bus 3023 before and after brake work

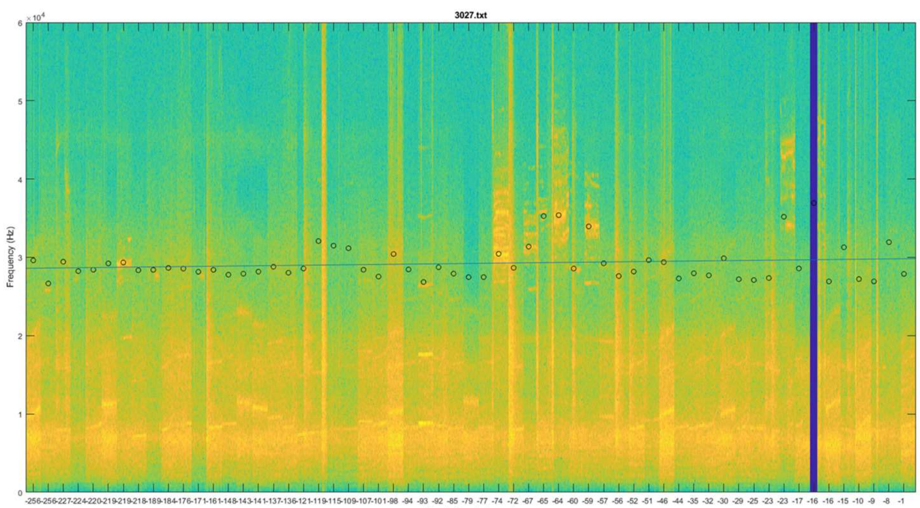

Figure 11f. Bus 3027 before brake work

Comparison to Theory

The averages of frequency centroid for buses with drum brakes and disc brakes are shown in Table 3.

Table 3. Averages of frequency centroid for drum and disc brakes

Type	New		Worn		Delta Theory	Delta Real
	Theory	Real	Theory	Real		
Drum shoes	9.2 kHz	8.2 kHz	11.2 kHz	9.2 kHz	21.0%	12.4%
Disc pads	18.8 kHz	28.6 kHz	27.1 kHz	35.7 kHz	44.1%	24.6%

The trends of frequency increasing with wear are consistent with theory but the differences between new and worn are not as dramatic. This may be because the experimental data is the centroid of spectra which can include up to 16 different pads; if only 8 were replaced during a brake job, the other 8 may be mid-life and raise the 'new' and lower the 'worn' measured frequencies. Also, the lining material is not known and the material properties are probably wrong (especially for disc pads).

Another factor may be that all brake pads are replaced on an axle when a single pad has worn below tolerances. Because pads wear at different rates, 7 of the 8 pads on an axle may be thicker than minimum tolerances but still replaced because a single pad on the axle exceeded minimum thicknesses. Thus, it would appear that the centroid of the 8 pads are not as high as the single pad that has worn away the most.

A simplistic way to evaluate this scenario would be to examine the highest tone in the spread; that would be the pad that gets changed. A quick estimate would be to add the spread to the centroid, as shown in Table 4.

Table 4. Averages of frequency centroid plus spread for drum and disc brakes

Type	**New**		**Worn**		**Delta Theory**	**Delta Real**
	Theory	Real	Theory	Real		
Drum shoes	9.2 kHz	8.2 kHz	11.2 kHz	10.4 kHz	21.0%	26.5%
Disc pads	18.8 kHz	28.6 kHz	27.1 kHz	40.5 kHz	44.1%	41.6%

This simple estimate of highest single pad frequency shows much better agreement with theory than the centroid.

Wear of Friction Linings

Further processing can examine how frequencies of emissions change as the linings wear.

Drum Brakes

The slopes of the linear curve fits for the resonances for worn drum brakes before their replacement are given in Table 5.

