STATE OF CALIFORNIA • DEPARTMENT OF TRANSPORTATION

TECHNICAL REPORT DOCUMENTATION PAGE

TR0003 (REV 10/98)

ADA Notice

1. REPORT NUMBER CA21-3232	2. GOVERNMENT ASSOCIATION NUMBER	3. RECIPIENT'S CATALOG NUMBER

4. TITLE AND SUBTITLE Brake Wear Particulate Matter Emissions Modeling	5. REPORT DATE May 2021
	6. PERFORMING ORGANIZATION CODE N/A
7. AUTHOR John Koupal, Allison DenBleyker, Sandeep Kishan, Ravi Vedula, Carlos Agudelo	8. PERFORMING ORGANIZATION REPORT NO. N/A
9. PERFORMING ORGANIZATION NAME AND ADDRESS Eastern Research Group, Inc. P.O. Box 845037 Boston, MA 02284-5037	10. WORK UNIT NUMBER N/A
	11. CONTRACT OR GRANT NUMBER N/A
12. SPONSORING AGENCY AND ADDRESS California Department of Transportation (Caltrans) Division of Research, Innovation and System Information, MS-83 1727 30th Street Sacramento, CA 95816	13. TYPE OF REPORT AND PERIOD COVERED Final Report
	14. SPONSORING AGENCY CODE N/A

15. SUPPLEMENTARY NOTES

16. ABSTRACT

California Department of Transportation (Caltrans) is required to use mobile source emission inventory tool known as Emission FACtor (EMFAC) developed by California Air Resources Board (CARB) to estimate and analyze on-road emissions of particulate matter (PM) while other states use the MOVES (Motor Vehicle Emission Simulator) model developed by U.S. Environmental Protection Agency. However, EMFAC brake wear PM emissions factors were developed based on limited data and are outdated. Caltrans funded a research project titled “Brake Wear in Particulate Matter Emission Modeling” to measure brake wear PM emissions and develop updated emission factors in EMFAC for heavy-duty vehicles (HDVs) and advanced regenerative braking technologies used by electric vehicles such as Tesla. The project also developed speed-dependent emission factors that are implemented in EMFAC. CARB funded and completed another research project focusing on light-duty vehicles (LDVs). As such, the HDV research was supplementing the LDV research. Many of the test methods, dynamometer setup, PM measurement and analysis methods are drawn from the LDV work. Eastern Research Group Inc. as a contractor and LINK Engineering Company as a subcontractor conducted the project. The Caltrans HDV project gathered brake PM emissions data on several HDV brake configurations to update EMFAC rates, and a Tesla Model 3 electric vehicle to expand California’s dataset on regenerative braking emissions. The emissions factors developed in this project are fully incorporated on the latest beta version of EMFAC 2021. With the new emissions factors now fully implemented, Caltrans will have the opportunity to have a better and a more realistic estimates of PM emissions when conducting project level air quality conformity analyses.

17. KEY WORDS Brake wear, particulate matter, emissions modeling, air quality, heavy duty vehicles, regenerative braking systems	18. DISTRIBUTION STATEMENT No Restriction.

19. SECURITY CLASSIFICATION *(of this report)* Unclassified	20. NUMBER OF PAGES 88	21. COST OF REPORT CHARGED

Reproduction of completed page authorized.

DISCLAIMER STATEMENT

BRAKE WEAR IN PARTICULATE MATTER EMISSION MODELING

FINAL REPORT

Prepared for:

California Dept. of Transportation (Caltrans)
1120 N. Street
Sacramento, CA 95814

Prepared by:

John Koupal
Allison DenBleyker
Yuke Zhao
Alan Stanard
Sandeep Kishan
Eastern Research Group, Inc.

Ravi Vedula
Carlos Agudelo
LINK Engineering Company

May 18, 2021

TABLE OF CONTENTS

REFERENCES

Appendix A: Heavy duty brake temperature model results

Appendix B: Heavy duty brake emissions dynamometer configuration (LINK engineering)

Appendix C: Real-time PM data samples (full data in test reports)

Provided separately: LINK test reports and raw test data

LIST OF TABLES

Page

LIST OF FIGURES

Page

EXECUTIVE SUMMARY

To support updates to EMFAC2021, Eastern Research Group, Inc. (ERG) and Link Engineering Company, Inc. (LINK) conducted a study for Caltrans to gather brake particulate matter (PM) data on a range of heavy-duty (HD) trucks and one light-duty (LD) electric vehicle with regenerative braking. The HD portion of the study measured brake PM on a variety of truck classes and brake configurations representing California's truck fleet. In-use brake temperatures were first characterized with track testing on four HD trucks and one trailer to simulate real-world thermal regimes for dynamometer emissions testing. These data were used to adapt and update a HD brake temperature model first published in the 1980s, with good agreement between predicted and observed temperature traces. Measured and modeled brake temperatures were then applied to emissions tests on a HD brake dynamometer equipped with gravimetric and real-time PM sampling. The emissions test matrix was determined from a brake wear mass balance analysis for California accounting for braking activity by truck vocation. The test matrix included Class 8 drum, disc and trailer configurations tested over three vocation cycles and two load points; a Class 6 hydraulic disc configuration tested over two vocation cycles; and a refuse truck and urban bus tested over representative cycles. For individual wheel tests, Class 8 disc brakes on a drive axle under full load and low speed brake-intensive operation had the highest PM emissions, at nearly 50 mg/mi. Loading and duty cycle were found to be significant sources of variability in overall PM emissions. Tests were repeated for original equipment and aftermarket brake pads to evaluate potential deterioration in brake emissions over time, though the differences between these equipment types was not statistically significant. Individual wheel PM filter results were then used to update EMFAC HD brake PM emissions based on statewide estimates of loaded/unloaded travel, axles per truck, speed distributions, and brake material replacement intervals. When rolled up to full truck emissions, Refuse trucks had the highest emission rates at 210 mg/mi, while Class 8 trucks were estimated to produce nearly 150 mg/mi when accounting for the projected 50/50 mix of drum and disc brakes within ten years.

A Tesla Model 3 was tested to provide another data point for brake emissions for vehicles with regenerative braking, adding to a Toyota Prius testing in a counterpart study sponsored by the California Air Resources Board. The Tesla exhibited very aggressive regenerative braking strategy which reduced the dependence on the vehicle's disc brakes. As a result the PM_{10} emissions for the Tesla were quite low, with a full vehicle estimate of 1.42 mg/mi, about 44 percent of the Prius' full vehicle emissions level. The $PM_{2.5}$ fraction based on filter data collected for the Tesla was relatively high however, at 70 percent. Analysis of real-time PM data found that speed effects were more pronounced on the Tesla vs. the Prius, though this was likely due to improvements in real-time PM data resolution between studies.

With many first in this test program, many lessons learned can help inform future brake projects. A significantly uncertainty that was difficult to capture within the scope of this program is the air dynamics that influence brake temperature and (for drum brakes) the amount of particle loss from drum housings. Additional uncertainties such as wind direction, effect of truck aerodynamic improvements (e.g. fairings), and road roughness could not be assessed. A more robust dataset of real-world temperatures over different environmental and driving conditions will help inform real-world brake emissions statewide.

INTRODUCTION

This report serves as the final deliverable by ERG and subcontractor Link Engineering Company (LINK) for California Department of Transportation (Caltrans) Project No. 65A0703, “Brake Wear in Particulate Matter Emission Modeling”. The objective of the project was to measure brake wear particular matter (PM) and update emission factors in California’s EMFAC model for heavy-duty trucks (including trailers), and one light-duty vehicle with regenerative braking, supplementing a program sponsored by the California Air Resources Board (CARB). The latter study is oft referenced in this report as the “CARB LD study” (Standard et. al 2020); many of the test methods, dynamometer setup, particular matter (PM) measurement and analysis methods are drawn from this prior work.

