Real World Brake Activity of Heavy-Duty Vehicles

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A Research Report from the National Center for Sustainable Transportation

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16. Abstract
Contribution of brake particle emissions to ambient PM2.5 is increasing. Previous studies focused on determination of brake emission rate from lab testing and so it lacks brake activity of real world conditions. The study aimed to establish a test method to determine brake activity of a heavy-duty vehicle. Brake parameters and vehicle parameters were measured during two chassis cycles and two on-road test tests. Brake activity was quantified with brake pressure signal as the first indicator and vehicle speed as the second indicator. Temperature increase was related to the kinetic loss of the vehicle and cooling and heating of brake pad was repeated during on road test. Resulting brake activity was presented in the form of histogram. Future test should use shorter copper cap for thermocouple to better sense friction surface temperature. It is recommended to measure both activity and emissions during on-road test so that a better relationship can be established between brake activity and brake particle emissions.

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Disclaimer

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NCST

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TABLE OF CONTENTS

List of Figures

Real World Brake Activity of Heavy-Duty Vehicles

EXECUTIVE SUMMARY

The contribution of non-tailpipe PM emissions are becoming more important as PM emissions from the internal combustion engines are being reduced from ongoing regulations where PM emissions from non-tailpipe sources, such as brake and tire wear, are not currently regulated. Previous CARB and Caltrans research projects investigated PM emissions from various types of brake pad materials for both light-duty and heavy-duty vehicles (HDV). These projects determined emissions factors at different constant deceleration rates that were correlated to real world activity using brake dynamometers. However, the frequency and extent of braking activity varies dynamically in the real world suggesting it is necessary to investigate brake activity for diverse vehicle classes and sizes under in-use conditions. In addition, the same vehicle can have different braking activity based on its vocation (such as goods movement, refuse, people transit, and other) as well as route differences.

The current study was designed around a method to quantify HDV brake pad activity during in-use chassis and on-road testing. The brake activity was quantified with an instrumented brake pad system that included brake temperature, brake fluid pressure, vehicle speed, vehicle position and elevation, and ambient conditions. For the chassis testing two cycles were utilized that represented common test cycles performed for HDVs. These were the Central Business District (CBD) and the Urban Dynamometer Driving Schedule (UDDS). Both the CBD and UDDS cycles were chosen to obtain pressure and temperature measurements of braking activity which varied in frequency and intensity. The on-road driving conditions included a local route, designed to have more urban operation to obtain data with speeds below 40 MPH and frequent braking activity, and a freeway route, designed to provide brake activity under higher speeds found when exiting a freeway and when going down a grade.

During chassis testing, the brake temperature increased from 60 °C to 130 °C during the triplicate CBD cycle and up to 170 °C for the UDDS where the brake pressure was higher for the UDDS compared to the CBD and ranged from 20 to 40 psi for both cycles. A unimodal “distribution” of deceleration was observed for the CBD test where a histogram of kinetic energy lost due to braking showed a left-skewed distribution. The brake pad temperature increased 2×10^{-5} °C per 1 Joule of kinetic energy loss assuming braking load is equally distributed among all the wheels. The UDDS showed a trimodal distribution from the histogram of deceleration and kinetic energy lost representing large, medium and small braking events during the dynamic cycle.

During on-road testing, the local route mimicked that of the CBD with a gradual increase in brake temperature over time with similar brake pressures and temperatures. The higher speed freeway route included a grade climb and decent where several acceleration events occurred during braking events. This negative energy that occurred during acceleration events appears to be occurring where the brakes are applied but the vehicle increases speed while traveling downhill. The freeway route kinetic energy lost ranged from -1.92E6 to 2.36E6 Joules and are

one order of magnitude larger than that of the chassis dynamometer tests. It is suggested the higher kinetic energy loss found on-road is the result of higher deceleration rates which are estimated at 2-3 times larger for the on-road testing compared to chassis testing.

A laboratory bench test was performed to evaluate the brake drum temperature measurement system. It was estimated that the temperature probe may have been reading the brake surface temperature low by 100 °C suggesting the real measured brake pad surface temperature may have been as high as 270 °C. Future studies will consider different probe designs for improved bake pad surface temperature estimation.

This study established a test method to determine brake activity of a HDVs during chassis and on-road conditions. The determination of brake activity from this study will help improve the quantification of brake particle non-tailpipe emissions.

Background and Introduction

Particulate matter (PM) emissions cause adverse effects on human health [1] and is typically reported as ultra-fine PM emissions ($PM_{2.5}$) and other larger particles PM_{10}. While $PM_{2.5}$ from vehicle combustion exhaust is being reduced from ongoing regulations, PM emissions from non-tailpipe sources, such as brake and tire wear, are not currently regulated [2]. Model estimators such as the MOtor Vehicle Emission Simulator (MOVES) and the EMission FACtor (EMFAC) suggest that traffic-related emissions of both $PM_{2.5}$ and PM_{10} will eventually be dominated by non-exhaust sources [3].

Inventories of tailpipe and non-tailpipe emissions are the product of the emission factor (EF) and the activity. Typically the EF is estimated from laboratory testing and the activity is estimated from in-use measurements. However, the laboratory test is typically limited to a short twenty-minute cycle that is reproducible where real activity can be over 10 hours of real-world operation. Tailpipe emission inventories have suffered from large discrepancies between laboratory and in-use measurements, where the in-use EF has been shown to be up to four times higher compared to laboratory testing [4]. Since brake and tire wear utilize a similar emissions inventory model, it is suggested real-world brake evaluations may also show similar higher emissions during real-world testing compared to laboratory dynamometer testing.

The California Air Resources Board (CARB) recently funded two brake wear projects, one investigated brake PM emissions from light duty vehicles using a brake dynamometer [5], and the other studying brake PM emissions from near road measurement (CARB project 18RD017). The California Department of Transportation (Caltrans) also funded a project [6] studying brake PM emissions from heavy duty vehicles (HDVs)using a brake dynamometer. None of these studies considered in-use brake activity for HDVs.

While vehicle activity has been studied to estimate tailpipe emissions, there is no previous brake activity measurement study to estimate brake wear emissions for HDVs. This study compares HDV brake activity during in-use chassis testing and real-world driving conditions. Brake parameters such as brake air pressure and brake pad temperature were measured along with vehicle parameters such as position and speed. Environmental conditions such as ambient temperature and humidity were also collected. This study will help improve our estimate of real-world brake activity and thus, improve our understanding of the particle emission inventory from HDV brakes.

Experimental

Test Vehicle

The test vehicle selected for this project was a Freightliner Cascadia as it represents the largest percentage of the HDV market share [7] and the drum braking system represents the most common braking system [8]. The brakes also represent the more easily replaceable brake components with common materials representing the largest impact for characterization of emissions. In addition, this truck is commonly used for regional deliveries suggesting the results from this study would impact local communities. The vehicle is a model year 2015 and is equipped with a 12.8 L Detroit Diesel engine with air brake system. The curbside vehicle weight was reported as 15,892 lb and was tested at a total vehicle weight (tractor + trailer) of 65,000 lb. Details of the vehicle specification can be found in Table 1.

Table 1. Test Vehicle Specifications

Year	2015
Make	Freightliner
Model	Cascadia
VIN	3AKJGBDV7FSGD9027
Style / Body	Truck-tractor day cab
Engine	12.8L
Engine Model	Detroit DD13
Engine Horsepower	450
Curbside Vehicle Weight	15,892 lb.
Brake System Type	Air

Brake Assembly

The test vehicle uses an air brake drum system as opposed to the less common disk brake type of system. During braking activity, the drum brake mechanism is activated through the rotation of an S shaped cam in response to the pressure change and motion of an internal diaphragm. The S cam then expands the brake shoes onto the inner surface of the brake drum. Under high vehicle speeds, the kinetic energy of the vehicles speed is converted into heat by friction while the brake lining material heats and begins to wear. A matched pair of Meritor Genuine Q Plus brake shoes (KSMA20014711QP) were installed on the left and right rear wheels of the test vehicle. A new pair of brake replacement components weighs about 43.45 lb with a brake diameter of 16.50 inch and shoe width of 8.625 inch. Figure 1 shows the full Meritor Q plus braking system while Figure 2 shows the catalog image of the top brake shoe. Although the brake lining material is not detailed by the manufacturer, it is classified as MA2001.

The brake lining is tapered where more material is at the leading edge of the brake pad and tapers off to less material at the end of the pad, see Figure 1. According to the technical details of drum braking, this taper is designed to help with an even braking load on the lining surface over the life of the brake where more load is on the leading each on a new pair a brakes [7]. As such, there is more friction and heat at the leading edge of the brake pad and less at the end. A used brake drum will have a uniform thickness that matches the thickness of the trailing edge. Based on discussions with our truck repair shop [7], it was decided to insert the temperature sensors two inches behind the leading edge of the drum as shown in Figure 1 to capture the higher wear area of the brakes.

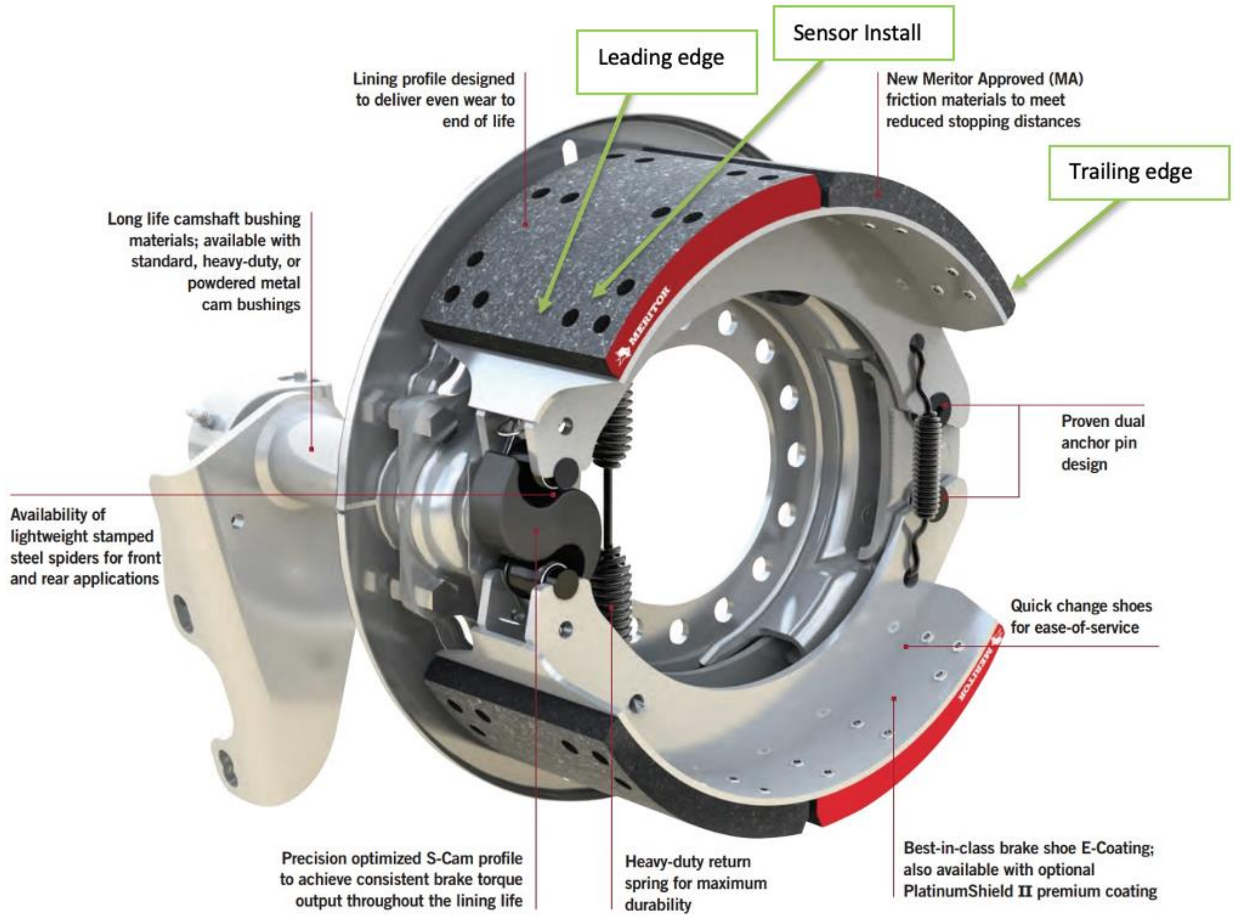

Figure 1. The Meritor Q Plus cam brake system (Meritor 2018)

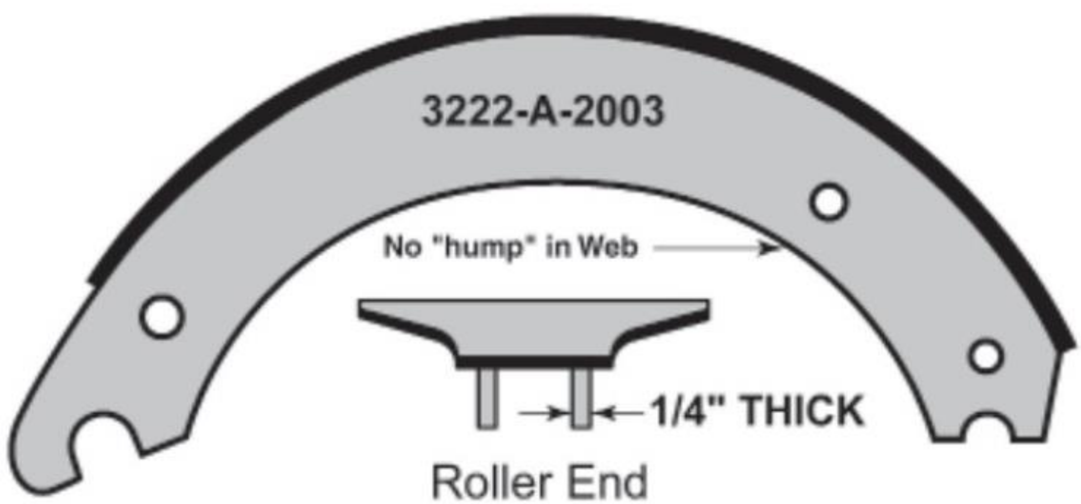

Figure 2. 16-1/2” x 8-5/8” Meritor Q Plus Brake shoe. (Meritor 2018)

Measurements

The measurements collected for the determination of brake activity included brake pressure, brake temperature, vehicle speed, and GPS and ambient information. The brake pressure was measured with an Omega PX319-200G5V pressure transducer with a maximum range of 150 psi. The pressure transducer was installed in the brake fluid line to the rear right brake canister, see Figure 3. Pressure transducer and thermocouple connections right rear brake-wheelFigure 3. This installation allowed for the closest measurement of pressure and temperature of the right brake assembly. This arrangement of pressure measurement worked for the right brakes and was a good estimate for the left brakes pressure as well which had a redundant temperature probe. The HDV brake system pressure was at 135 psi which is common for most HDV [7] and during testing UCR measured values ranging from 10 to 40 psi during deacceleration events.