Table 5. Frequency changes per day and frequency at time of replacement for drum brakes

Vehicle	**Hz / day**	**Freq. at replacement**	**# data points**
282	1.46	11.0 kHz	75
289	4.20	9.4 kHz	37
290	0.88	7.9 kHz	47
291	1.33	8.7 kHz	58
294	3.60	9.0 kHz	62
mean	**2.29**	**9.2 kHz**	
theory	**2.70**	**11.2 kHz**	

It is shown that the resonant frequency increases by several Hertz every day, though this will depend on miles driven per day; the average is fairly close to the change predicted by theory. The resonant frequency at time of brake replacement is also fairly close to theory though the material properties are probably not correct.

Disc Brakes

Trends in disc brakes also show an increase in frequency with wear. The slopes of the linear curve fits for worn disc brakes before their replacement are given in Table 6.

Table 6. Frequency changes per day and frequency at time of replacement for disc brakes

Vehicle	Hz / day	Freq. at replacement	# data points
3001	21.9	38.3 kHz	67
3006	32.9	40.1 kHz	40
3007	39.4	41.4 kHz	66
3012	24.8	32.3 kHz	41
3023	25.1	32.3 kHz	42
3027	5.3	29.7 kHz	59
mean	**24.9**	**35.7 kHz**	
theory	**11.4**	**27.1 kHz**	

It is shown that the resonant frequency increases by several tens of Hertz every day, though this will depend on miles driven per day; both the change in frequency per day and frequency at brake work differ from theory however, most likely due to incorrect material assumptions. Still, the overall trend of increasing frequency with increased brake wear is fairly consistent.

Use as Predictive Maintenance Indicator

It is observed that frequencies appear to increase as brakes age but can this information be useful for predictive maintenance planning? For example, if an acoustic system issued alarms to the maintenance manager that a vehicle's brake resonances were approaching a critical frequency, would that help improve timeliness of finding worn brake linings? One way of examining operational performance is the use of a receiver-operator characteristic (ROC) curve. A ROC curve enables the examination of the influence of different alerting sensitivities and understanding the resulting performance of a detection system. For example false alarm rates for different detection sensitivities can be varied and improvements to the overall performance on brake maintenance can be estimated.

No detection system is 100% perfect; there will always be a tradeoff between detection sensitivites and false alarms. For example a system can be set very sensitive to catch as many problems as possible but will also result in more false alarms. If false alarm rates are too high the customer may ignore any alert issued by the system. On the other hand if the detection rate is set too low the customer may not have faith that the system can find enough problems and return to their previous maintenance methods (IE periodic maintenance). Each customer and fleet is different and the sensitivity should be set to customer preferences.

ROC curves are computed by plotting the distributions between acoustic spectra before and after brake work and then adjusting an alerting threshold between those; IE when a buses' brakes start to exceed that threshold frequency an alert would be passed on to the maintenance manager. This results in both false alarms and missed true positives, as shown in Figure 12 from Wikipedia.

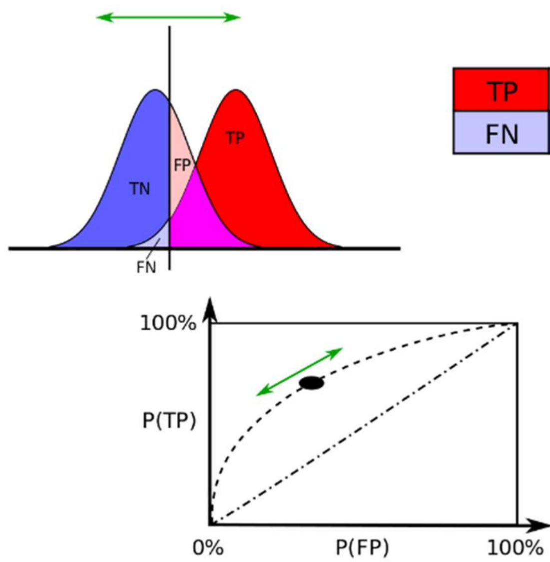

Figure 12. Illustration from Wikipedia's page on ROC curves showing how detector sensitivity can be adjusted to tradeoff between false alarms and higher detection rates