This report presents results for the full scope of the Caltrans project, which gathered brake PM emissions data on several heavy-duty vehicle brake configurations to update EMFAC rates, and a Tesla Model 3 electric vehicle to expand California’s dataset on regenerative braking emissions. A summary of project tasks are as follows:

- Task 1 gathered realistic brake temperature data on a test track for a light-duty (LD) passenger vehicle with regenerative braking, and multiple heavy-duty (HD) truck configurations, to inform air flow settings during dynamometer emissions testing to be conducted in the next phase of the project. This task included extensive update of a heavy-duty truck brake temperature model to provide target temperatures on test conditions not directly measured on the test track.

- Task 2 conducted market share analysis to inform the selection of brake configurations and friction materials for dynamometer testing. For HD trucks, this evolved into a brake wear mass balance analysis to determine how a test matrix of limited scope could be constructed to cover as much of California’s brake wear activity as possible.

- Task 3 parlayed the result of the market share and mass balance analysis into a test matrix for emissions testing. The emission test matrix was informed by the results of Tasks 1 and 2.

- Task 4, led by LINK, conducted PM emission measurement in LINK’s test facility in Dearborn, Michigan. This encompassed a built-out of a HD brake emissions dynamometer, extensive dynamometer shakedown and calibration, emission measurement, and reporting. After a delay from COVID-related shutdowns, Task 4 was conducted from October – December 2020.

- Under Task 5, ERG analyzed PM results and developed updated emissions rates for use in CARB’s EMFAC2021 model, released in January 2021.

These steps are documented in Part I for HD vehicles, and Part II for the Tesla Model 3.

PART I: HEAVY DUTY VEHICLE TESTING

SECTION 1 HEAVY DUTY BRAKE TEMPERATURE MEASUREMENT

1.a Track Test Matrix Development

The objective of Task 1 track testing was to gather brake temperature data on a representative range of HD truck brake systems, truck weights, loading and braking activity. The data were used to calibrate brake temperature models used to estimate temperature control needed for brake dynamometer emissions testing under Task 4. Because the full range of brake systems, truck weights, loading and vocations in California could not be covered within the scope of this project's track testing, our focus for selecting a track test matrix was to ensure the testing included a) representative brake systems, with means of direct comparison in heating/cooling behavior across different systems; b) a representative range of driving and braking, with emphasis on vocations with higher power braking events in urban areas; and c) variation in loads, from which to better calibrate the brake temperature models. To represent the most common foundation brakes in conjunction with the broadest coverage of truck vocation and axle position, the scope for Task 1 focused on conducting track testing for four general vehicle configurations:

- One tractor trailer (10 wheel-ends) with drum brakes all-around on the steer, the two drive, and the two trailer axles.
- One tractor trailer (10 wheel-ends) with disc brakes on the steer and the two drive axles, and drum brakes on the two trailer axles.
- One bus with disc brakes on the steer and the drive axles.
- One municipal work truck with hydraulic disc brakes on the steer and the drive axles.

The development of the text matrix was affected by vehicle availability, and the desire for testing in loaded vs. unloaded configuration for some application. LINK was able to leverage the presence of a bus coach on-site for another project for use in the track testing, to add a fifth vehicle to the sample. However, a municipal work truck could not be readily obtained, and in the interest of representing high brake power operation of refuse trucks, LINK developed a simulated refuse truck configuration with Class 8 tractor and trailer. This vocation was simulated with a Class 8 tractor fitted with brake actuators that represent refuse truck braking power, with weight distribution and an unbraked trailer. Given vehicle availability at LINK's Ohio test track, it was not feasible to ensure that vehicles comply with California-specific aerodynamic requirements. The impact that equipment for improving tractor and trailer aerodynamics, such as side fairings, will have on heavy-duty truck brake temperatures is uncertain, and recommended as a topic for future study.

With these modifications, track testing was conducted on four vehicles and one trailer at LINK's HD proving ground track in East Liberty, Ohio during June and July 2019. Vehicles were tested in multiple configurations and loadings to represent different vocations. HD vocation cycles were chosen from each of four usage pattern categories defined in the UC Riverside HD activity study conducted for CARB (Boriboonsomsin et al. 2017): long haul, short haul, pickup/delivery and service. As several vocation cycles exist within these categories, cycles with higher overall braking power levels per distance were selected to represent each. The purpose of this was to avoid the need for brake temperature models to extrapolate to high braking power levels when determining dynamometer cooling settings. To differentiate each of CARB's HD vocation cycles, a unitless "brake power density" metric was developed to quantify the degree of braking intensity for each. Braking horsepower is a product of brake torque and wheel speed (Fancher et al. 1986), represented by a surrogate of (kinetic energy x deceleration rate). For each vocation cycle, brake power density was estimated as the summation of the following term over each second of deceleration divided by the distance of the vocation cycle, as follows:

Equation 1. Vocation Cycle Brake Power Density

$$Brake\ Power\ Density_{cycle} = \frac{\sum_{t=1}^{duration}[(Speed_{t-1}^2 - Speed_t^2) \div (Deceleration\ Rate)]}{Cycle\ Distance}$$

The cumulative power and power density metrics are shown in Table 1. Average cycle speed is also included to illustrate that Brake Power Density and average cycle speed are strongly correlated, as one might expect.

Table 1. Brake Power Density of CARB HD Vocation Cycles

Usage pattern	Vocation Cycle	Cycle Distance (miles)	Brake Power Density (unitless)	Average Speed (mph)
Long haul	Long haul - out of state	21.1	0.66	48.6
Long haul	Long haul - in state	18.5	1.21	41.3
Pick-up & delivery	Airport shuttle	7.5	2.60	15.0
Pick-up & delivery	Refuse	5.2	4.32	11.1
Pick-up & delivery	Food distribution	17.8	0.88	36.1
Pick-up & delivery	Beverage distribution	5.6	2.85	14.2
Pick-up & delivery	Local moving	15.3	1.28	32.6
Pick-up & delivery	Urban buses	7.1	3.82	14.9
Pick-up & delivery	Express buses	14.5	1.50	30.2
Service	Utility - repair	11.3	2.19	22.7
Service	Public - freeway work	10.9	2.06	24.5
Service	Public - sweeping	8.5	1.49	18.2
Service	Public - municipal work	13.6	1.87	28.6
Service	Public - towing	16.8	1.59	36.8
Short haul	Drayage - Northern CA	4.3	3.33	11.9
Short haul	Drayage - Southern CA	9.4	1.94	19.3
Short haul	Agriculture - Southern	18.3	0.85	44.8
Short haul	Construction	15.4	1.44	32.3
Short haul	Cement mixers	11.6	1.89	28.1

Because refuse truck and bus coach were specifically chosen for track testing, the Refuse and Urban Bus cycles were run on their respective vehicles. Remaining vocation cycles were chosen to represent each usage category, represent a range of operating speeds, and represent higher brake power densities. The cycles which best fit these criteria were Long Haul In State, Beverage Distribution, Drayage (Northern CA), and Towing. The choice of loading for the Class 8 tractor-trailer was based on research on existing studies of Weigh-In-Motion (WIM) data from California (Hernandez 2017). Figure 1 is an excerpt from this analysis at select spots in California for a subset of trucks presented in the Hernandez paper. This figure shows the distribution of truck weights for different truck body types, and a Gaussian Mixed Model (GMM) fit of the distributions. For many of the trucks there is a bimodal distribution - i.e. they are mostly either empty or near full load. Vans (e.g. box trucks) and auto carriers are the exception. The bi-modal distribution suggested that fully loaded and unloaded were necessary to capture the range of data, as opposed to an average weight. While it is possible to produce average weights from these data, an average weight would not be representative of the bi-modal patterns seen in many of these trucks. Loaded and unloaded tests were therefore run on select cycles for the Class 8 configurations.