The brake temperature was measured with a custom-made type k thermocouple. The thermocouple was encased in a 1/8 copper tube cap that was just under an inch long where the temperature junction was bonded to this cap for fast thermal response. The thermocouple was inserted into the brake pad by drilling a 1/8 hole from the backing plate through to the friction material and milling the last 10 mm to have a flat square surface at the bottom of the hole. The thermocouple was then installed in the hole after applying conductive paste to the surface of the thermocouple cap, again to improve thermal response between the brake surface and the thermocouple. The thermocouple was installed two mm below the pad surface to reduce the risk of brake damage, as well as considering brake pad wear during testing. This approach was recommended by other brake measurement studies [9, 10].

The thermocouple and pressure sensor lead wires were secured outside the wheel-brake assembly to allow for connection to a data logger as shown in Figure 3. UCR instrumented both the rear right and left brakes with temperature in case one of the probe installations failed. Only the right rear pressure was recorded where the pressure is expected to be consistent between brake drums for consistent system braking [7]. The datalogger could measure only one temperature and one pressure sensor, so the backup temperature sensor would need to be connected to the datalogger if desired to use the backup sensor.

A data logger was built for this project since it was envisioned the brake measurement system would be installed on a fleet vehicle and would be collecting data over a month where a custom design would be needed for durability and longevity. In the end, the fleets were not open to working with UCR since UCR did not show previous HDV brake modification experience. Future HDV brake activity projects may be able to take advantage of UCRs experience from this project for a future fleet application. An image of the brake data logger is shown in Figure 4 along with the location of the power supply input, start & stop button, thermocouple input, and pressure sensor input.

Ambient conditions can impact the cooling and heating rate of the brakes as such we also included ambient temperature and relative humidity measurements using available on-line data stations. The ambient data was recorded using three local weather stations managed by the California Irrigation Management Information System (CIMIS). The CIMIS data is audited and well managed and is considered of high quality. For this project we used station 44 in Riverside, station 251 in Highland (part of the freeway route), and station 117 located in Victorville where the freeway route ended and the team turned around. The online weather data can be found at the following link, https://cimis.water.ca.gov/Stations.aspx. The ambient temperature and humidity were consistent between the chassis and on-road testing and varied from 40 to 55 F on both days where the RH was between 60-80%. A copy of this data is presented in Appendix A.

Second-by-second data was recorded onto a micro-USB chip inside the brake data logger which included ambient temperature (°C), brake pad temperature (°C), and brake pressure (psi). An OBD2 HEM logger was used in conjunction with the brake data logger in order to record the vehicle's GPS data including latitude, longitude, vehicle speed, and altitude.

Chassis testing was powered with wall power where on-road power was supplied with a Honda 2200-watt generator secured in the space between the truck and the cargo. Prior to the chassis dynamometer and on-road testing, the brake data logger underwent a set of three one-minute-long warm up tests. This was necessary to record an averaged offset start time between the equipment and NIST official U.S. time. The data logger was three seconds ahead the NIST time and was adjusted for each chassis test and nine seconds for the on-road tests.

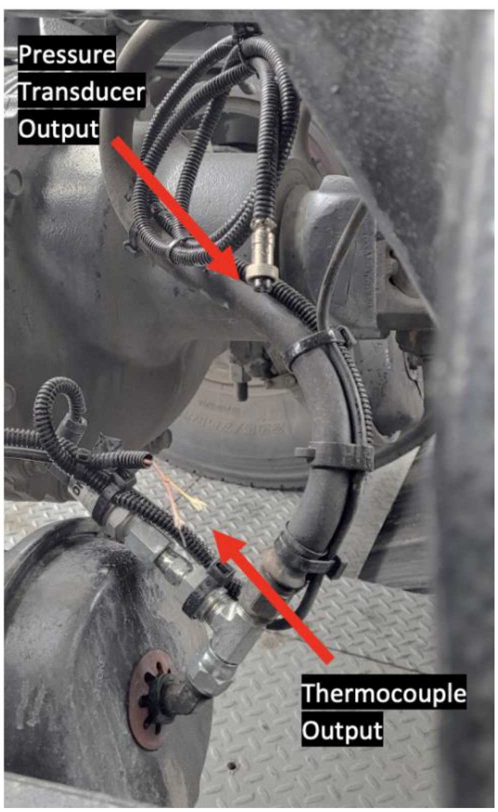

Figure 3. Pressure transducer and thermocouple connections right rear brake-wheel

Figure 4. Brake logger with temperature and pressure inputs

Test Procedure

In this study, chassis dynamometer tests and on-road tests were conducted to incorporate varying HDV driving brake loads. The chassis testing was utilized to compare brake activity with previous emissions testing activity. The on-road testing was selected in order to compare chassis testing to the real world. A summary of each test performed is shown in Table A1 of the Appendix section. For the chassis testing, the Central Business District (CBD) Cycle and the Urban Dynamometer Driving Schedule (UDDS) cycles were performed. The CBD cycle was performed four consecutive times which is similar to how emissions testing is performed. The first cycle is used as a warm-up, followed by three continuous CBD cycles. A single CBD cycle time duration is approximately 560 seconds and follows a sawtooth driving pattern with 14 repetitions of idle, acceleration, cruise, and deceleration modes, see Figure 9. The CBD is representative of a city bus or transportation vehicle driving patterns where frequent braking is observed.

The UDDS was performed three times where the first cycle was used as part of our analysis and did not have a preparation cycle since the vehicle and brakes were already warmed up, which is also similar to how emissions testing is performed. The UDDS is a chassis representation of the engine certification cycles so it is commonly used test cycle for HDVs. The UDDS represents heavy-duty vehicle urban driving conditions with varying acceleration, deceleration, and idle modes. A single UDDS cycle has a time duration of approximately 1060 seconds where the vehicle speed can range from 0 to 60 miles per hour, see Figure 16. Both the CBD and UDDS cycles were chosen to obtain pressure and temperature measurements of braking activity which varied in frequency and intensity. The chassis was configured for a total test weight of 65,000 lb which represents the tractor plus trailer weight. This weight was selected to match the on-road weight of the tractor trailer combination discussed next.

The real-world testing was performed on the road and was performed after the chassis testing to ensure the data measuring tools were working correctly. The HDV was driven along two different California routes. The first route, called the Local route, focused on local Riverside city streets shown in Figure 5 while the second route, called the Freeway route, was a longer distance route and included freeways from the city of Riverside to Victorville shown by Figure 6. During both on-road tests, the vehicle utilized a total test weight of 65,000 lb similar to that performed during the chassis testing.

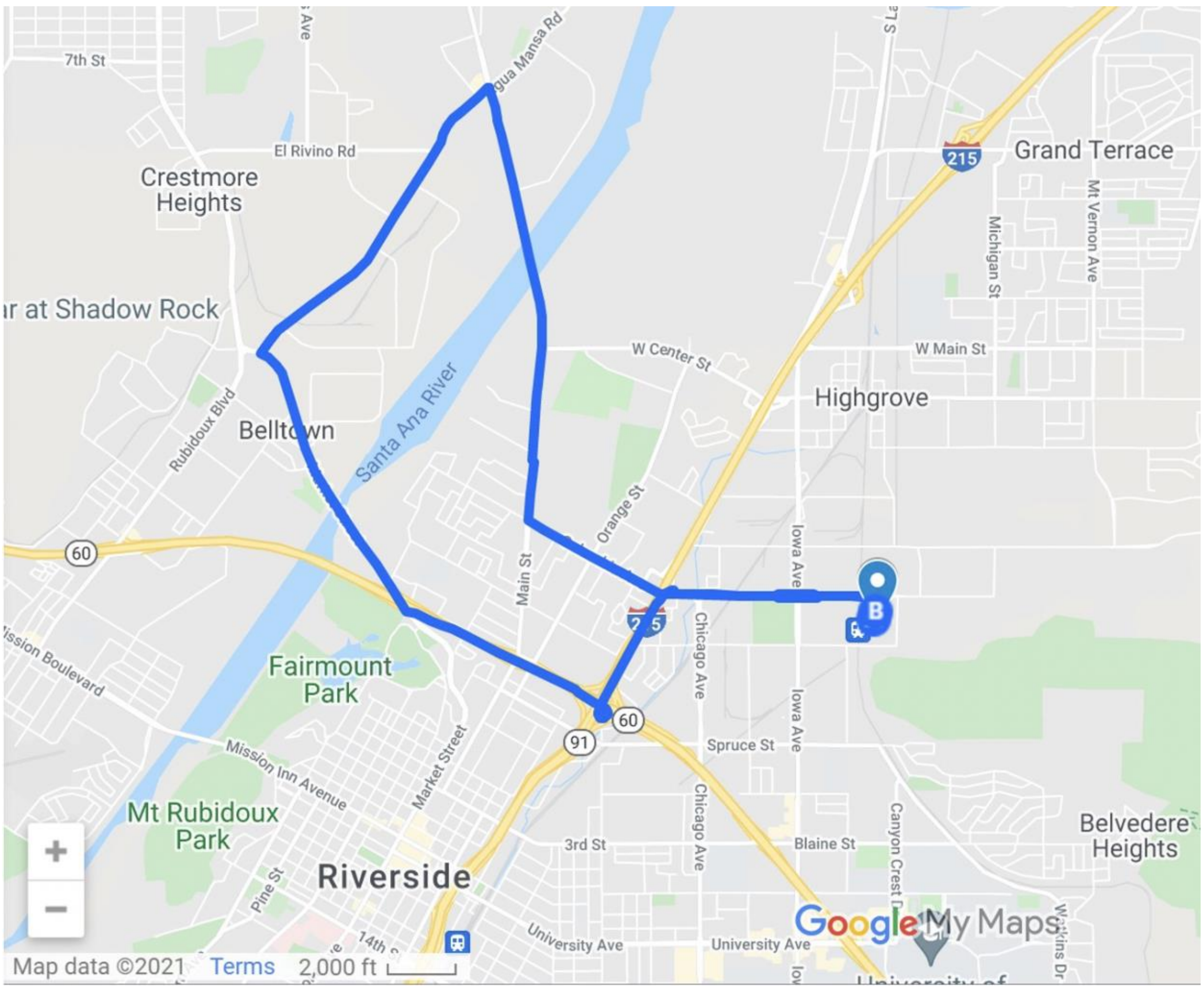

Figure 5. Local Riverside City on-road test route

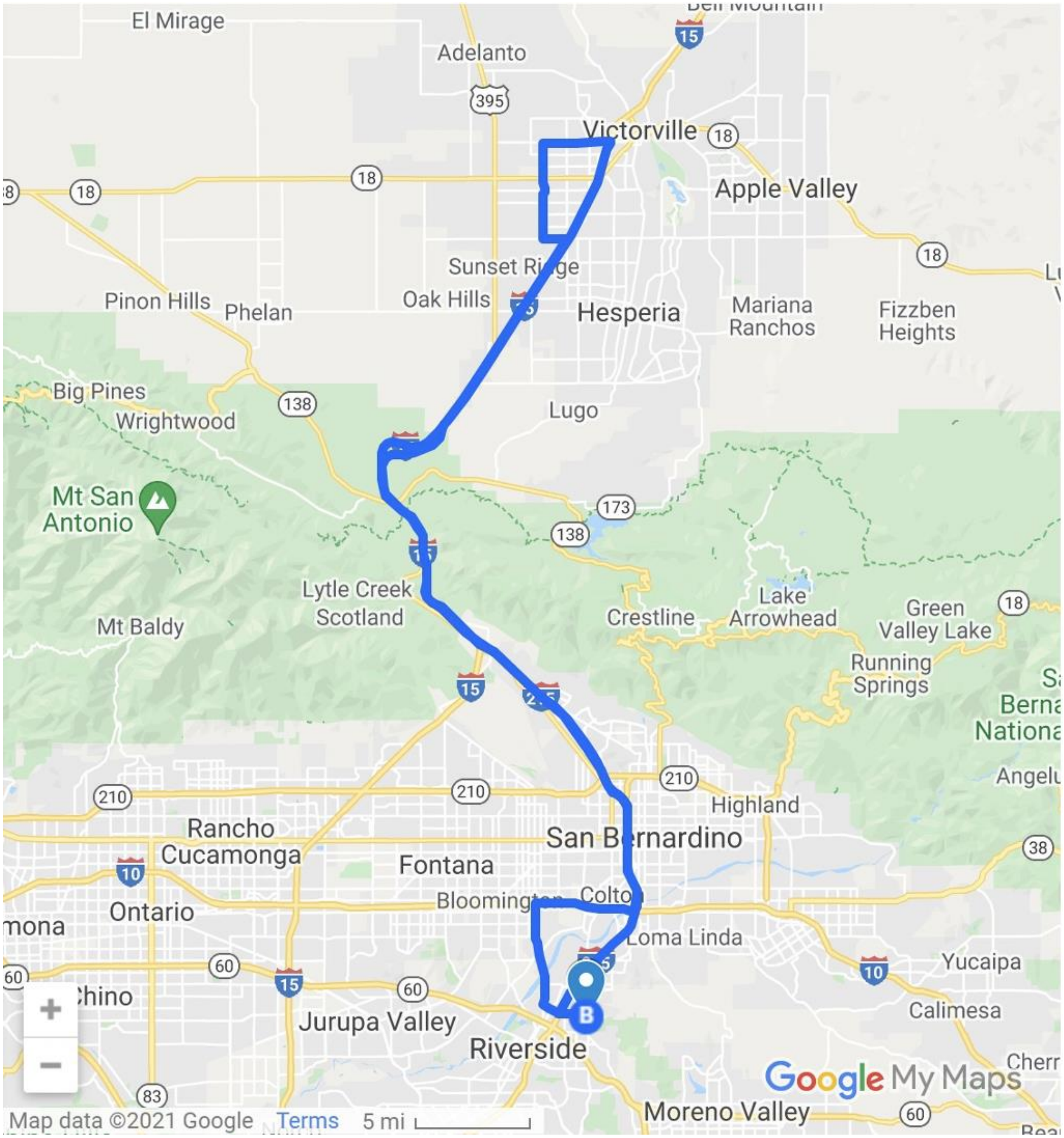

Figure 6. Long distance Riverside City to Victorville on-road Freeway test route

Results

Chassis Dynamometer Test

CBD: Figure 7 shows the vehicle speed results from the triplicate CBD test cycle where the speed increases and decreases from the 20 mph saw tooth test cycle. The speed profile represents 45 acceleration events and 42 braking events. Figure 8 and Figure 9 show right rear brake temperature and pressure results, respectively. The temperature sensor was showing signs of data dropout associated with an intermittent connection problem. The dropout data was filtered out and removed from the analysis. The brake temperature gradually increased in temperature from 60 °C to 130 °C. Three individual CBDs were performed prior to the test CBD which resulted in an elevated brake pad starting temperature from the ambient 15 °C to 60 °C , see the test log in Appendix A Table A1. The gradual increase in temperature shown in Figure 8 is expected since this represents the continuous and repetitive use of the brakes which then corresponds to increasing braking friction and, thus, a gradual increase in brake pad temperature. The actual ambient temperature during the chassis testing was between 40 and 55 °F, see Appendix A Figure A1. The vehicle speed is coupled with the braking pressure where speed follows an inversed sawtooth pattern compared to braking pressure. As the braking pressure is applied and reaches a maximum, vehicle speed respectively decreases reaching a minimum. During braking activity, the brake pressure varied from 20 psi to about 30 psi with one spike up to 38 psi which are all well below the 135 psi maximum rating of the HDV braking system, seeFigure 9. Figure 9.