Single Feature Discriminator: Highest Frequency

Figure 13 shows the application of this methodology to the data collected in this program and the use of the highest frequency of a wheel end resonance as an alerting mechanism for brake problems. The left graph shows frequency distributions for brakes before and after brake work. The right graph shows the resulting detection and false alarm rates as the alerting frequency threshold is varied between the frequencies on the left graph. Lastly, the false alarm rate for different detection rates are show in the bottom graph of Figure 13. To convert probability of false alarms in the right figure to the false alarm rate in the bottom figure the probability is multiplied by the number of buses in the fleet and how frequently the buses get scanned.

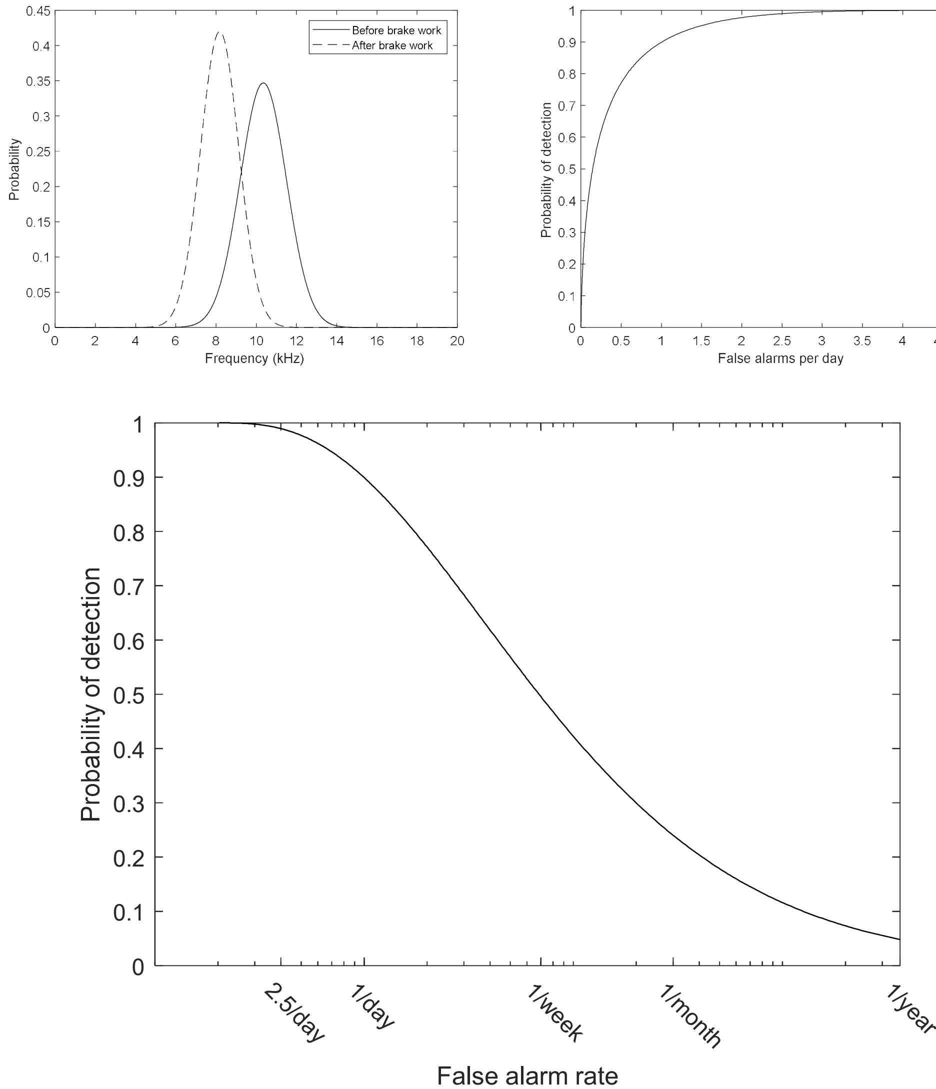

Figure 13. Probability distributions, ROC curve, and false alarm rates using the highest frequency as a discriminator

What would this mean to a maintenance manager? The system as envisioned would issue alerts when a problem was detected; that bus would then get inspected but a fraction of those inspections would be false alarms. But some of those will be true positives, meaning if the bus actually had a problem it would be detected quicker than waiting for the next periodic inspection. So the tradeoff is between more manpower for inspections (some of which will be false alarms and thus wasted manpower) and catching brake problems quicker than the normal periodic inspection period. To examine this tradeoff first a baseline will be established then two scenarios evaluated.