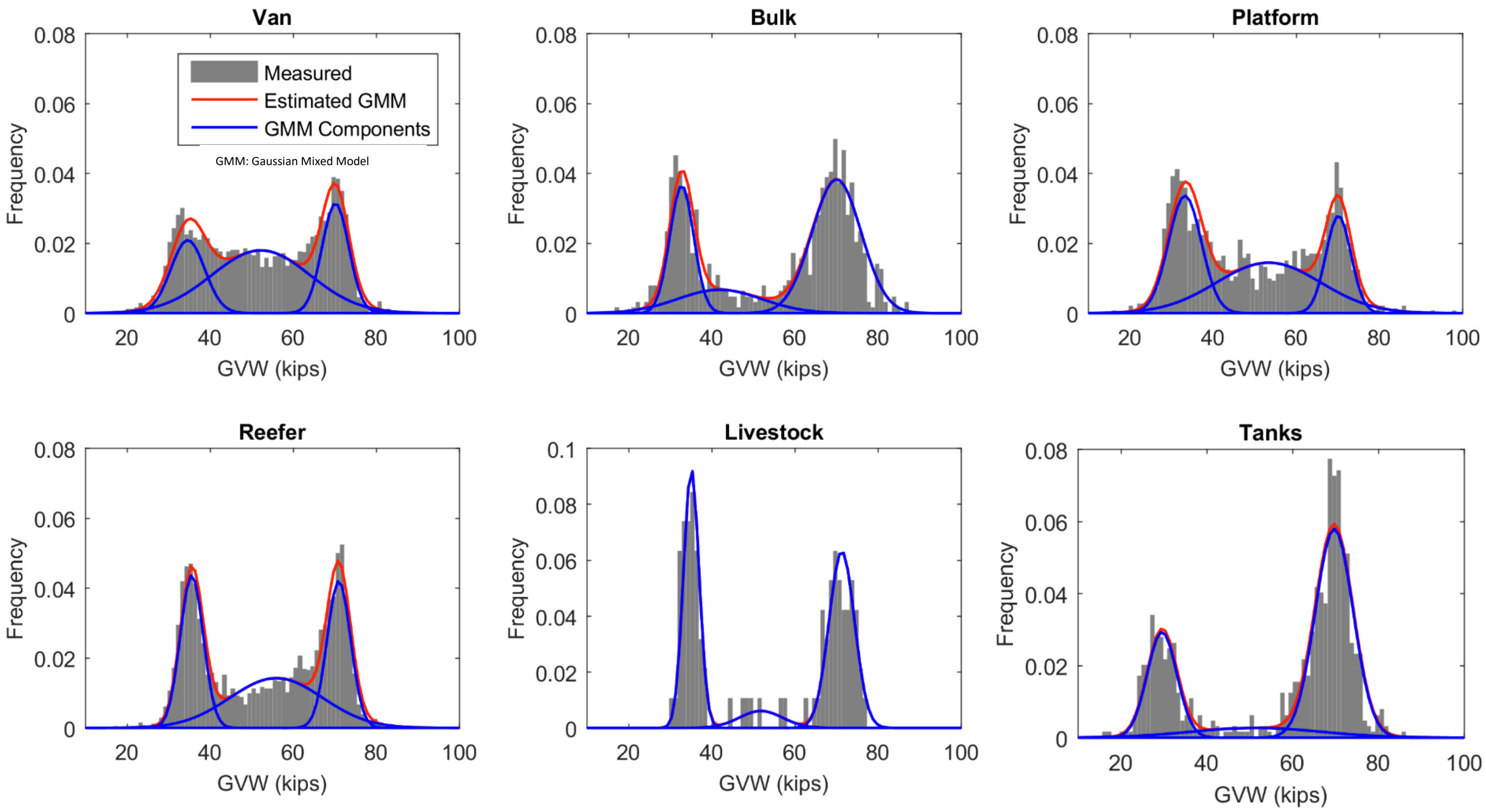


Figure 1. California HD Weigh-In-Motion Data – Select Truck Types (Hernandez 2017)

The track test vehicles are shown in Figure 2 and test matrix in Table 2, detailing the vehicle, configuration, loading and vocations (the emissions testing matrix was developed separately, as discussed in Section 7). Only three physical vehicles were tested; the same truck was used for the Class 8 and refuse truck configurations, with only the brake components and loading modified as noted. As noted in the table, one test was inadvertently switched – rather than running the Class 8 all drum configuration over the Long Haul In-State cycle, it was run over the Beverage Distribution cycle, unloaded. Upon reviewing results, this was not considered a problem – as discussed in the next section, the effect of loading was found to be more important than cycle type, and the inadvertent addition of an unloaded test provided useful data for temperature modeling.

Class 8 truck used for drum, air disc, refuse track tests

Class 6 truck used for hydraulic disc track tests

Bus coach used for urban bus air disc track tests

Figure 2. Vehicles used for track testing

Table 2. HD Track Temperature Test Matrix

Vehicle/Configuration	Load	Vocation Cycles					
		Drayage Northern California	Beverage Distribution	Long Haul In-State	Towing	Refuse	Urban Bus
Class 8 All-Disc Tractor + Drum Trailer	Full Load (80,000 lbs)	●	●	●			
	Unloaded (37,500 lbs)	●					
Class 8 All-Drum Tractor + Drum Trailer	Full Load	●	●	intended			
	Unloaded	●	actual				
MD Hydraulic disc	26,000 lbs		●		●		
Refuse truck simulation: Class 8 All-Disc Tractor + Actuators representing refuse + Unbraked 28’ Control Trailer	Full Load (over tractor king pin)					●	
Bus Coach	37,500 lbs						●

1.b Track Testing

Track testing was conducted on four vehicles and one trailer at LINK’s HD proving ground track in East Liberty, Ohio during June-July 2019. Details on the trucks tested, instrumentation, test procedure protocol and raw results are presented in LINK’s test reports, provided along with the interim report. Some key points are summarized below:

- New brake pads were installed before testing, and underwent a burnish procedure prior to testing on the vocation cycles.
- The vehicle brakes were instrumented with thermocouples in the inboard brake pads and primary brake shoes of all wheel ends.
- GPS parameters, ambient conditions and brake pressure where also measured.
- For consistency across tests in a variety of ambient temperature conditions, brake temperatures were brought to nominally 100°F before commencing the test cycle.
- All tests were run with brake retarder off. If desired for emissions testing, the impact of brake retarding can be estimated via modeling.
- Variability between different wheels of the same axle were attributed to wind direction.

1.c Temperature Results

Complete temperature results for each wheel are contained in the LINK test reports. A summary of median and maximum brake temperatures are shown in Figure 3- Figure 6, to provide a snapshot of temperature trends. The test reports should be consulted for more detail on real-time temperature trends across trucks, cycles, brake types, axle types and load. The raw temperature data are also included in Appendix A charts in comparison to brake temperature model predictions.

Figure 3 shows median and maximum brake temperatures by vehicle and brake configuration. For a given vehicle, the median and max temperatures over all wheels, cycles and loadings are shown. The chart shows that the bus and refuse truck had highest overall brake temperatures, with the bus maxing out over 500 °F, and median temperatures above 350 °F. The Class 8 tractor-trailer configuration had relatively lower temperatures, with comparable temperatures between the drum and disc configurations on these trucks, driven by the less brake-intensive long haul cycle included in the matrix for these trucks.