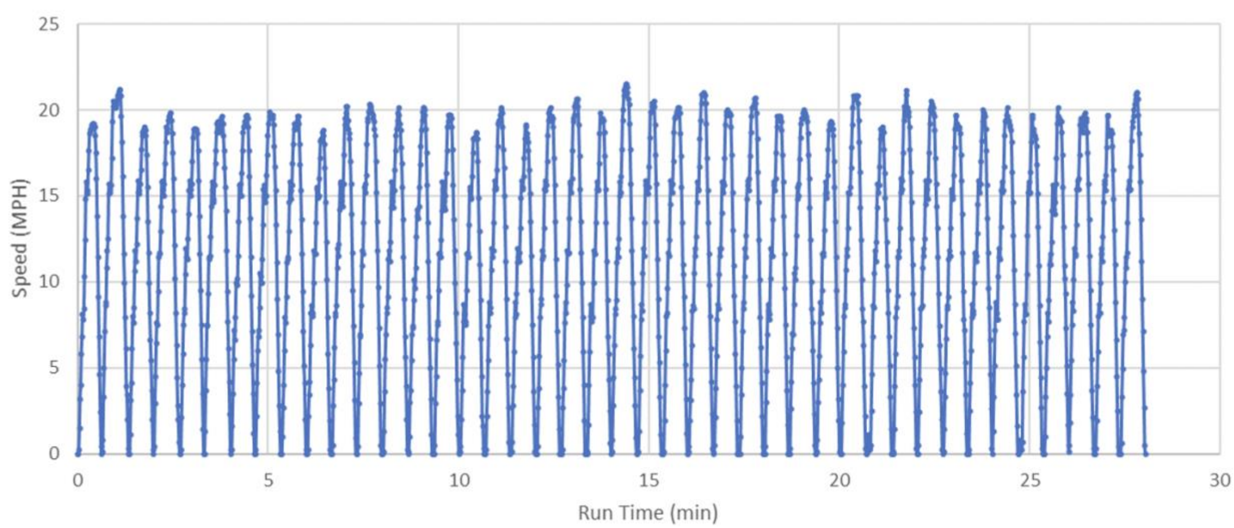

Figure 7. Vehicle speed in MPH for the CBD triplicate test cycle

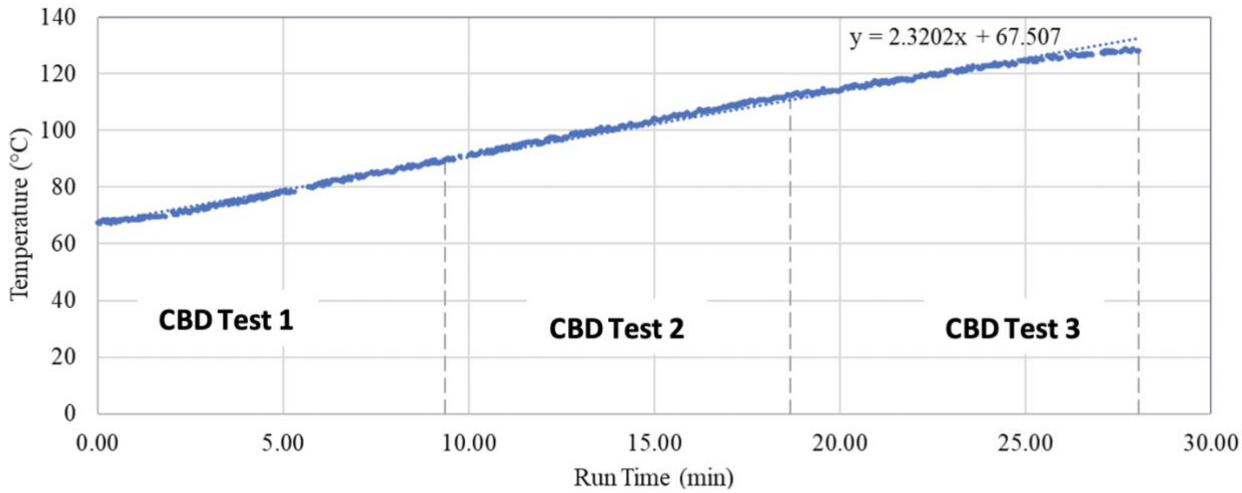

Figure 8. Brake pad temperature (right rear brake): CBD

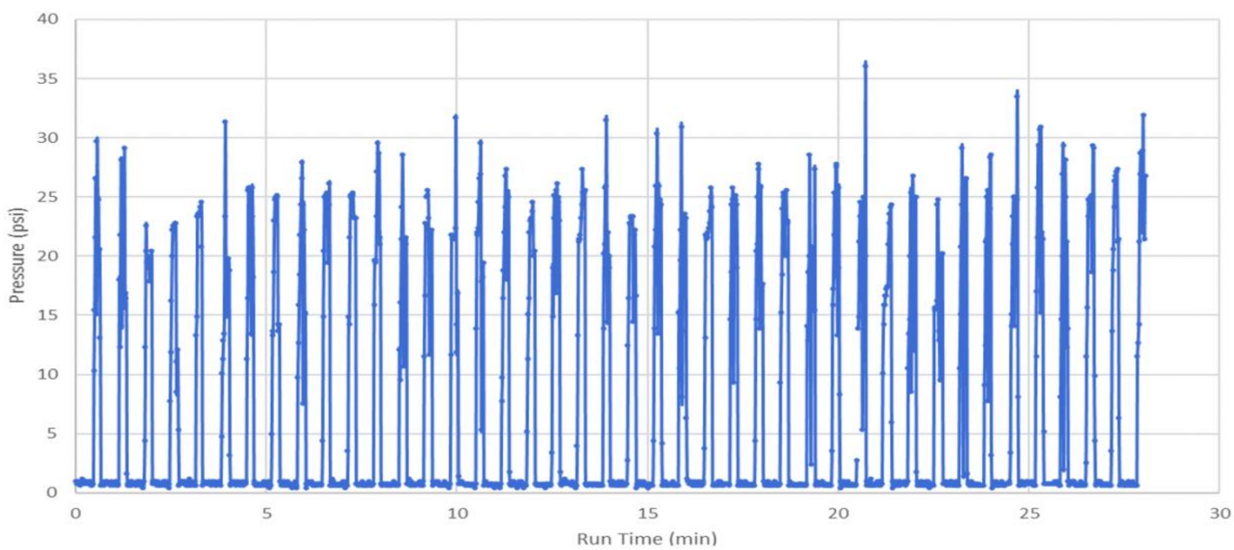

Figure 9. Brake pad pressure (right rear brake): CBD

The vehicle acceleration is shown in Figure 10 as a three second moving average to better observe braking activity deceleration trends. Negative acceleration values were approximately linear with respect to time with minimal variations in the CBD cycle. Braking activity was defined to be the range of increased braking pressure larger than 1.5 psi during which the speed was a non-zero value. This filters out high pressure events where the vehicle at a momentary stop and any events with decreased speed where the vehicle slows down without the use of brakes. The histogram in Figure 11 follows a bell curve shape with higher frequency in acceleration events within the -0.70 to -0.66 m/s^2 bin. Given the linearity of acceleration, kinetic energy (KE) lost in Joules (J) was estimated by using the initial and final recorded GPS speeds in m/s of each defined braking activity event. Values of kinetic energy lost (J) were multiplied by a factor of -1 to display positive numbers during deceleration events as shown in Figure 12. Average KE lost per braking event for the three consecutive CBD tests were 2.6E5 J, 2.7E5 J, and 2.6E5 J with standard deviations of 1.9E4 J, 2.4E4 J, and 2.2E4 J respectively. The histogram in Figure 13 depicts variations in frequency with a skewed distribution. This can be attributed to changing sawtooth speed profile peaks as the vehicle was controlled by a driver.

The total kinetic energy lost was used to compare the slope in braking temperature within each cycle run time. This ratio was divided by the number of brakes (n=4) installed in the test vehicle. 2.4E-5 °C/J, 2.3E-5 °C/J, and 2.3E-5 °C/J were obtained for the three consecutive CBD tests. These values are likely a slight overestimate as we assumed equal distribution of kinetic loss between rear and front brakes.