Baseline

First, the baseline of the current periodic maintenance program: the maintenance manager indicates that periodic inspections are conducted every 6,000 miles which equals roughly every 60 days per vehicle for this fleet and approximately 2.5 inspections every day for a fleet of 150 vehicles, which equals almost 18 inspections per week. At the extreme it is theoretically possible for a brake problem to go 59 days before next inspection.

Scenario 1: One Additional Inspection Every Day

If the sensitivity of the acoustic system were set to issue alerts on average one false alarm per day human inspections would increase by 40%, which is a substantial increase in manpower requirements. However, it would detect 90% of any potential brake problems. On average this means 90% of brake problems would be detected after the initial evaluation period of 15 days and to get 99% of all brake problems would take 1 more scans of 3 days so the total maximum time a bus could go with a brake problem would be 15+3=18 days. This is a significant reduction from the maximum time of 59 days with periodic inspections but the cost of one additional inspection per day is also significant.

Scenario 2: One Additional Inspection Every Other Day

If the sensitivity of the acoustic system were set to issue alerts on average every other day, human inspections would increase by 20%, which is less burdensome but still substantial. However, it would only detect 77% of any potential problems after the initial evaluation period of 15 days and to get above 99% confidence would take 3 more scans of 3 days so the total maximum time a bus could go with a brake problem would be 15+9=24 days. This cuts the time between periodic inspections by half.

Scenario 3: One Additional Inspection Every Week

Here if the sensitivity of the acoustic system were set to issue alerts on average of one false alarm per week, human inspections would increase by only 6% which seems minor. However, it would only detect 50% of any potential problems. On average this means 50% would be detected after the initial evaluation period of 15 days and then to get above 99% confidence level it would take 6 more scans of 3 days each so the total maximum time a bus could go with a brake problem would be 15+18=33 days.

These scenarios are tabulated in Table 7.

Table 7. Summary of tradeoff between increased manpower to handle additional inspections and reduction in time a bus could go with an undetected brake problem using the centroid of the spectra

False Alarm Rate	Manpower Increase	Days brake problem could go between inspections
Baseline	0	59
1 per day	40%	18
Every other day	20%	24
1 per week	6%	33

Discussion

The good news: there does appear to be a signal that could be used as an operational indicator of brake service requirements. The spectra of ultrasonic emissions of braking buses appear to be higher and more complex as the brake ages and matches trends in fundamental acoustic theory.

However, false alarm rates using a simple frequency detector are currently high. The research team believes performance would be improved with additional data and a multi-feature discriminator, perhaps by applying machine learning to the larger data set. The current limited data set is too small for machine learning however. Installing the system with enough power for night time operations would also significantly increase the data collection rate.

Qualitatively, if the system were installed permanently (IE enabling night-time operations) and sufficient data collected, the team believes that the false alarm rate could be reduced to a more reasonable rate, for example maybe with a 10-20% increase in inspections the time a bus could operate with an undetected brake problem would be reduced to a few days. While Omniride did not appear to have any unplanned brake problems during the course of this study, this increase in safety would be significant to other agencies with more frequent problems (WMATA with 3 brake-related roadcalls per day and Miami-Dade has 2 brake-related roadcalls per day).

Plans for Implementation

These findings are are exciting; with low-cost, roadside drive-through sensors, transit agencies can improve detection of brake problems and transition toward predictive maintenance. This system is currently being installed at a commercial truck carrier independent of this project; preliminary real-world results show promise. The research team plans on several publications which can include calls for research partnerships with additional fleets.