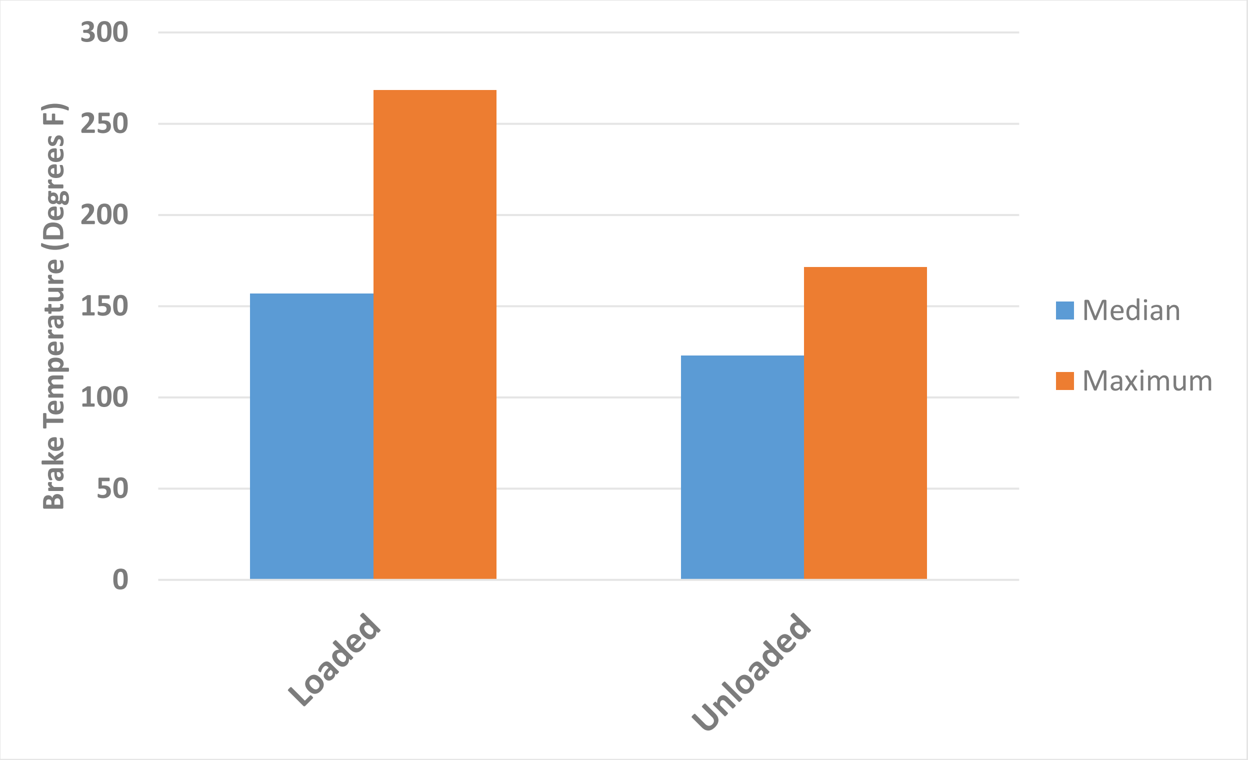


Figure 3. Brake Temperature by Vehicle & Brake Configuration

Figure 4 shows brake temperatures by vocation cycle. For a given cycle, the median and max temperatures over all wheels, vehicles, brake configurations and loadings are shown. Consistent with the prior chart, the bus and refuse truck had highest overall brake temperatures. The beverage and towing cycles had moderate temperatures, which in part reflects the presence of hydraulic disc Class 6 truck on these cycles. The long haul in-state and drayage cycles on the Class 8 tractor-trailer had lower temperatures, influenced in part by the testing of the dray cycle in unloaded configuration.

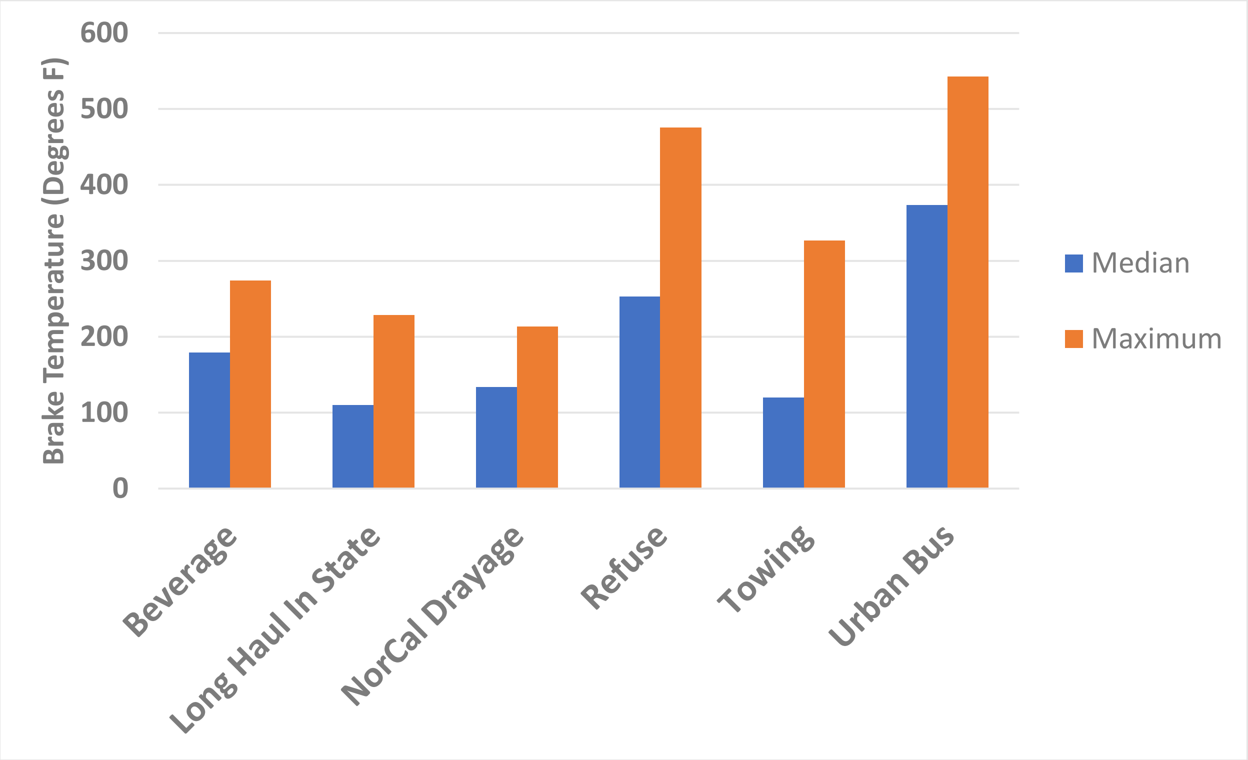


Figure 4. Brake Temperature by Vocation Cycle

Figure 5 and Figure 6 focus on the Class 8 tractor-trailer to highlight distinctions between axle type, and the impact of loading. Figure 5 shows the trailer axle having the highest maximum temperatures compared to the steer or drive axles. Figure 6 shows a significant difference between temperatures with full loading, and without loading over both Class 8 brake configurations, all axles and vocation cycles – the temperature differences are larger than those shown in prior charts by vocation cycle, axle and brake configuration.