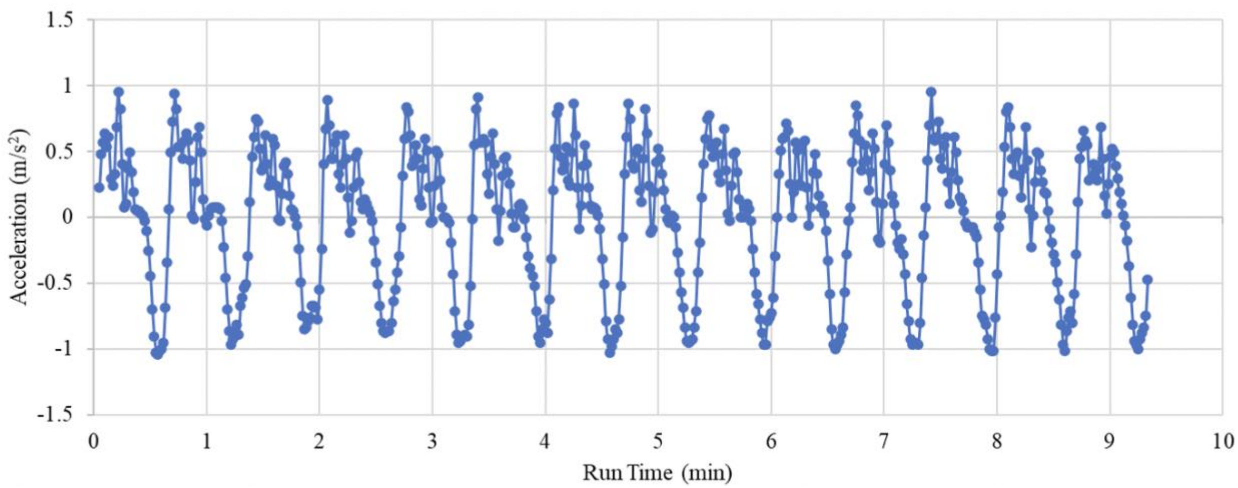

Figure 10. Moving average acceleration (m/s^2) for the 1st CBD cycle

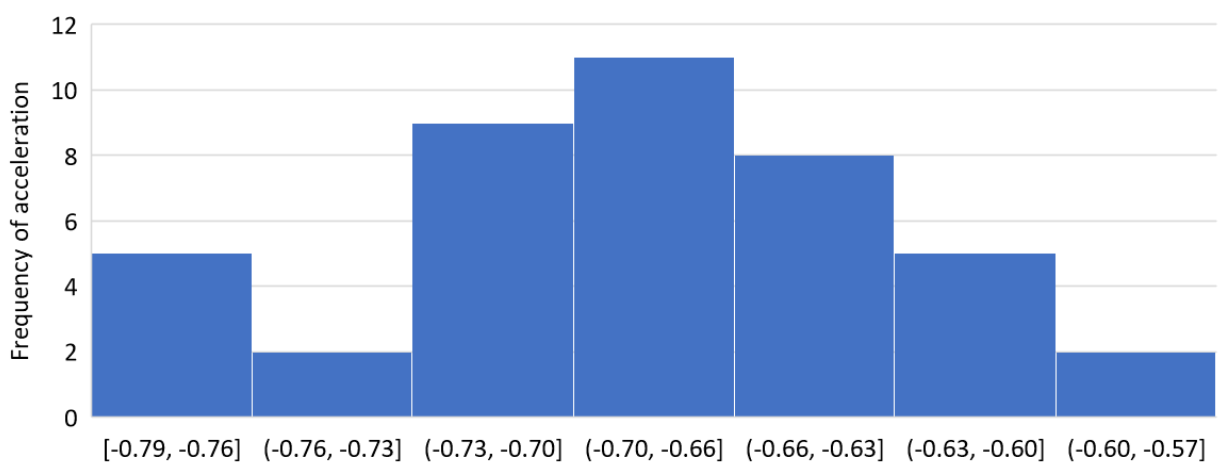

Figure 11. Average acceleration (m/s^2) histogram for braking activity: CBD

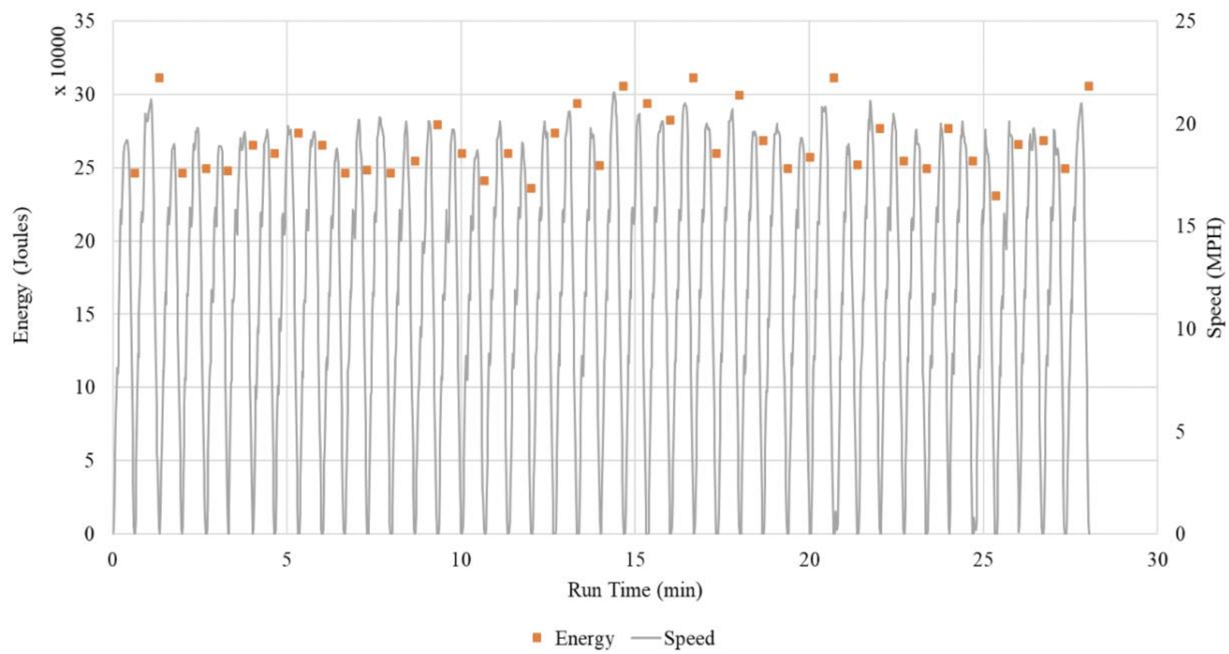

Figure 12. Braking event energy: CBD

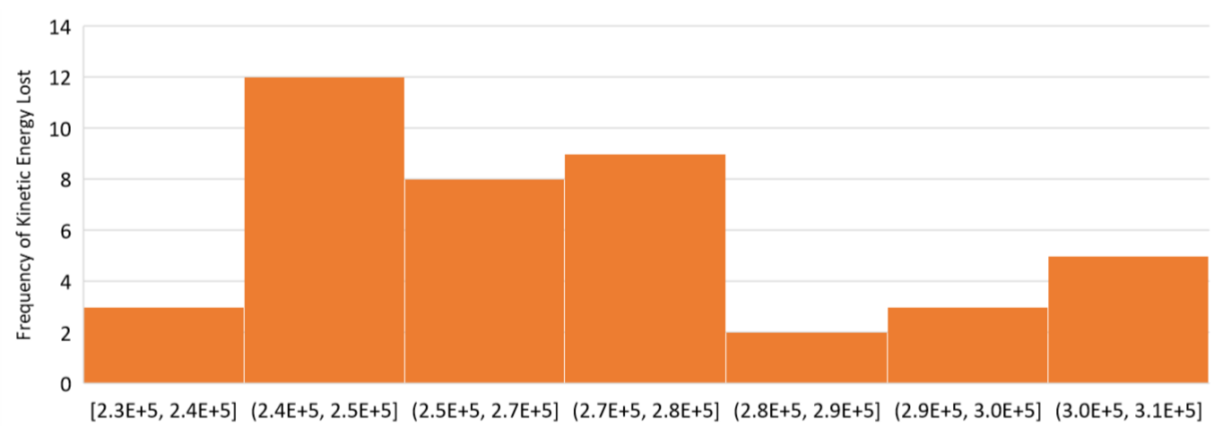

Figure 13. Histogram of the Kinetic Energy lost during braking activity: CBD

UDDS: Figure 14 shows vehicle speed for the triplicate UDDS test cycle and Figure 15 and Figure 16 show the left rear brake temperature and right rear brake pressure results, respectively. We switched from the right to the left temperature sensor due to the temperature drop out issues discussed earlier, however, the temperature dropout problem was also present on the left sensor as well. This suggest the problem is not with the sensor, but possibly with the data logger. The same temperature filtering was performed on the left sensor. The UDDS brake temperature started out at a high initial temperature of 135°C since the UDDS testing followed the CBD testing. Note, there was only a 20-minute delay between the CBD and UDDS tests where the brakes may not have had time to cool down. The temperature profile for the UDDS tests showed a gradual increase in temperature with some decreasing trends associated with varying braking pressure events, see Figure 15. During active braking, the brake pressure varied from 10 psi to about 30 psi with one spike up to 45 psi, see Figure 16.

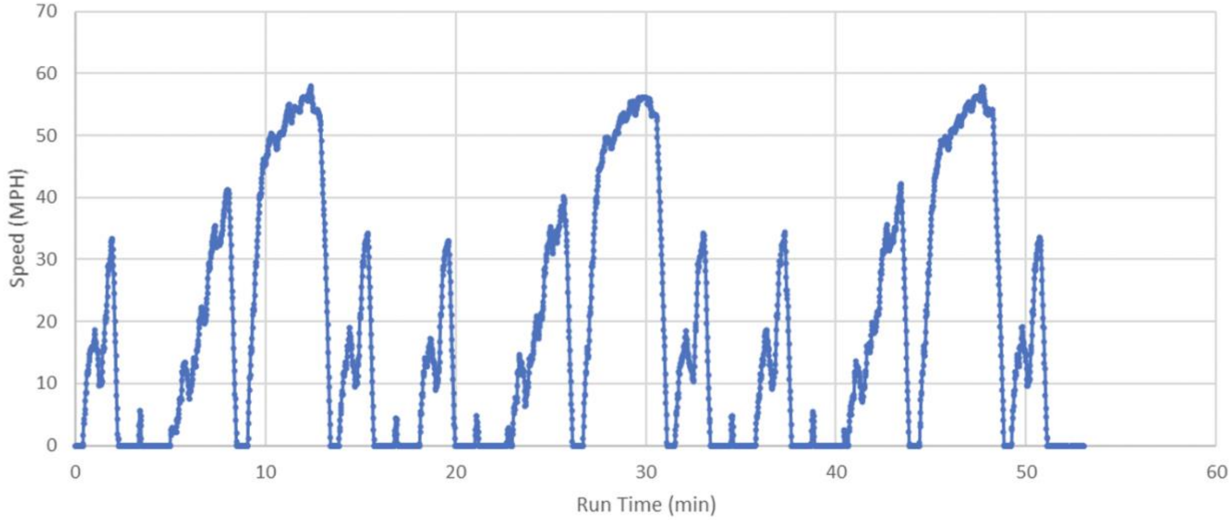

Figure 14. Vehicle Speed in MPH during triplicate UDDS test cycle

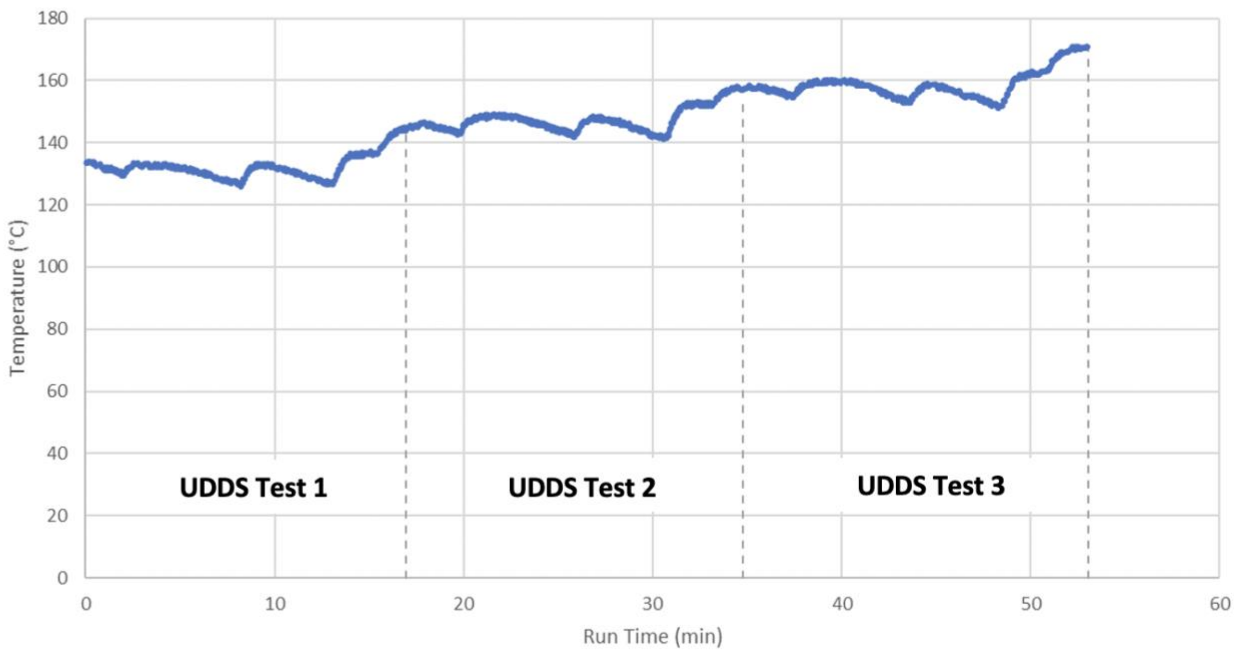

Figure 15. Brake pad temperature (left rear brake): UDDS

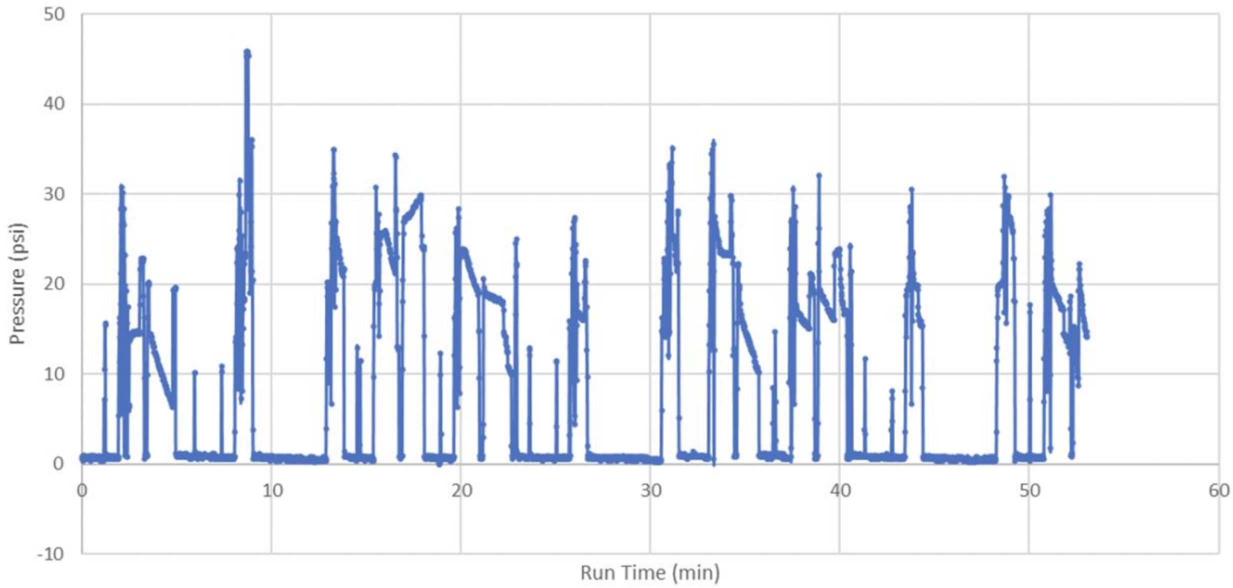

Figure 16. Brake pressure (right rear brake): UDDS

A histogram of the average acceleration (m/s^2) during the three UDDS cycles is shown in Figure 17. The UDDS braking events has two main frequency modes, one in the -0.76 to -0.69 m/s^2 bin and a second one in the -0.48 to -0.35 m/s^2 bin. The two mode observation may be the result of the different distinct speed profile of the cycle. Within each major speed peak, there exist smaller deceleration events which cause increased frequencies in the -0.55 to 0.48 m/s^2 bin and -0.35 to -0.28 m/s^2 bin. As a result, the braking event energy ranged from 3.2E3 to 2.0E6 J, see Figure 18.