However, more data is needed to strengthen the statistics. First, longer data collection time is needed in order to monitor changes in frequency as the friction linings wear. The average lifetime of the drum brakes was 4 years and the disc pads over 2 years, so it will take time to collect data over the entire lifetime of a friction lining. Examining data before and after pad replacement is a quicker way to evaluate the differences between worn and new pads but this 9 month study only collected a few vehicles with enough data (due to slowdowns caused by COVID-19. Finally, more detailed data from maintenance would also help. Specifically, thicknesses of linings of individual friction pads as they are inspected or replaced would be helpful to explore monitoring individual thicknesses.

Conclusions

How results expand knowledge base of transportation community

In this study the research team examined the changes in bus brake acoustic emissions over the life of the brake. It was found that the frequency of the spectra increases as the brakes age, agreeing with acoustic theory. This information can be useful in tracking wear of individual friction pads and can be used for predictive maintenance as well as alerting to cracks, breakages, and other brake problems.

The team also explored the practicality of this as an alert to maintenance managers that maintenance may be required. It was found that with a modest increase in number of brake inspections there could be a significant reduction in the maximum time a problem could go undetected before the next inspection. It is postulated that this could be significantly improved with more data.

Lessons learned

Installing illumination so collections aren't limited to daylight hours is imperative since many buses start service well before dawn and don't stop until after dark. Access to some real-time bus location GIS system to identify which bus drove through the acoustic system is another alternative.

Global pandemics can impact municipal bus activity both in operational volume and maintenance. The team experienced a significant reduction in data collected during this program due to the pandemic.

Potential to contribute to breakthrough in transportation practice

These findings are are exciting; with low-cost, roadside drive-through sensors, transit agencies can improve detection of brake problems and transition toward predictive maintenance. Routine maintenance can be improved by shifting to predictive schedules and more immediate problems such as friction material breakages and excessive wear can be identified sooner.

Path to implementation to product application

This system is currently being installed at a commercial truck carrier independent of this project; preliminary real-world results show promise. Additional work is needed to establish a larger data set, and the research team will be proposing a Phase II program to TRB to continue the research.

References

1. U.S. Department of Transportation, Federal Motor Carrier Safety Administration, *Large Truck and Bus Statistics*, 2014.
2. U.S. Department of Transportation, Federal Motor Carrier Safety Administration, *Report to Congress on the Large Truck Crash Causation Study*, 2009.
3. Commercial Vehicle Safety Alliance, *CVSA Releases Results from Brake Safety Day*, November 2017.
4. *2010 MetroBus Fleet Management Plan*, Washington Metropolitan Area Transit Authority, 2010.
5. *Metrobus Fleet Management Plan*, Miami-Dade Transit, 2005.
6. *Ride On Bus Fleet Management Plan, 2013 to 2020*, Maryland Transit Authority and Montgomery County Department of Transportation, 2014.
7. M. Eriksson, *Friction and contact phenomena of disc brakes related to squeal*, ACTA Universitatis Upsaliensis, 2000.
8. Chiello, Olivier & Lorang, X. *Numerical investigations into the squeal propensity of a railway disc brake*. The Journal of the Acoustical Society of America. 2008.
9. Blau, Peter. *Compositions, Functions, and Testing of Friction Brake Materials and Their Additives*. ORNL/TM-2001/64, 2001.
10. Castellini, Paolo, et al. *Vibration and acoustic analysis of brake pads for quality control*. Structural Dynamics, Volume 3. Springer, New York, NY, 2011. 43-52.
11. Triches Jr M, Gerges SN, Jordan R. *Reduction of squeal noise from disc brake systems using constrained layer damping*. Journal of the Brazilian Society of Mechanical Sciences and Engineering. 2004 Sep; 26(3):340-8.
12. Wikipedia. *Fundamental frequency*. https://en.wikipedia.org/wiki/Fundamental_frequency. 2020.