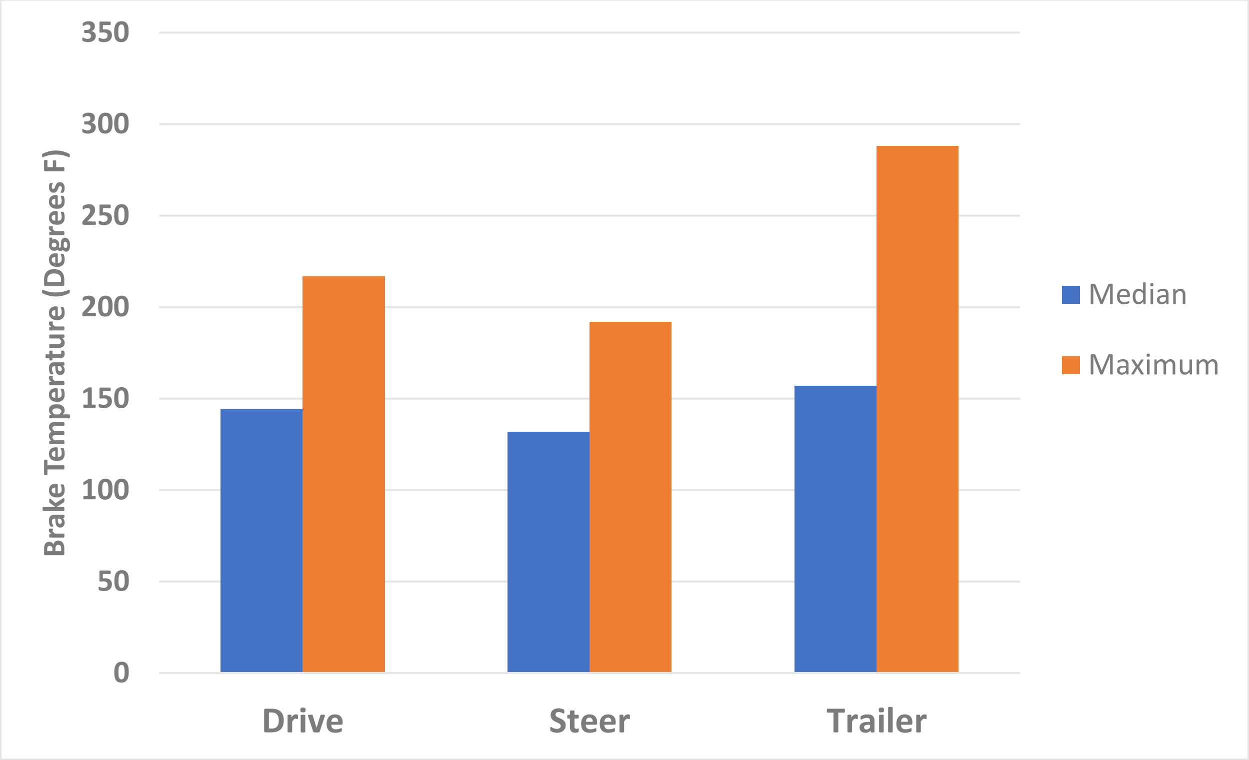


Figure 5. Brake Temperature by Class 8 Axle Type

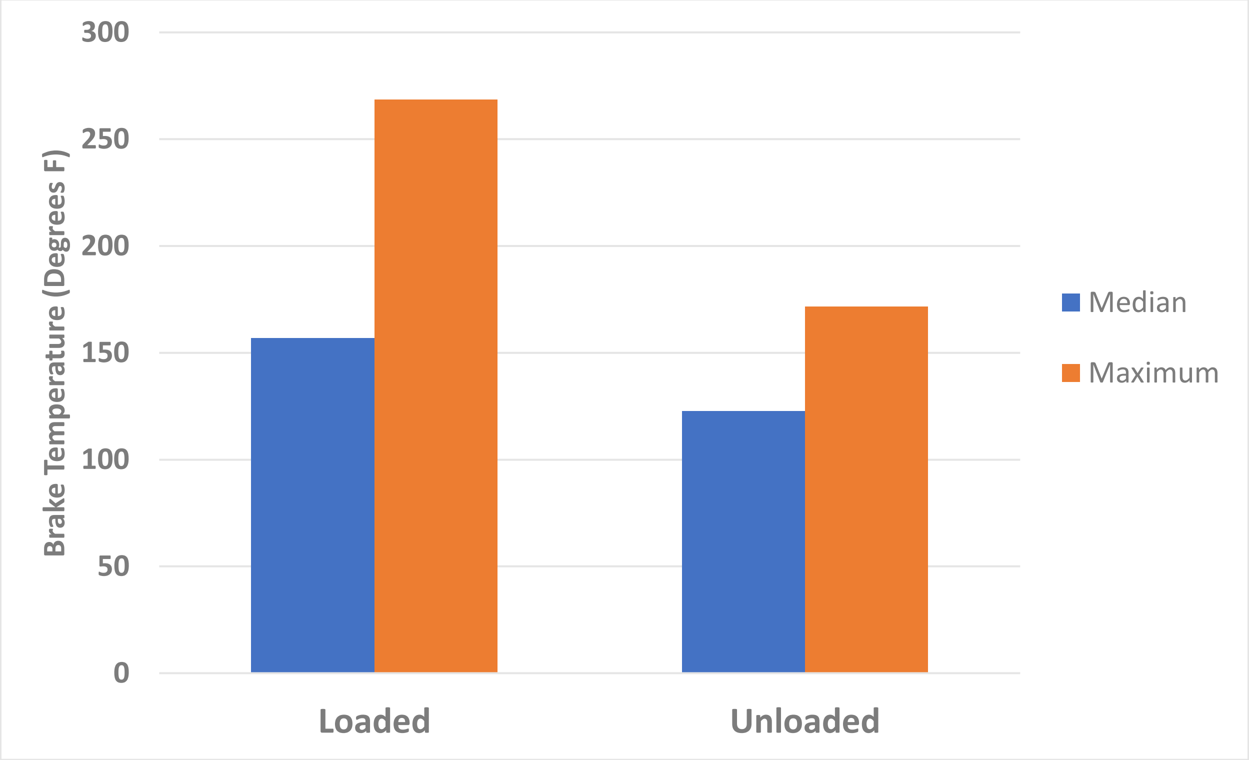


Figure 6. Brake Temperature by Class 8 Loading

SECTION 2 HEAVY-DUTY TRUCK BRAKE TEMPERATURE MODELING

A brake temperature model was developed for heavy-duty trucks to estimate brake temperatures for other vocation cycles and/or loadings that may be desired for emissions testing under Task 4. While the temperature model developed for light-duty vehicles under the CARB LD study was initially considered, a key difference for trucks is the desire to model the impact of truck loading on brake temperatures. A literature review of heavy-duty truck brake temperature models turned up work by the University of Michigan Transportation Research Institute (UMTRI) in the late 1980s to model drum brake temperatures on Class 8 trucks during a steady downhill descent (Fancher et al 1987). The model was evaluated with initial success on the first set of bus data collected by LINK, as presented to Caltrans in April 2019. From this the model was chosen to adapt to all truck configurations, with an important consideration being that it would allow explicit modeling of truck loading.

3.a Modeling Approach

In order to assess the brake temperatures of a set of heavy-duty cycles under varying loads, the UMTRI brake temperature model was extended from drum brake downhill conditions it was developed for in the 1980s, to air and hydraulic disc configurations across the different vocation cycles tested in Task 1. The UMTRI brake temperature model is given in Equation 2, where T is the temperature [°F] at time t [hours], T_i is the initial temperature [°F], τ is the heating and cooling time constant [hours], HP_B is the braking horsepower, h(v) is the cooling coefficient [horsepower/°F], and T_a is the ambient temperature [°F].

Equation 2. UMTRI Brake Temperature Model

$$\boldsymbol{T = T_i e^{-t/\tau} + \left(\left(\frac{HP_B}{h(v)}\right) + T_a\right)(1 - e^{-t/\tau})}$$

The initial temperatures were set according to the first measured temperature of each test configuration. An initial brake temperature of 100 °F was targeted for consistency between tests. The tests applied pre-heating to more accurately characterize vehicles under sustained use; the longest test lasted for nearly 29 minutes, while heavy-duty vehicles tend to operate for significantly longer durations. To predict subsequent axle temperatures, the vehicle speed, ambient temperature, brake horsepower, and set of calibrated heating and cooling coefficients were used.