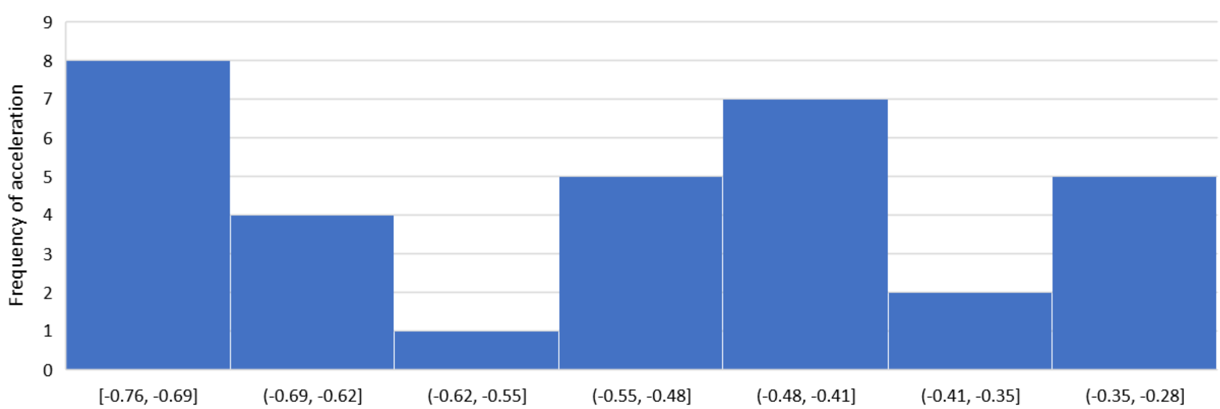

Figure 17. Average acceleration (m/s^2) histogram: UDDS

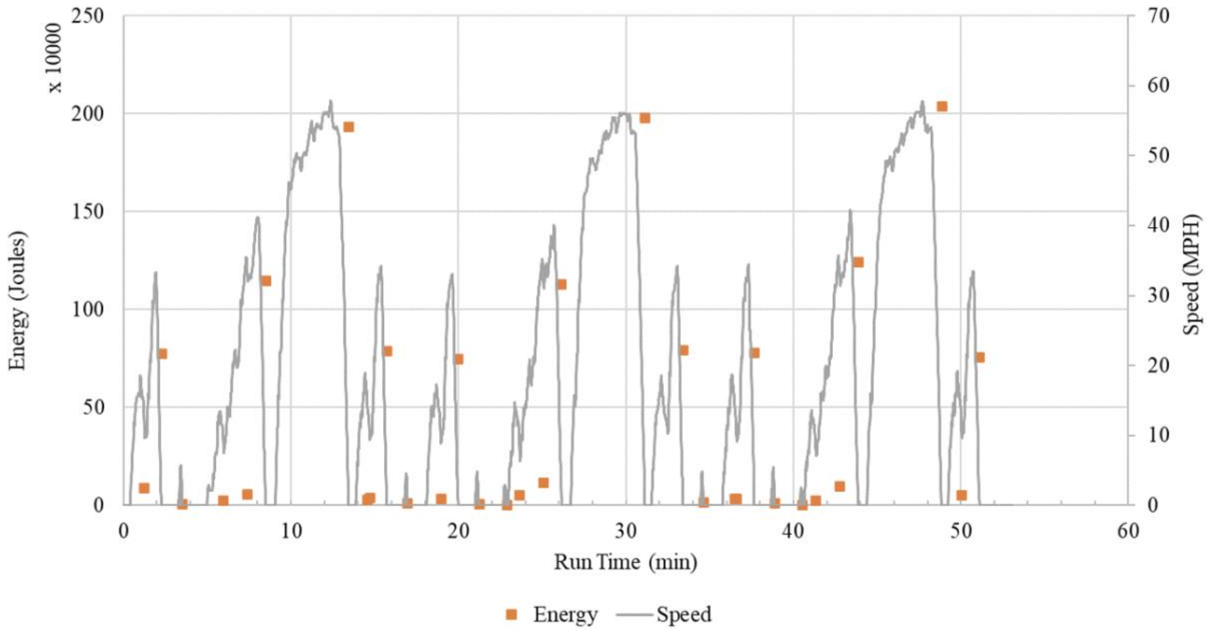

Figure 18. Braking Event Energy: UDDS

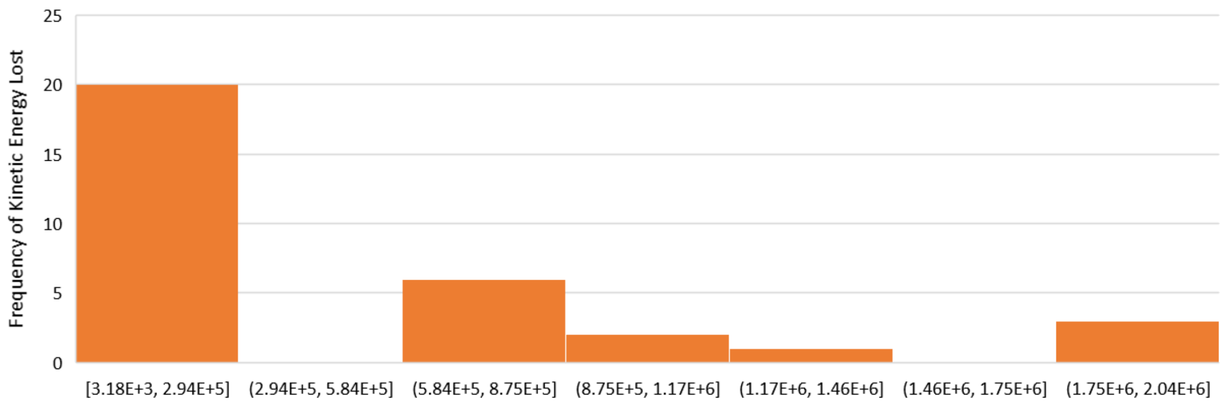

Figure 19. Histogram of the Kinetic Energy lost during braking activity: UDDS

On-Road Tests

Two routes were selected for the on-road testing while pulling a trailer which provided a total vehicle+trailer weight of 65,000 lb. One route was a local Riverside city route that included slower speeds representative of local deliveries. The other was a longer distance freeway route from Riversity to Victorville to represent freeway speed driving. The local route was designed to have more urban operation to obtain data with speeds below 40 MPH and frequent braking activity. The freeway route was designed to provide brake activity under higher speeds found when exiting a freeway and when going down a grade. For the on-road routes, the left rear brake temperature and right rear pressure measurments were utilized. Similar data filtering was utilzed for the brake temperature as described ealier. The Kinetic Energy lost and braking event energy were defined the same as with the chassis testing.

Local Route: Figure 20 shows the vehicle speed for the GPS and backup ECU wheel-based speed measurments for the local route. The GPS data was limited due to a connection issues resulting in data loss for all but the end of the test. The redundant ECM vehicle speed measurements also showed periods of drop out unfortunately. The ECM wheel-based vehicle speed was used in areas where GPS data was missing. Figure 21 and Figure 22 show the brake temperature and pressure measurements. The temperature started out at 10 °C matching the ambient conditions for the day and increased up to 60 °C at the end of the local route. The pressure ranged from 10 psi to 20 psi with a few spikes as high as 33 psi. The pressure spikes are similar to the chassis testing.

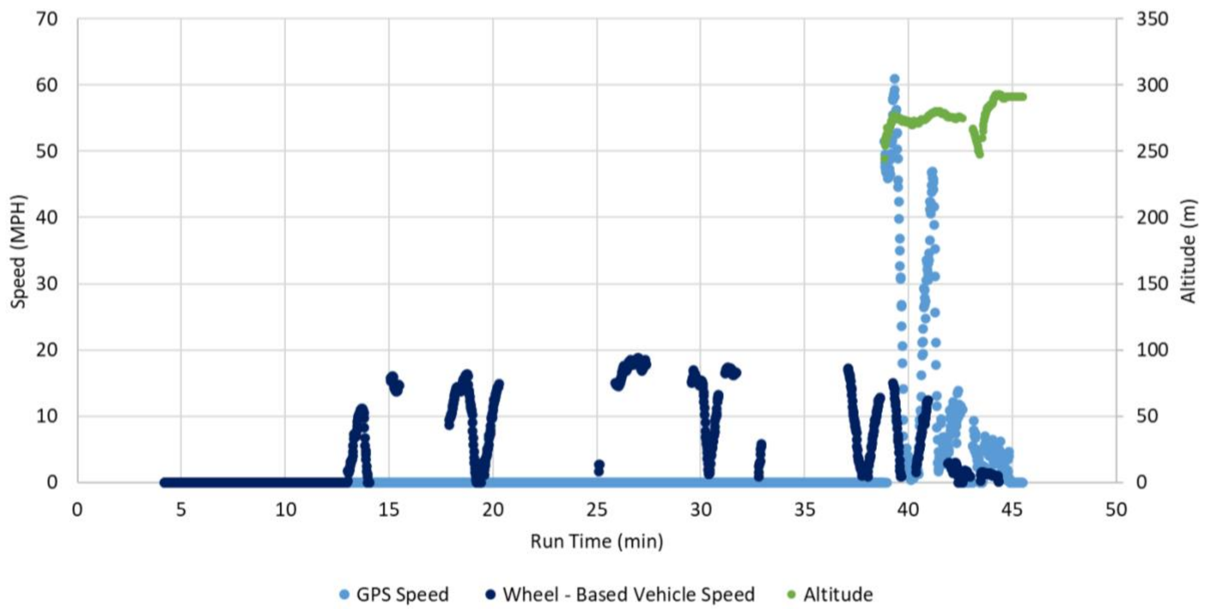

Figure 20. Vehicle speed in MPH and Altitude in meters: Local

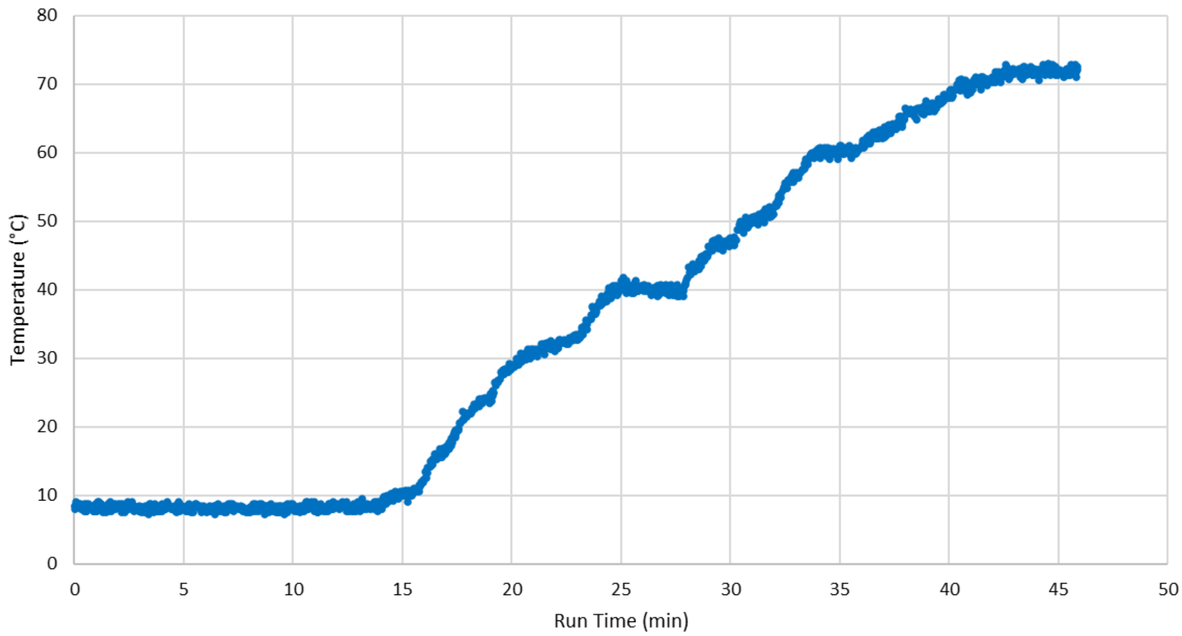

Figure 21. Brake temperature (left rear brake): Local

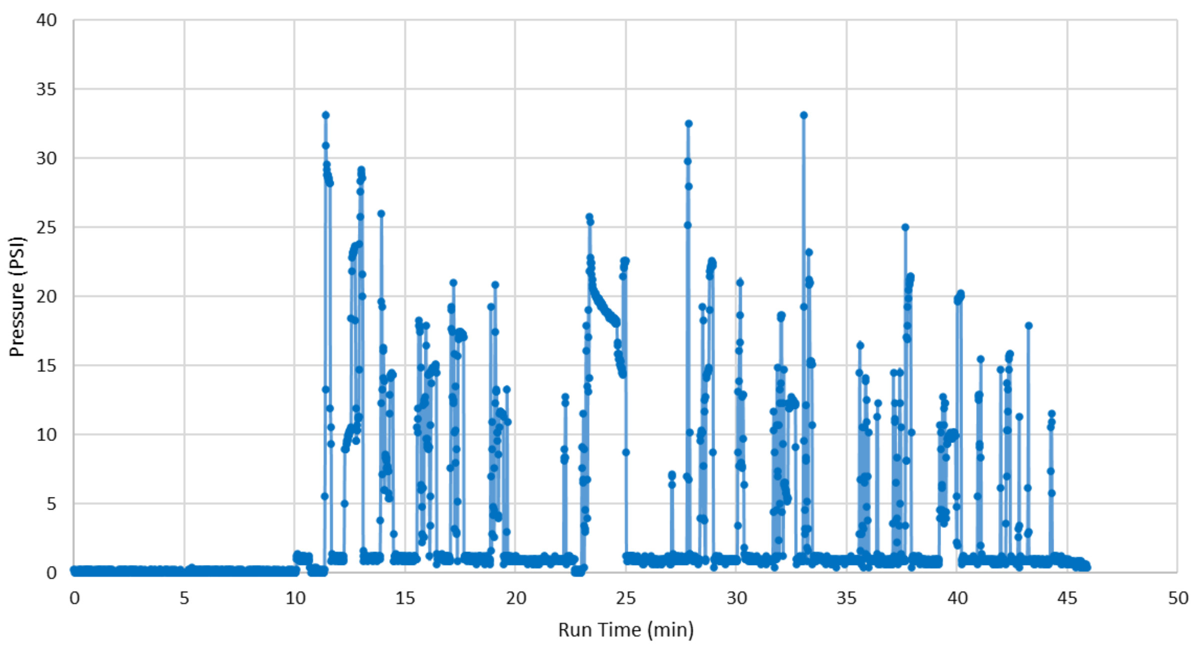

Figure 22. Brake pressure (left rear brake): Local

The average acceleration had a higher frequency ranging from the -4.43E-1 to -2.56E-2 m/s^2 as shown by the histogram in Figure 23. The braking event energy lost is shown in Figure 24 and the histogram in Figure 25. The braking energy lost suggests a higher frequency in the -7.33E5 to 1.43E6 Joule bin compared to the chassis testing.