A braking horsepower surrogate and coefficient were used in place of directly-measured or calculated braking horsepower. The horsepower surrogate is shown below as the product of braking kinetic energy and vehicle speed:

$$\textit{HP Surrogate}_t = (\textit{Coastdown Speed}_t^2 - \textit{Speed}_t^2) * \textit{Average}(\textit{Speed}_t, \textit{Speed}_{t-1})$$

Coastdown speed represents deceleration that occurs without braking, i.e. “road load” forces from rolling resistance, aerodynamic drag and friction. During a deceleration event, braking is defined when actual speed is less than coastdown speed. Coastdown functions published in EPA 2014 were used to estimate coastdown speed for each second of the vocation cycles. After coastdown was incorporated, significant improvements were observed in the model. Because decreases in speed due to coastdown do not increase brake temperatures, they should not be included in horsepower surrogate calculations. The current iterations of the models employ coast-down coefficients developed for light-duty vehicles, as heavy-duty coastdown coefficients were not provided in EPA 2014. The accuracy of the deceleration due to braking could be further improved by incorporating the coast-down of heavy-duty vehicles, which is recommended as part of future study.

To adapt the UMTRI model to each truck configuration, brake type, axle, vocation and loading, the heating and cooling coefficients, A, B, C, and D, were defined within the original UMTRI formulation as shown in Equation 3.

Equation 3. Heating & Cooling Coefficient Expressions

$$\boldsymbol{\tau = \frac{1}{A + B * v}}$$

$$h(v) = C + D * v$$

The coefficients associated with UMTRI’s 1987 study were 1.23, 0.0256, 0.1, and 0.002 for A, B, C, and D, respectively. These values were used to calibrate a horsepower surrogate coefficient for each truck and vocation; once this was determined, an optimization process was undertaken to find the best fit of A,B,C and D for each condition. In order to model each heavy-duty configuration, the heating and cooling coefficients were calibrated by minimizing the sum of squares of the modeled and measured temperatures, executed via the MS Excel 2016 solver function.

3.b Optimization Method

To optimize the model temperatures, preset UMTRI and horsepower surrogate coefficients were used. The horsepower surrogate coefficient used for Drum-Drum and Disc-Drum configurations was 6.0×10^{-7}, while the four remaining cycles used 2.505×10^{-5}. These horsepower surrogate coefficients, along with their corresponding sets of heating and cooling coefficients, produced initial temperature prediction curves that resembled the plots of the actual axle temperatures. Excel Solver convergence can depend on the initial coefficients. If convergence is not met, the sum of squares between the measured and modeled temperatures cannot be minimized, leading to inaccurate heating and cooling coefficients.

The modeling approach for hydraulic disc configurations was modified in order to improve the fit between the modeled and experimental data, to account for increased temperature sensitivity of hydraulic disc brakes relative to drum and air disc brakes observed in the track testing. While minimizing the sum of squares between the modeled and measured temperatures of the hydraulic disc tests, the sums of squares were only accounted for where the horsepower surrogates were positive. This restriction to the model facilitated a more accurate heating simulation and hit the temperature peaks of the hydraulic disc experimental data with greater consistency.

Generalization was attempted by grouping the sum of squares across different vehicle cycles and loads while applying a uniform set of heating and cooling coefficients. When the sum of squares was minimized, various Excel Solver artifacts appeared. In some instances, axles that experienced low durations of cooling were given high cooling rates. These generalized coefficients minimized the sum of squares, but they induced almost-vertical temperature drops when the speed was low. Additionally, the minimized sums of squares were significantly higher when common heating and cooling coefficients were applied; unloaded axles had overestimated temperatures, while loaded axles had underestimated temperatures. Because the generalized coefficients represented the overall trend of axle heating less accurately and modeled the ranges of temperatures less precisely, they were not developed further.

3.c Results

The calibrated UMTRI heating and cooling coefficients are given in Tables 3-6. Graphs of the resultant temperature models are given in Figure 7 for one configuration, with the remaining charts in Appendix A. Each model has been optimized for its unique axle type, vehicle cycle, and vehicle load. Orange lines show the calculated average axle temperature, while grey bands represent the temperature range of the individual axles. The temperature ranges were large for some test configurations, and the trailer axle temperatures tended towards the greatest variation. The differences in temperature for the same axle type can be attributed to wind effects, uneven loading, and localized changes over time. Additional sources of variation are likely, but none of these effects are easily measured or accounted for with the current set of instrumentation and techniques.

Table 3. Modeled Heating and Cooling Coefficients for Class 8 Drum-Drum Configuration

	Loaded Beverage Cycle			**Unloaded Beverage Cycle**			**Loaded Drayage Cycle**			**Unloaded Drayage Cycle**		
	Steer	Drive	Tr	Steer	Drive	Tr	Steer	Drive	Tr	Steer	Drive	Tr
A	4.7287	4.3865	3.7945	3.2415	2.1371	4.5259	2.6949	3.6182	1.5624	0.8808	2.9029	3.9794
B	-0.0585	-0.0233	0.0227	-0.0478	0.0321	-0.02	-0.033	-0.0003	0.1219	0.0589	0.0244	0.0441
C	0.0055	-0.0008	-0.0013	-0.0017	-0.0034	-0.001	0.0134	-0.0011	-0.002	-0.003	-0.0064	-0.0041
D	0.0015	0.0019	0.0015	0.0022	0.003	0.0013	0.0009	0.002	0.0019	0.0031	0.0031	0.002

Table 4. Modeled Heating and Cooling Coefficients for Loaded Class 8 Disc-Drum

Loaded Beverage Cycle	**Unloaded Beverage Cycle**	**Loaded Drayage Cycle**	**Unloaded Drayage Cycle**

	Steer	Drive	Tr	Steer	Drive	Tr	Steer	Drive	Tr	Steer	Drive	Tr
A	3.9183	4.9866	2.938	3.568	3.2991	1.4198	4.9777	4.9171	0.2382	4.3346	3.528	-1.1199
B	-0.044	-0.0277	-0.0284	0.0422	0.0269	0.0671	-0.0017	-0.0537	0.0647	-0.0412	0.0181	0.1453
C	0.0112	0.0018	0.0052	0.0358	0.0325	0.0175	-0.0011	-0.0018	-0.0004	-0.0038	-0.0036	-0.0027
D	0.001	0.0016	0.0006	0.0012	0.0006	0.0008	0.0025	0.0017	0.0008	0.0026	0.0025	0.0013

Table 5. Modeled Heating and Cooling Coefficients for Refuse Truck & Bus

	Refuse Cycle		**Urban Bus Cycle**	
	Steer	Drive	Steer	Drive
A	4.0879	1.9480	3.0474	2.5650
B	0.0115	0.0326	-0.0194	0.0580
C	-0.0365	-0.0238	-0.0335	-0.0318
D	0.0345	0.0278	0.0192	0.0224

Table 6. Modeled Heating and Cooling Coefficients for Class 6 Hydraulic Disc

	Beverage Cycle		**Towing Cycle**	
	Steer	Drive	Steer	Drive
A	10.34	6.9594	-1.5265	-4.9772
B	-0.0899	-0.0899	0.4395	0.3158
C	-0.0324	-0.0276	-0.0466	-0.0331
D	0.0226	0.0241	0.0335	0.0251

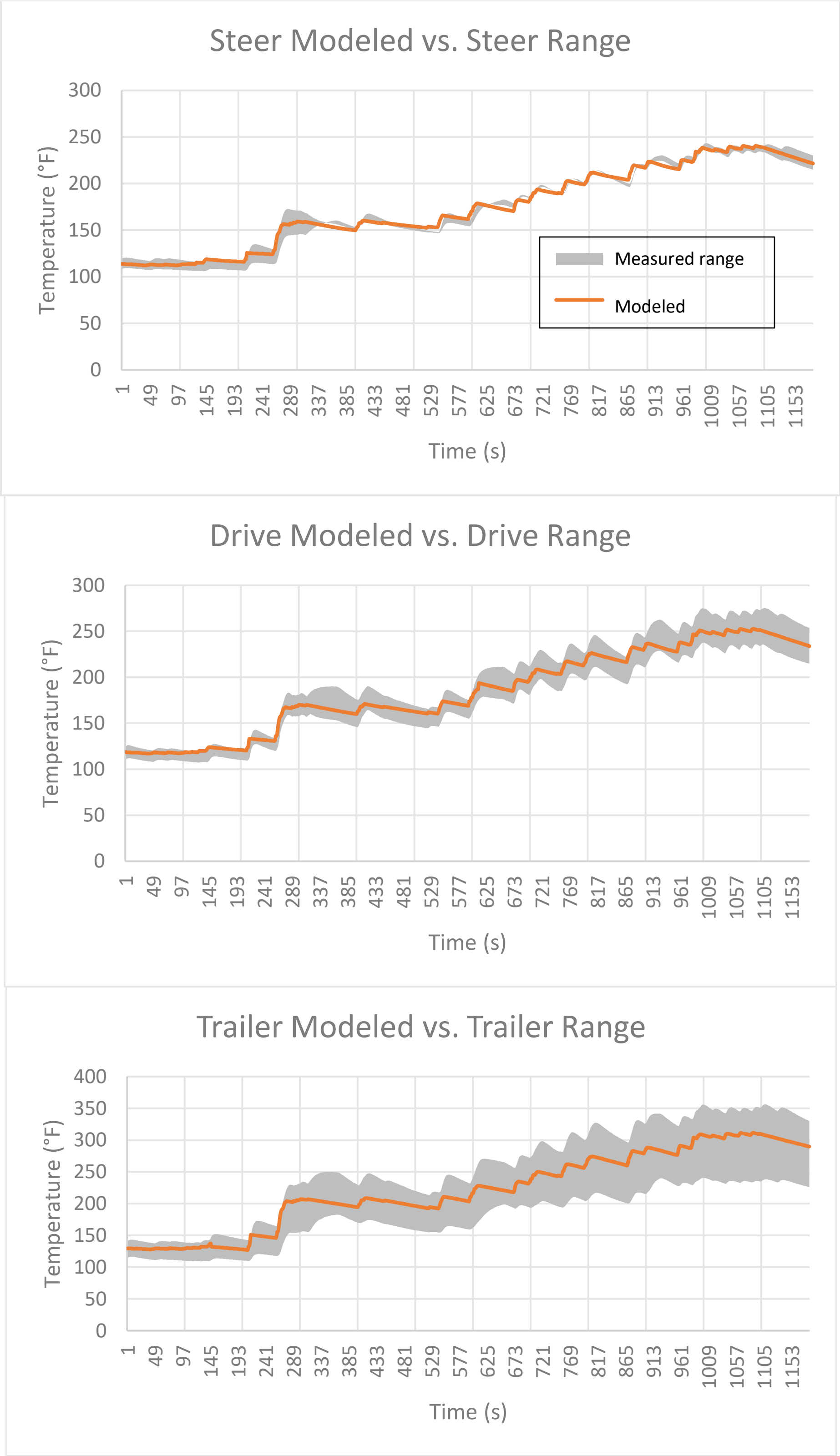


Figure 7. Modeled Temperatures for Steer, Drive and Trailier Axles of Loaded Class 8 Drum-Drum Beverage Cycle, vs. Observed Range

SECTION 4 HEAVY TRUCK MARKET SHARE & MASS BALANCE ANALYSIS

Under Task 2 ERG and LINK conducted a market share analysis to inform the selection of brake configurations and friction materials for dynamometer emissions testing; this task focused on heavy-duty vehicles since the scope of passenger vehicle testing is limited to one vehicle. Combining brake component and friction material market penetration, durability, vocation-based brake intensity and EMFAC vehicle miles travelled, ERG and LINK have constructed a mass balance for heavy duty truck brake wear in California. The mass balance estimates the total volume of brake material worn from brake components and friction material in a typical day. This can be interpreted as the total *potential* amount of brake PM emissions, but does not equate to actual brake wear particulate matter emissions as it does not account for the fraction of generated PM that is dispersed into the air, retention of brake material within the brake system, or distribution of particle sizes. The results from this analysis do however provide an analytical tool for understanding the relative contributions of truck category, vocation, and brake type to brake wear PM emissions. This will be used to inform the emissions test matrix discussed later, and to help provide weighting factors to develop composite brake wear emission rates for EMFAC as needed.

Central to Task 2 was a market share analysis of brake materials and types for HD vehicles. LINK conducted this survey drawing upon existing industry relationships and access to friction material information. A survey of two major brake component and friction material suppliers, covering over 80 percent of a narrow HD brake component market, identified the predominant friction material formulation for HD vehicle categories, durability in terms of lifetime mileage, and replacement rates. LINK was able to estimate specific wearable mass for a spectrum of HD vehicles types based on these data, which were used by ERG and LINK to construct a California brake wear mass balance. The following sections discuss each of these tasks in detail.

4.a Heavy truck brake survey

LINK estimated the penetration of brake configurations, components and friction material lifespan by heavy-duty truck vocations. LINK based these estimates on information gathered from experts at two major suppliers of brake components and friction materials, Federal Mogul and Arvin Meritor. The commercial vehicle brake component market is narrower than for passenger vehicles, and LINK estimates that combined, these two suppliers produce over 80 percent of brake components for heavy trucks.

LINK polled the two brake suppliers, supplemented by internal experts, on the penetration of brake configurations (drum, air disc, hydraulic disc) on the different truck classes and vocations tested in Task 1 brake temperature testing. The results of this survey are presented in Table 7. These results were then expanded as discussed in the mass balance analysis. Though the questions were framed to obtain differences in penetration by axle type and vocation, responses could not distinguish this level of detail.