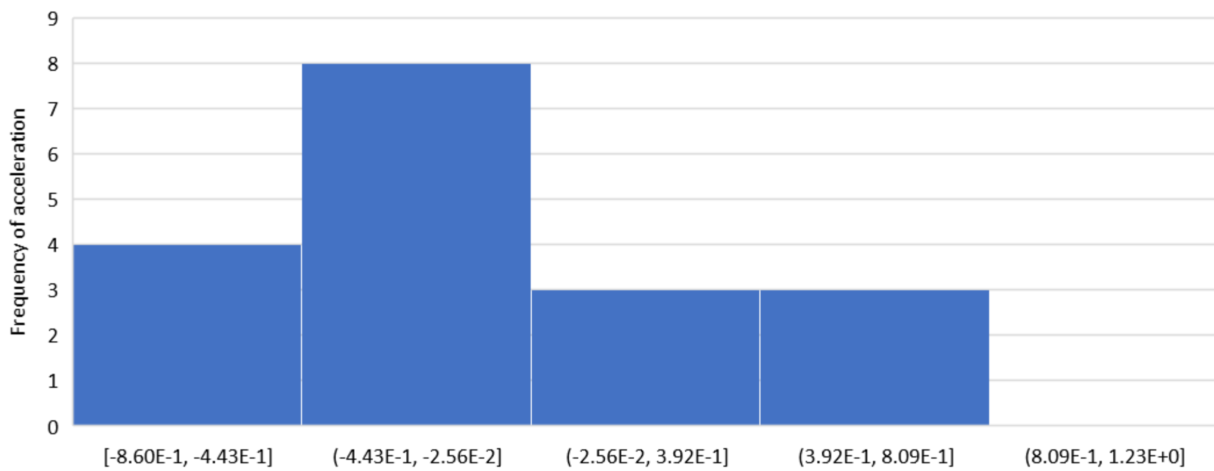

Figure 23. Average acceleration (m/s^2) histogram for braking activity: Local

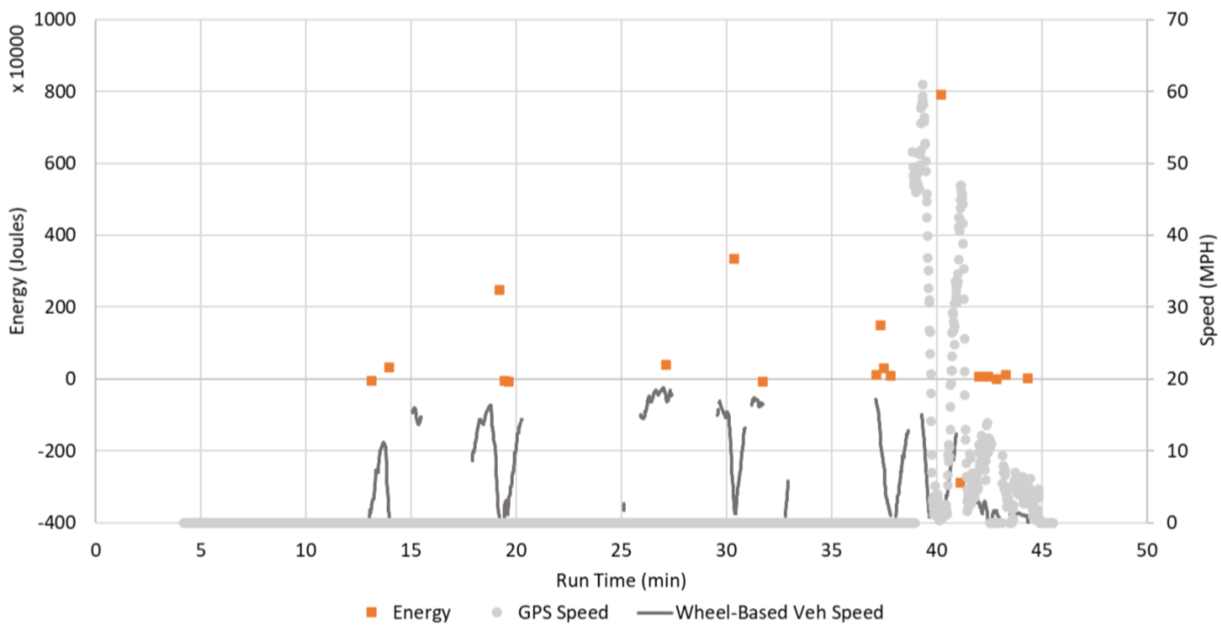

Figure 24. Braking Event Energy: Local

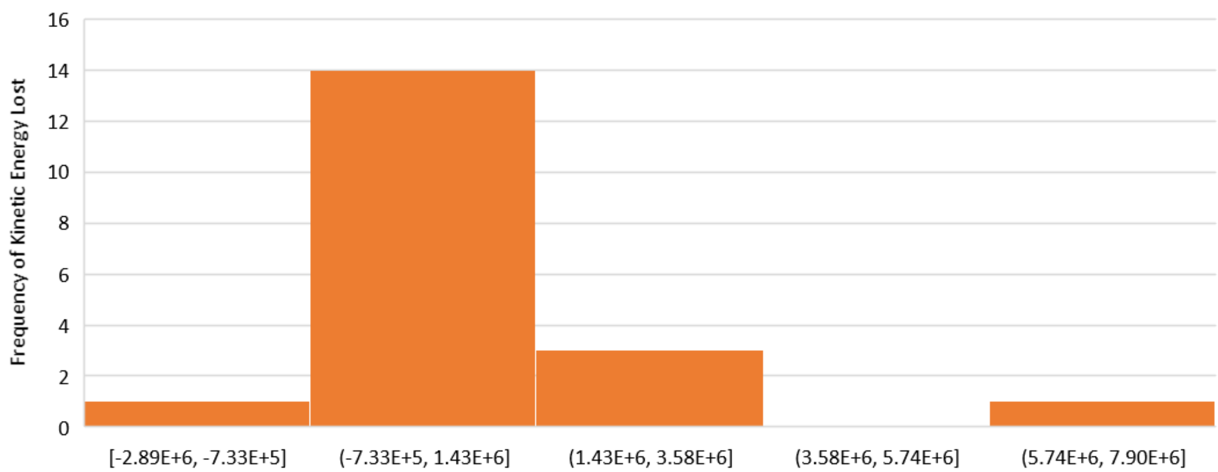

Figure 25. Histogram of the Kinetic Energy lost during braking activity: local route

Freeway Route: Figure 26 shows the GPS vehicle speed for the freeway route where the brake temperature and pressure are in Figure 27 and Figure 28, respectively. The brake temperature showed an increasing trend over the freeway route with a few periods of brake cooling. The brake pressure was the highest during the freeway testing and was typically around 20 psi with several spikes over 30 psi and one up to 39 psi. The brake pressure averaged 20 psi during the downhill grade in the middle of the route suggesting downhill brake pressure is similar to other stop and go brake pressures for a truck loaded at 65,000 total lb.

Figure 29 shows the braking activity acceleration and the braking energy is shown in Figure 30 where positive energy values correspond to braking events with initial speed larger than the final speed. The negative kinetic energy values are of importance because when the brake pressure was applied, the final speed of that braking event showed a larger speed than that of the initial speed. The negative energy may be due to changes in road elevation where brakes are applied but the vehicle increases speed while traveling downhill. The histogram of kinetic energy is shown in Figure 31. The most frequent values of kinetic energy lost are in the -1.92E6 to 2.36E6 Joules. The kinetic energy loss for the on-road tests are one order of magnitude larger than that of the dynamometer tests as the vehicle decelerates from speeds that are 2-3 times larger.

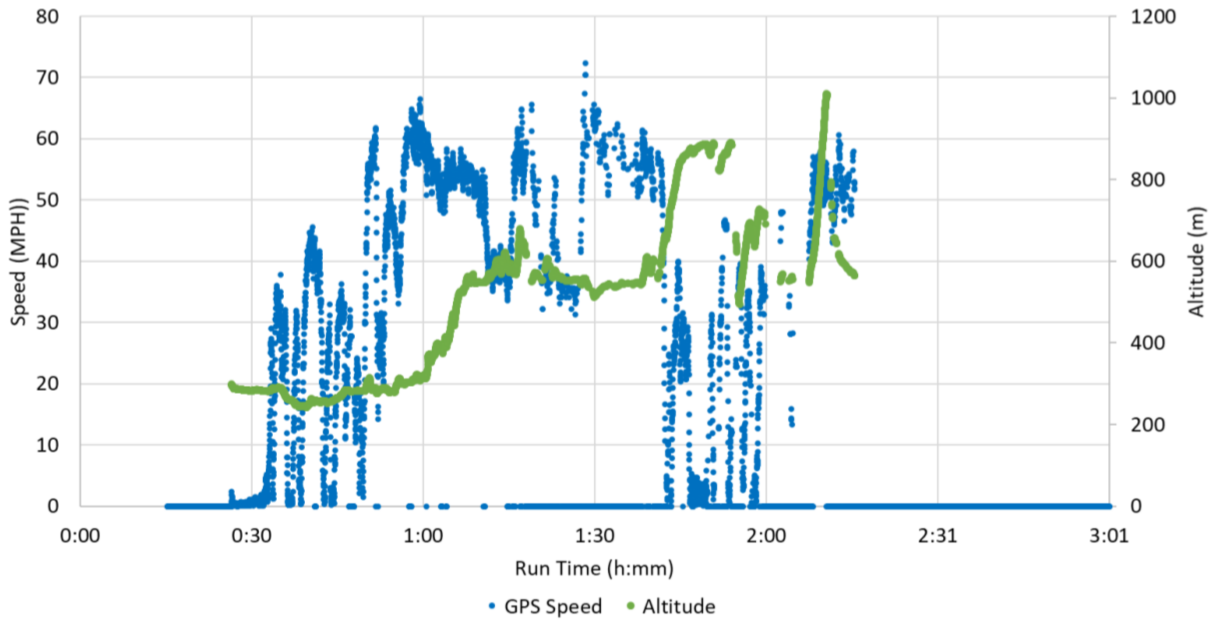

Figure 26. Vehicle speed in MPH: Freeway route

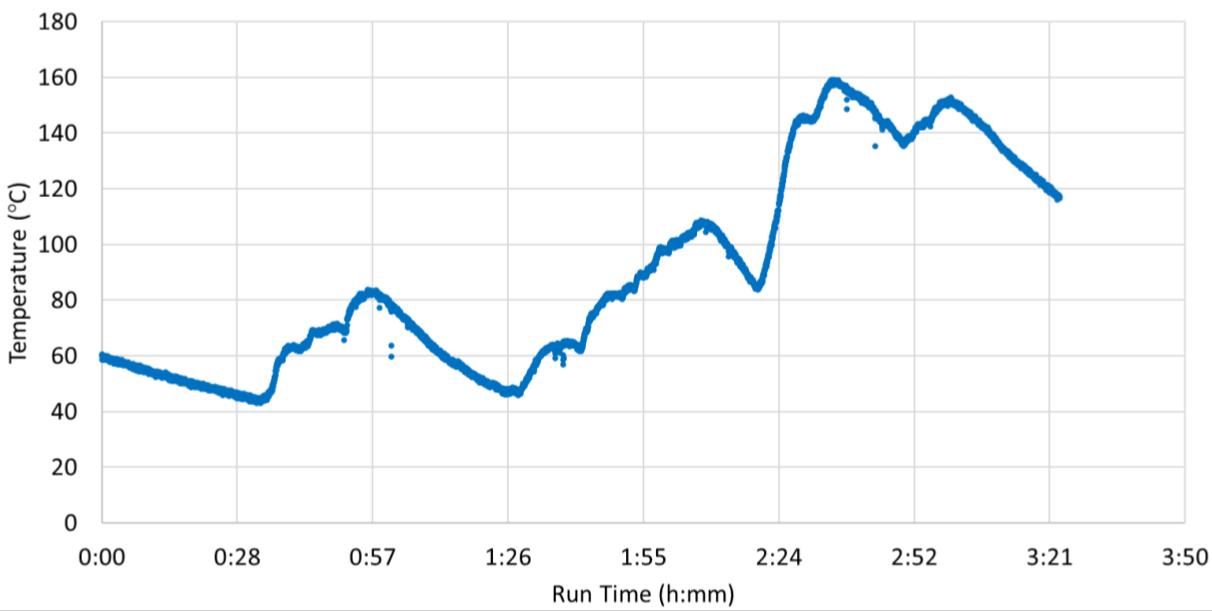

Figure 27. Brake temperature (left rear brake): Freeway route

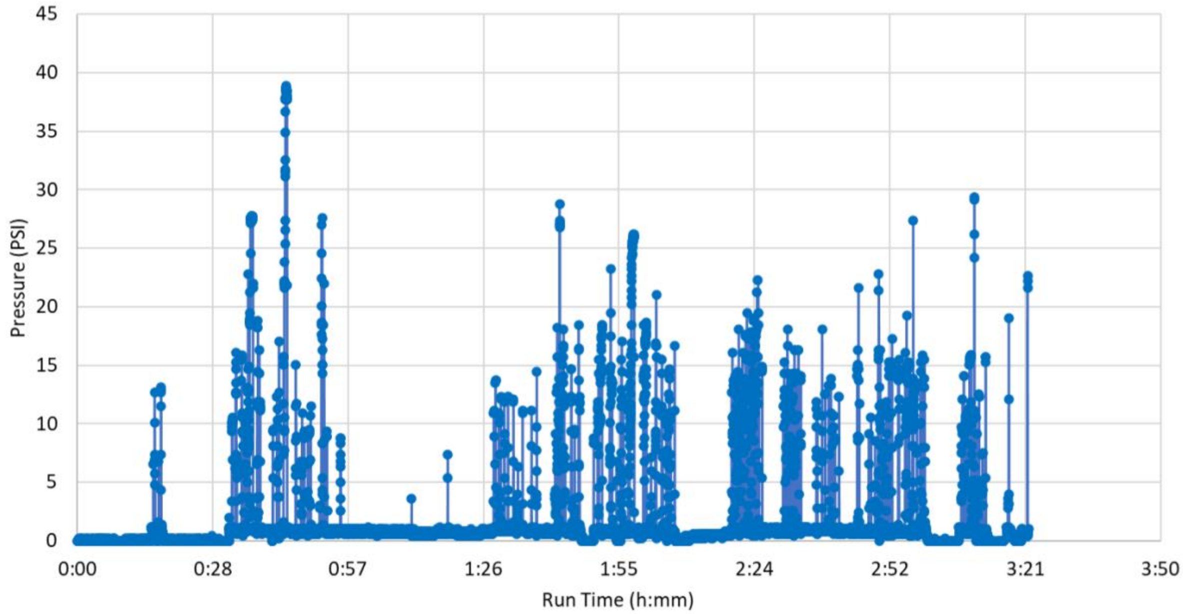

Figure 28. Brake pressure: Freeway route

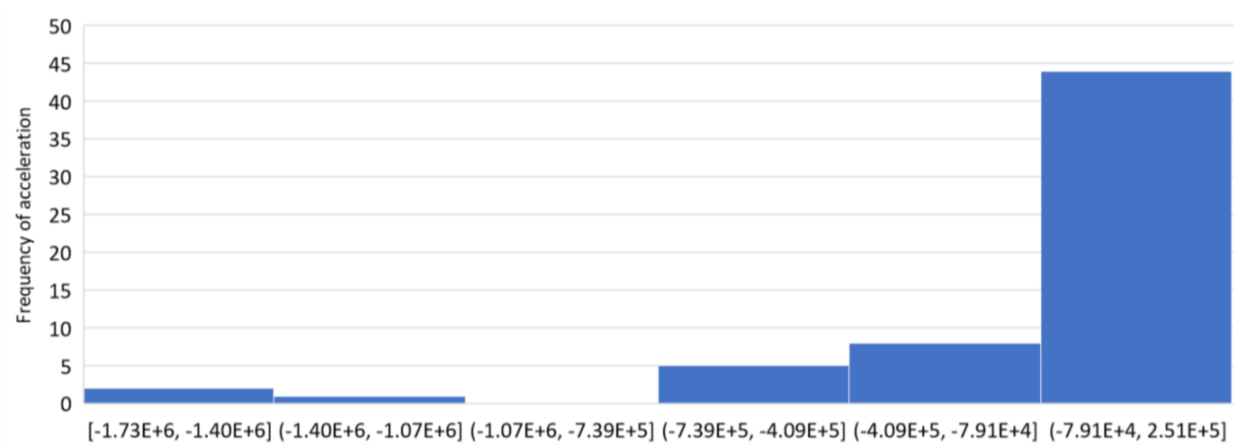

Figure 29. Average acceleration (m/s^2) histogram for braking activity: Freeway route

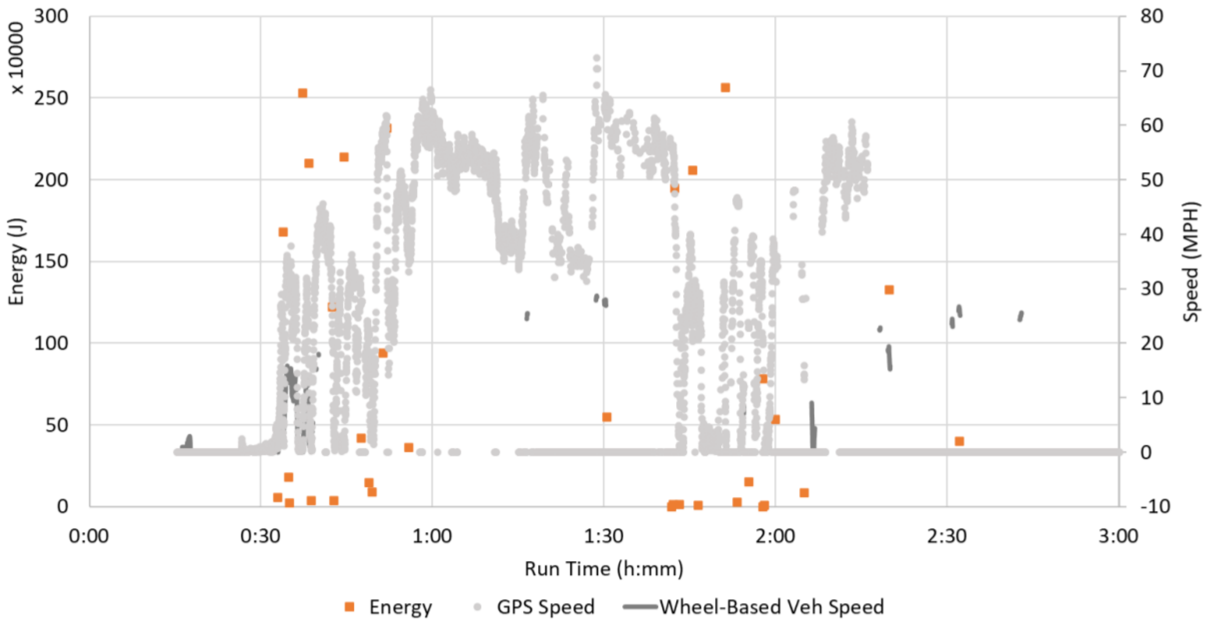

Figure 30. Braking Event Energy: Freeway route

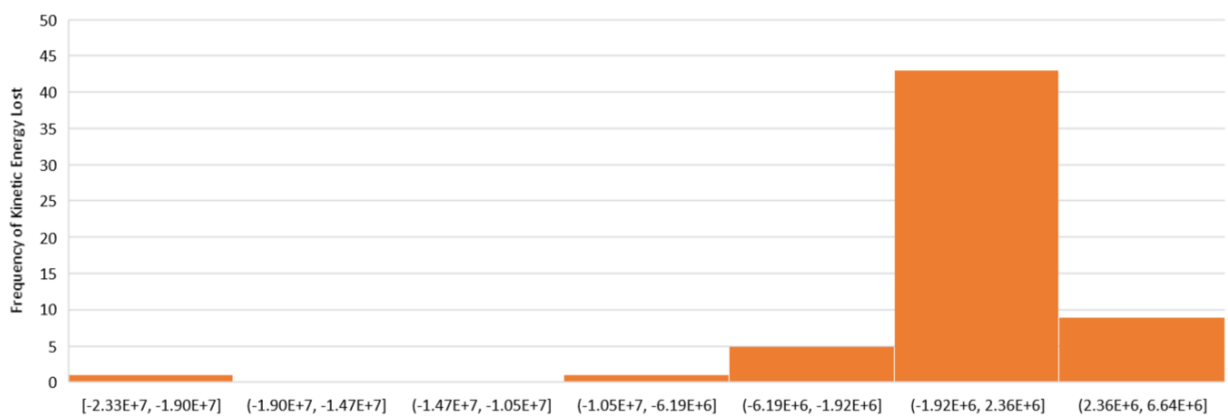

Figure 31. Histogram of the Kinetic Energy lost during braking activity: Freeway route

Bench top laboratory testing

The chassis and on-road brake testing showed relatively low brake pad temperatures based on discussions with our brake service company [7]. This suggests something may be wrong with the installation of the temperature measurement system where either the targeted 2 mm distance was off or the temperature probe design was a problem. As such, a lab experiment was setup to evaluate the temperature probe in the “as-found” condition. The “as-found” sensor was then also compared with an exposed tip temperature probe and with a modified sensor installation depth. All of these conditions were designed to evaluate differences in brake surface temperature estimates. A heat source utilizing a 3” diameter blue flame from a camping stove with the brake supported approximately 1” over the flame source was setup, see Figure 32 and Figure 33.

Figure 32. Brake setup with blue flame heat source. Note: The butane camping stove was setup to produce a 3” diameter blue flame ~1” from the surface. Data was logged with a CR10x data logger.

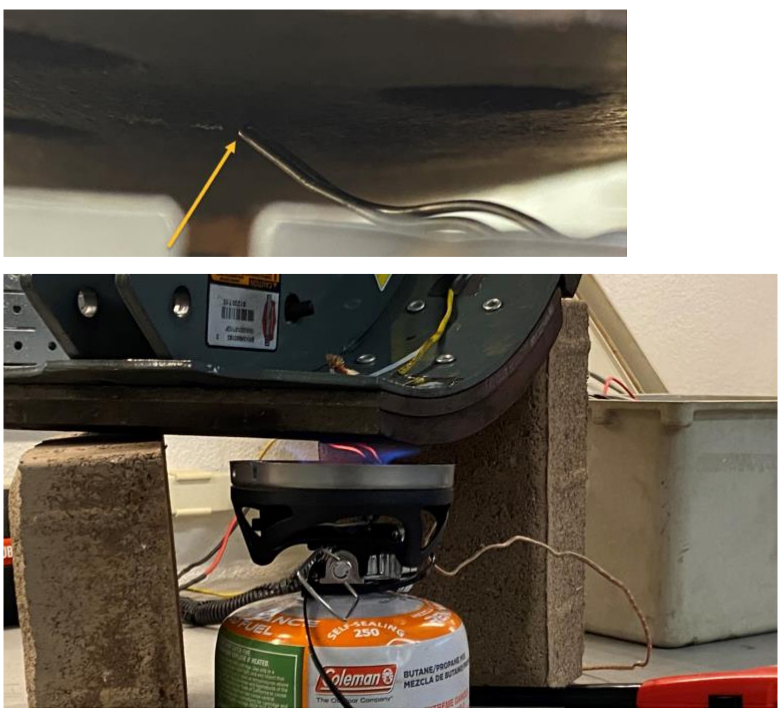

Figure 33. Measurement of the brake pad surface temperature for consistent heat input. Note: This figure shows the detail of the exposed tip forced up against the brake in the top picture and glowing red in the lower picture.

The modified probe was an exposed junction probe to evaluate the true heat transfer from the brake surface to the location of the temperature probe. This type of probe may not work in a vehicle application where some type of cap is needed to protect the tip during braking activities. Since the “as-found” probe was secured with an epoxy glue the plan was to evaluate the existing system first then remove the existing probe then install an exposed junction temperature probe. Then verify the actual depth and modify the depth to something closer to 2 mm if it is off, see sketch in Figure 34. Figure 35 shows a photo of the two types of thermocouples tested in the bench testing. The top one is the exposed tip type of probe and the second is exposed tip capped with a copper tube. The latter was used for the chassis and on-road testing. The longer cap was recommended from the probe designer given his durability concern.

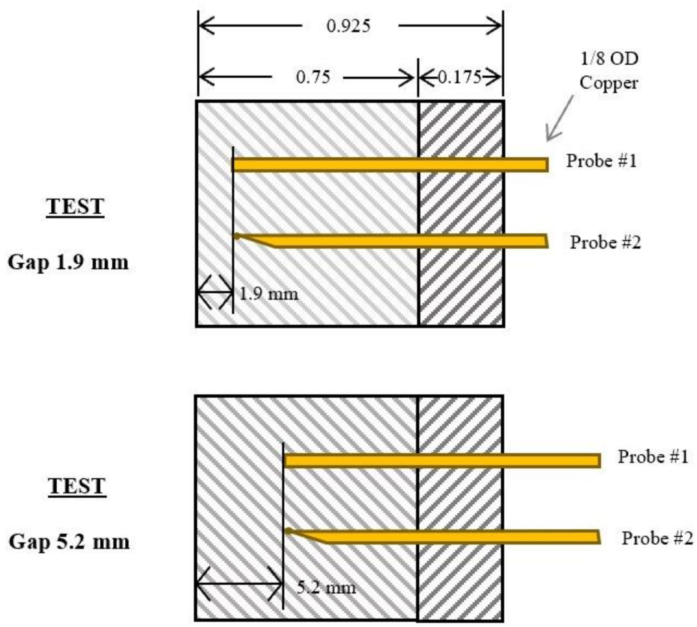

Figure 34. Cross section diagram of thermocouple installation

Figure 35. Probe tips: brake test probe (bottom) used in the study and exposed tip (top).
Note: Probe used is a 1” cu by 1/8 diameter with 0.035 wall

Figure 36 shows lab results for the two different probes and at three different depts from 5 mm to 0 mm. The 0 mm was estimated from the 5 and 2 mm depts tests and was not measured. The temperature presented was the maximum temperature reached after 2 minutes. The exposed tip thermocouple showed a much higher temperature by almost 100 C compared to the copper capped thermocouple. We attribute this to the long copper cap exchanging heat along the linearly decreasing temperature away from the heated surface. The copper capped thermocouple measured a somewhat averaged temperature along the brake pad depth. At the lab test condition where heat flux was relatively constant the difference between the exposed tip and Cu probe was about 100 °C to 150 °C.

Post correction of the temperature with Cu probe is possible, but because the calibration could change as a function heat flux it is unclear how best to incorporate these corrections. The heat flux is a variable of brake pressure and cooling loads during non-braking events. Some empirical correction might be possible if one were to relate kinetic energy loss to heat flux but it is recommended to redo the test with a redesigned thermocouple probe in the future for better accuracy.

However, given the large difference demonstrated by the bench top experiment, the data presented in this report suggest braking temperatures may be low by around 100 C.

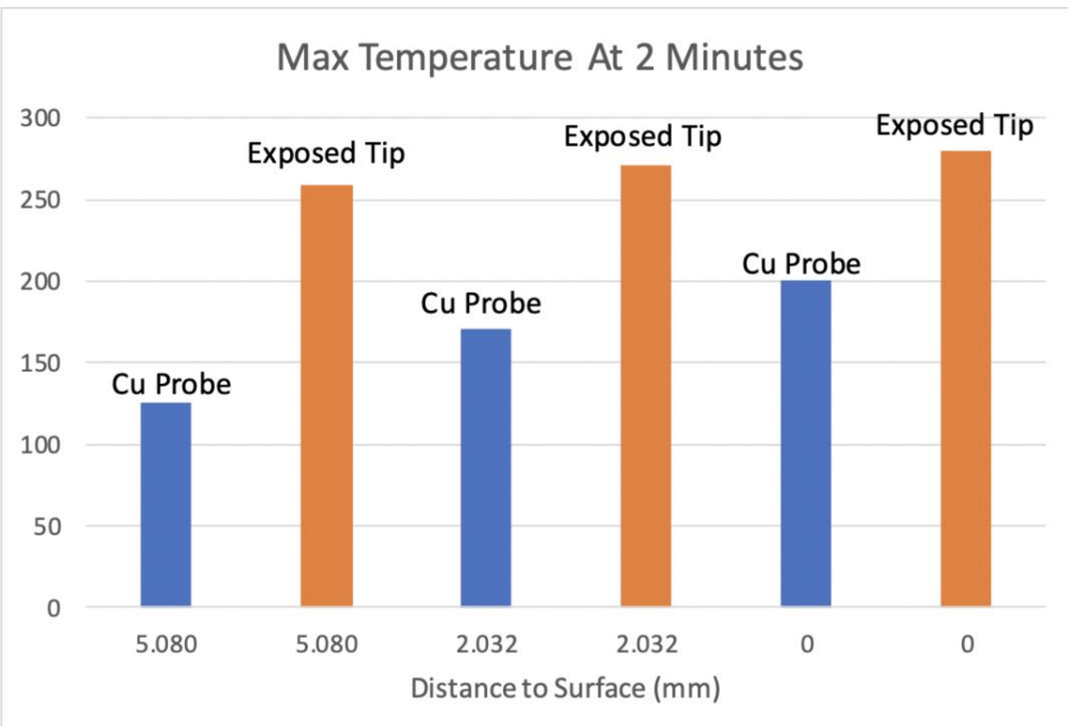

Figure 36. Maximum temperature measured during the 2 min heating cycle for RT plot

Summary and Conclusion

Brake activity was measured for two laboratory cycles (CBD and UDDS) and two on-road routes utilizing a heavy-duty vehicle along while measuring brake fluid pressure and brake pad temperature. Brake emissions is an emerging area of interest to regulators and investigators where brake activity data is limited and needed for the estimation of brake emissions inventory.

Key take always:

- The brake activity widely varied between laboratory cycles and on-road test.
- It should be noted brake activity from the same vehicle can vary as a function of hauling load.
- Brake pressures ranged from 20 psi typically up to a maximum of 45 psi.
- Brake temperatures ranged from 60C to 160C where it is possible the maximum temperature could be over 260C if the correct temperature probe were utilized.

We recommend the following future work:

- utilize an exposed tip thermocouple to measure brake pad temperature at the targeted depth of 2 mm.
- simultaneous measure the brake particle emissions along with brake activity to find relationship between brake activity and brake particle emissions.
- measure brake activity for vehicles with different vocations such as sweeper vehicle, buses, trucks as well as other applications.

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Data Summary

Products of Research

The research team collected brake activity data of a Freightliner Cascadia MY2015 heavy-duty vehicle for two chassis dynamometer tests and two on-road driving tests. Each test required the use of a brake data logger created for the purpose of this project which recorded temperature from thermocouples installed below the surface of the rear drum brake pads, as well as pressure from a sensor installed along the brake line of the rear passenger side. Additionally, during each test, an OBD2 HEM logger acquired vehicle parameters from the engine control unit (ECU) including GPS data such as latitude, longitude, altitude, and velocity. The heavy-duty chassis dynamometer (HDCD) system monitored various parameters such as test run times, vehicle speed, front and rear roller speeds, and acceleration torque, force, and power. Road load forces used for the simulated cycles were set at 461.6583 lb (A), -1.07E-14 lb/MPH (B), and 0.205953 lb/MPH^2 (C).

Data Format and Content

The brake logger raw data files were output as comma separated values (CSV) which contain second by second cold junction compensation temperature in °C, brake temperature in °C, pressure sensor voltage, and pressure in psi. A total of 21 Files were saved as DATAXX.CSV where XX ranged from 23 to 43. Files numbered from 23 to 35 pertain to chassis dynamometer tests while 36 to 43 pertain to on-road driving tests. The Logger_Notes.pdf details which files were used for warm up tests, troubleshooting, and cycle or on-road testing.

During Chassis dynamometer tests, the HEM logger output second by second data in CSV files titled as 1C15XXXX.CSV where XXXX corresponds to file 2217 for the CBD cycle warm up test, 2229 for the CBDx3 cycles, and 2305 for the UDDSx3 cycles. Similarly, HDCD CSV files were obtained for each respective chassis test. The 20200315_HangLog.pdf file gives further detail on the dynamometer tests.

During on-road testing, the HEM logger output second by second data in CSV files titled as 1C16XXXX.CSV where XXXX corresponds to file 1614 for the local Riverside route, and 1734 for the Riverside to Victorville route. Further detail can be seen in the UCR_of_College_of Engineering-Center_for.pdf.

Data Access and Sharing

Data sets described above is accessible using the University of California's data repository, Dryad. https://doi.org/10.6086/D14H5C

Reuse and Redistribution

Data set is available for download to the general public using the University of California’s data repository and can be cited using: Lopez Reyna, Brenda (2021), NCST Real World Brake Activity of Heavy-Duty Vehicles, Dryad, Dataset, https://doi.org/10.6086/D14H5C

Appendix A

The tables and figures below are additional summary information for the project. Table A1 shows the chronological testing log and Figures A1–A4 show ambient weather station data for temperature and RH during the on-road testing.

Table A1. Summary of Tests Performed

	Test Type	Start Time hh:mm:ss	End Time hh:mm:ss	Thermocouple Location	Pressure Sensor Location	Details
Day 1 03/15/2021	1. CBD Prep	13:42:50	13:52:45	Right Rear	Right Rear	Test to verify logger temperature and pressure data collection.
	2. CBD Prep	15:04:04	15:14:37	Right Rear	Right Rear	Failed test, Hem logger was disconnected.
	3. CBD Warm Up	15:17:40	15:28:00	Right Rear	Right Rear	One CBD cycle only. Warm up test successful.
	4. CBD x 3	15:30:43	15:58:50	Right Rear	Right Rear	Three consecutive CBD cycles. Test successful.
	5. Datalogger Test	16:15:45	16:17:51	Left Rear	Right Rear	Intermediate braking activity at low speeds to verify logger temperature and pressure data collection
	6. UDDS x 3	16:21:44	17:14:49	Left Rear	Right Rear	Three consecutive UDDS cycles. Test Successful.
Day 2 03/16/2021	7. Local Riverside Route	09:09:50	09:56:10	Left Rear	Right Rear	Tractor and trailer load of 69,000 lb. Test Successful.
	8. Riverside to Victorville Route	10:51:16	13:44:10	Left Rear	Right Rear	Tractor and trailer load of 69,000 lb. Test Successful, vehicle idle at 11:52:31 to verify equipment was connected.

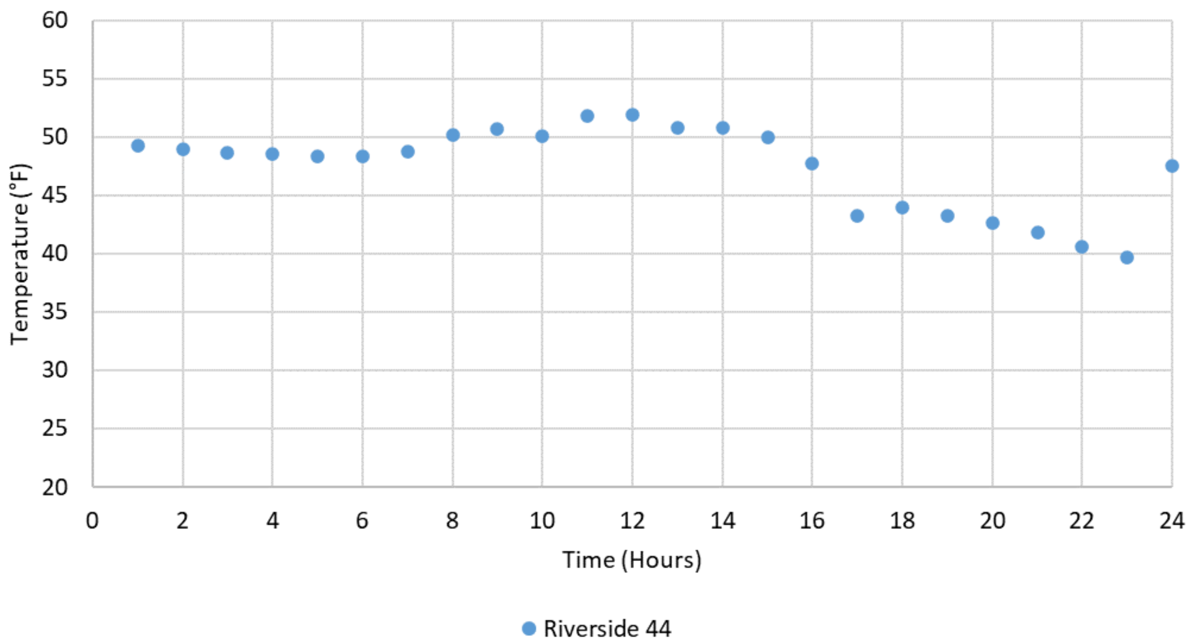

Figure A1. Ambient temperature for Riverside station March 15, 2021.

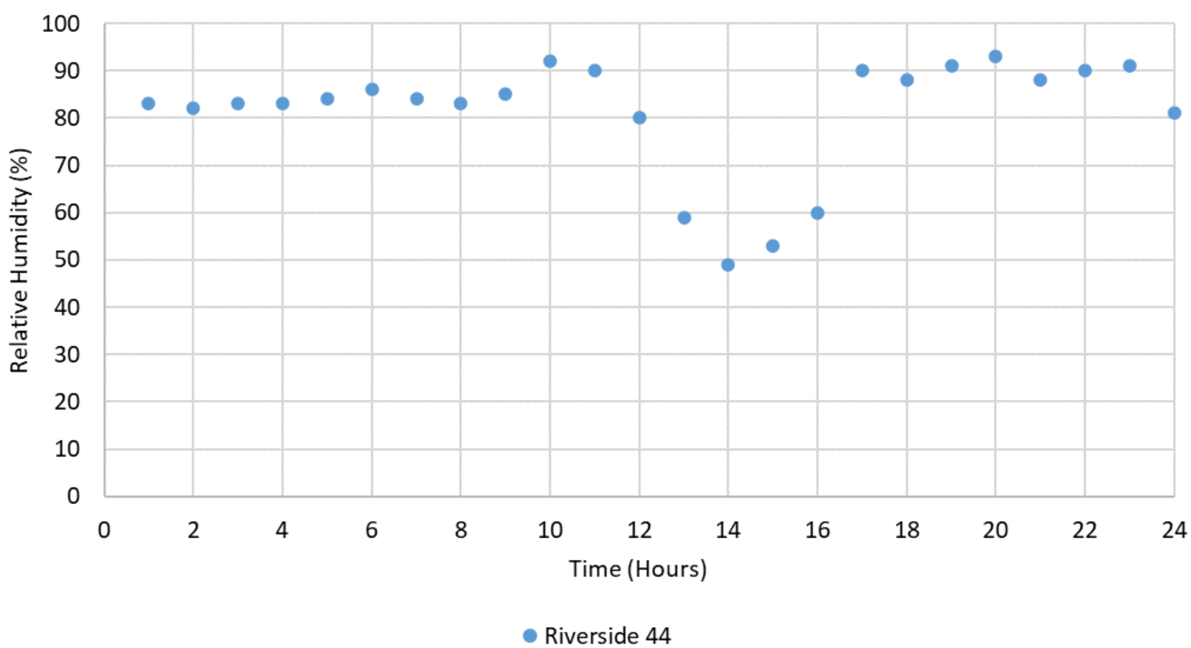

Figure A2. Relative Humidity for Riverside station March 15, 2021.

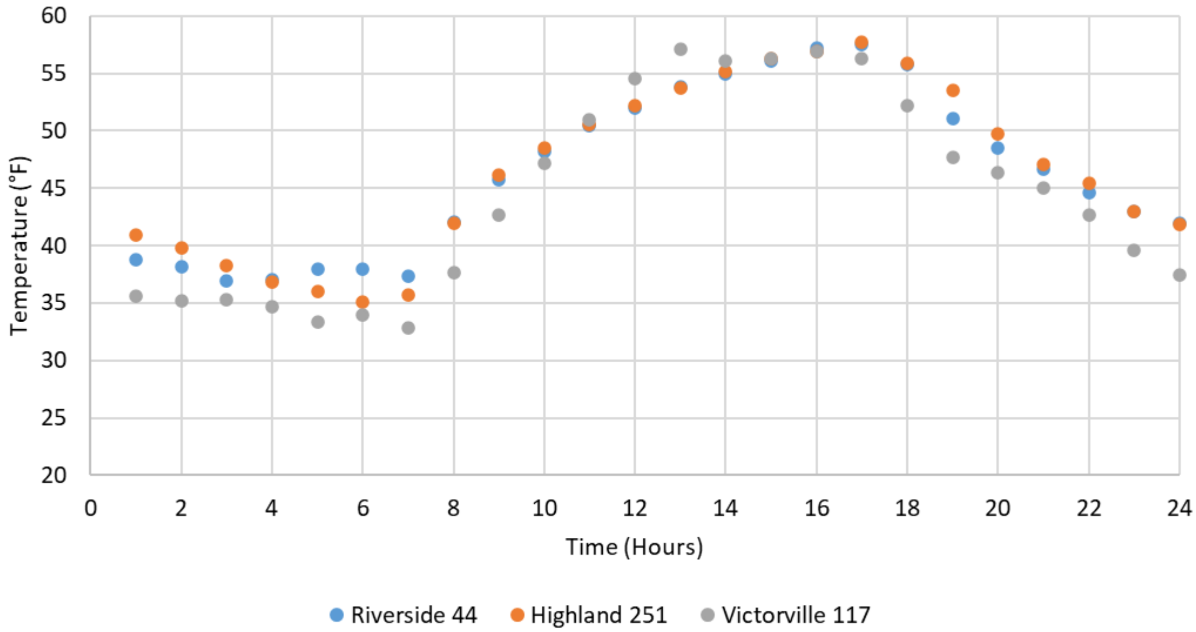

Figure A3. Ambient temperature for the three weather stations March 16, 2021.

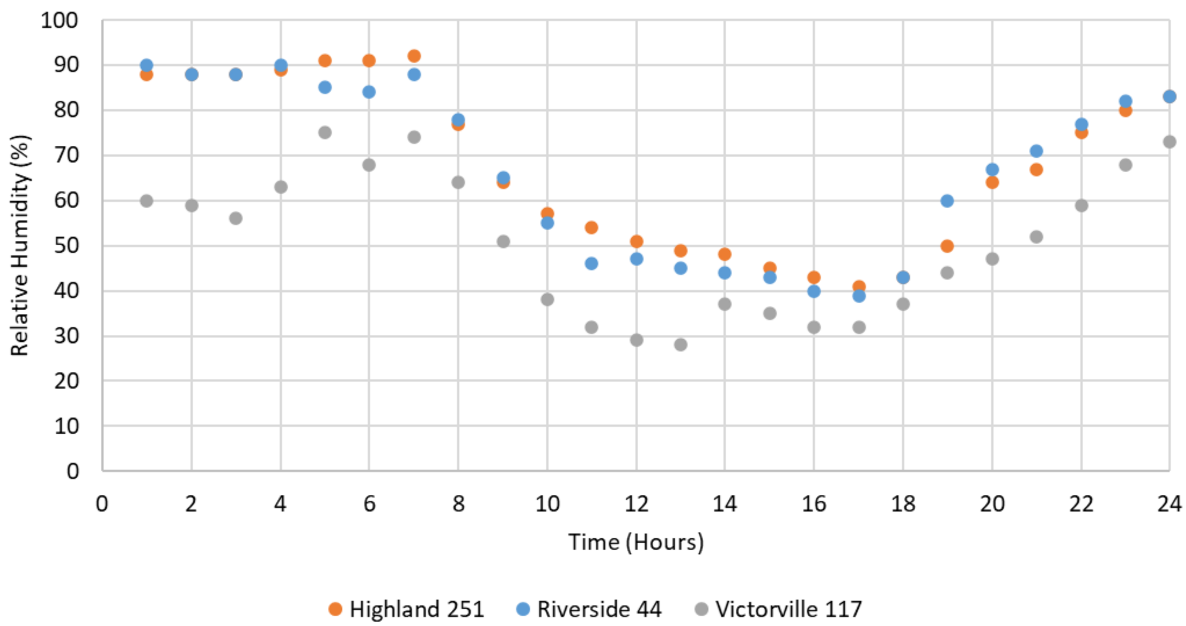

Figure A4. Relative Humidity for the three weather stations March 16, 2021.