Table 7. Heavy Duty Brake Market Survey Results

Truck Weight Class	Axle Type	Brake Type	Market Share	Foundation Brake Size (Friction Material)	Friction Life (miles)	Aftermarket Friction Material
Class 8 Pickup & Delivery	Steer	Drum	85%	Q+ 16.5x5 (MA1201)	150K-300K	ABEX 6326 GG
		Air Disc	15%	Mer. EX+L/EX225 (MA761)	150K-300K	ABEX 6315 GG
	Drive	Drum	85%	Tandem - Q+ 16.5x7 (MA2001)	150K-300K	ABEX 685/ABEX 6326
		Air Disc	15%	Tandem - Mer. EX+L/EX225 (MA761)	150K-300K	ABEX 6315 GG
	Trailer	Drum	100%	Tandem - Q+ 16.5x7 (MA212A)	150K-300K	ABEX 6008-1
Class 8 Short Haul	Steer	Drum	85%	Q+ 16.5x5 (MA1201)	150K-300K	ABEX 6326 GG
		Air Disc	15%	Mer. EX+L/EX225 (MA761)	150K-300K	ABEX 6315 GG
	Drive	Drum	85%	Tandem - Q+ 16.5x7 (MA2001)	150K-300K	ABEX 685/ABEX 6326
		Air Disc	15%	Tandem - Mer. EX+L/EX225 (MA761)	150K-300K	ABEX 6315 GG
	Trailer	Drum	100%	Tandem - Q+ 16.5x7 (MA212A)	150K-300K	ABEX 6008-1
Class 8 Long Haul	Steer	Drum	85%	Q+ 16.5x5 (MA1201)	250K- 650K	ABEX 6326 GG
		Air Disc	15%	Mer. EX+L/EX225 (MA761)	250K- 650K	ABEX 6315 GG
	Drive	Drum	85%	Tandem - Q+ 16.5x7 (MA2001)	250K- 650K	ABEX 685/ABEX 6326
		Air Disc	15%	Tandem - Mer. EX+L/EX225 (MA761)	250K- 650K	ABEX 6315 GG
	Trailer	Drum	100%	Tandem - Q+ 16.5x7 (MA212A)	250K- 650K	ABEX 6008-1
Class 7 & "Light" Class 8 Refuse	Steer	Drum	40%	Q+ 16.5x5 (MA1201)	25K-50K	ABEX 6326 GG
		Air Disc	60%	Mer. EX+H/EX225 (MA703)	25K-50K	ABEX 6098 GG
	Drive	Drum	40%	Tandem - Q+ 16.5x7 (MA2001)	25K-50K	ABEX 685/ABEX 6326
		Air Disc	60%	Tandem - Mer. EX+H/EX225 (MA703)	25K-50K	JURID J539
Class 6 Pickup & Delivery	Steer	Hyd. Disc	100%	Mer. Quad. 4x70 (MA707)	50k-150k	ABEX SM2186 EE
	Drive	Hyd. Disc	100%	Single - Mer. Quad. 4x64 (MA707)	50k-150k	ABEX SM2186 EE
Class 6 Public	Steer	Hyd. Disc	100%	Mer. Quad. 4x70 (MA707)	75k-150k	ABEX SM2186 EE
	Drive	Hyd. Disc	100%	Single - Mer. Quad. 4x64 (MA707)	75k-150k	ABEX SM2186 EE
Urban Bus	Steer	Air Disc	100%	Knorr-Bremse SN7 (Jur. 539)	60k-80k	ABEX 6315 GG
	Drive	Air Disc	100%	Single - Knorr-Bremse SN7 (Jur. 539)	60k-80k	ABEX 6315 GG

The foundation brake sizes and friction material numbers provide access to data needed to estimate wearable mass of brake material on a vehicle, the latter via the Friction Material Standards Institute (FMSI) database. Additional notes from the experts providing data in Table 7 are important to consider in applying market share to overall brake wear in California:

- Aftermarket and original equipment (OE) friction material were judged to have the same lining life.

- Relative to friction material, OE drum and disc components were estimated to last twice as long (i.e. 2x friction life), while aftermarket components were estimated to last the same (i.e. 1x friction life).

- It is estimated that at least 50 percent drum and 75 percent disc of first vehicle owners replace friction with OE.

4.b Heavy truck brake wear mass balance

For the purpose of emission inventory, a market share analysis needs to extend beyond sales data to consider miles travelled, braking intensity and wear rate of brake components. These factors vary by truck category, vocation, and brake type, and help to define the importance of each in generating brake PM emissions in California. The market share analysis conducted for Task 2 therefore took on a broader estimate of brake wear mass in California, to estimate relative potential contributions of different configurations to brake PM emissions. We define this mass as brake wear index (BWI), to distinguish from a brake wear emissions inventory. This analytical exercise is not a replacement for emissions testing – it cannot account for factors that require emission testing to collect such as brake temperature, actual wear rate, the fraction retained within brake housing, and particle size distribution. BWI is intended only to give a relative sense of contributing factors by brake configuration, truck type, and vocation type.

An estimate of daily BWI from EMFAC category T6 and T7 HD trucks (14,001 lb GVWR and higher) was built up from brake component and friction material market share, dimensions, and wear rates estimate for each EMFAC truck category, coupled with daily VMT for that category. The assignment of CARB vocation cycles was an important element of this calculation, as varying braking intensities were used to estimate wear rate.

For a given EMFAC truck category, the general calculation of statewide daily BWI (kilograms) is shown in Equation 4.

Equation 4. Brake Wear Index Calculation

$$\boldsymbol{BWI_V = \sum_{N=1}^{A,B} Market\ Share_{A,B} \times Wearable\ Mass_{A,B} \times Wear\ Rate_{A,B}}$$

Where:
V= EMFAC2011 Vehicle Category
A= Axle Type (Steer, Drive, Trailer)
B = Brake Type (Drum, Air Disc, Hydraulic Disc)

Market shares were taken from Table 7 above. Wearable mass and wear rate are detailed in the following sections. In short, wearable mass is the physical amount of brake component (drum or disc) and friction material (lining or pad) on one vehicle that will wear off over the life of the component. Wear rate is how long it takes for the mass to wear off, estimated based on lining life from Table 7, VMT, and vocation braking intensity. Wearable mass and wear rate are calculated separately for foundation brake component (drum or disc) and friction materials (lining or pad).

4.b.1 Wearable Mass

LINK calculated wearable mass for each brake and axle type based on brake and friction material dimensions from the foundation brake sizes listed in Table 7. This quantity is the volume of brake component and friction material lost between the beginning and end of component life, estimated from before- and-after thickness tolerances estimated by LINK. This is scaled up to number of wheels assigned by brake configuration and vehicle weight class, as shown:

- Drum and Air Disc
    - Class 8 (T7): 2 steer axle wheels; 4 drive axle wheels on 2 tandem axles; 4 trailer axle wheels on 2 tandem axles.
    - Refuse truck (applied to all single unit T7 and heavy T6): 2 steer axle wheels; 4 drive axle wheels on 2 tandem axles.

- Hydraulic Disc
    - Class 6 (light T6): 2 steer axle wheels; 2 drive axle wheels.

Accounting for all wheels, resulting wearable mass estimates per vehicle are shown in Table 8. Total wearable mass for a given vehicle is the sum of steer, drive and trailer (if applicable) masses from Table 8, accounting for the brake types used on that vehicle. Component and friction material masses are additive, and were accounted for separately because of variation in wear rates.

Table 8. Wearable Mass Estimates (grams/vehicle)

	Drum		**Air Disc**		**Hydraulic Disc**	
	Drum	Friction Material	Disc	Friction Material	Disc	Friction Material
Steer	3.73	6.45	0.07	8.26	1.72	5.12
Drive	10.46	18.07	0.14	16.51	1.72	5.12
Trailer	10.46	17.81	n/a	n/a	n/a	n/a

4.b.2 Wear Rate

Wear rate quantifies how quickly wearable mass is exfoliated from drums, discs and friction material. Friction life estimates from Table 7 provide total miles required to erode wearable mass; the rate at which these miles accumulate can be estimated for each truck category from EMFAC estimates. Estimates of statewide daily VMT from EMFAC2017 account for both the number of trucks (vehicles in operation, VOI) and their mileage accumulation in a single day. Using daily VMT therefore scales up to total mass worn in a single day. For this calculation, wear rate is expressed as vehicles per day - in other words, how many vehicles' worth of wearable mass is worn through in a day.

The friction life estimates provided by brake suppliers account to some degree for the intensity of brake use by vocation – for example, on the same Class 8 truck configuration, friction life estimates for long-haul applications were estimated to range from 250,000-650,000 miles, while on short haul and delivery applications they were estimated to range from 150,000-300,000 miles. On a parallel path, the intensity of braking activity for different vocations was quantified for Task 1 as brake power density, total brake event power over each CARB HD vocation cycle divided by cycle distance. Since friction life estimates from suppliers and the brake power density calculations from Task 1 provide two independent estimates of braking intensity, we compared these estimates to develop a friction life estimates as function of truck vocation. The estimates are compatible; Figure 8 shows linear regressions between the mid-point of friction life estimates provided by suppliers for selected vocations, and the brake power density calculated for these vocations in Task 1. Separate regressions were run for drum and air disc brakes, and hydraulic disc brakes as their wear patterns are markedly different.

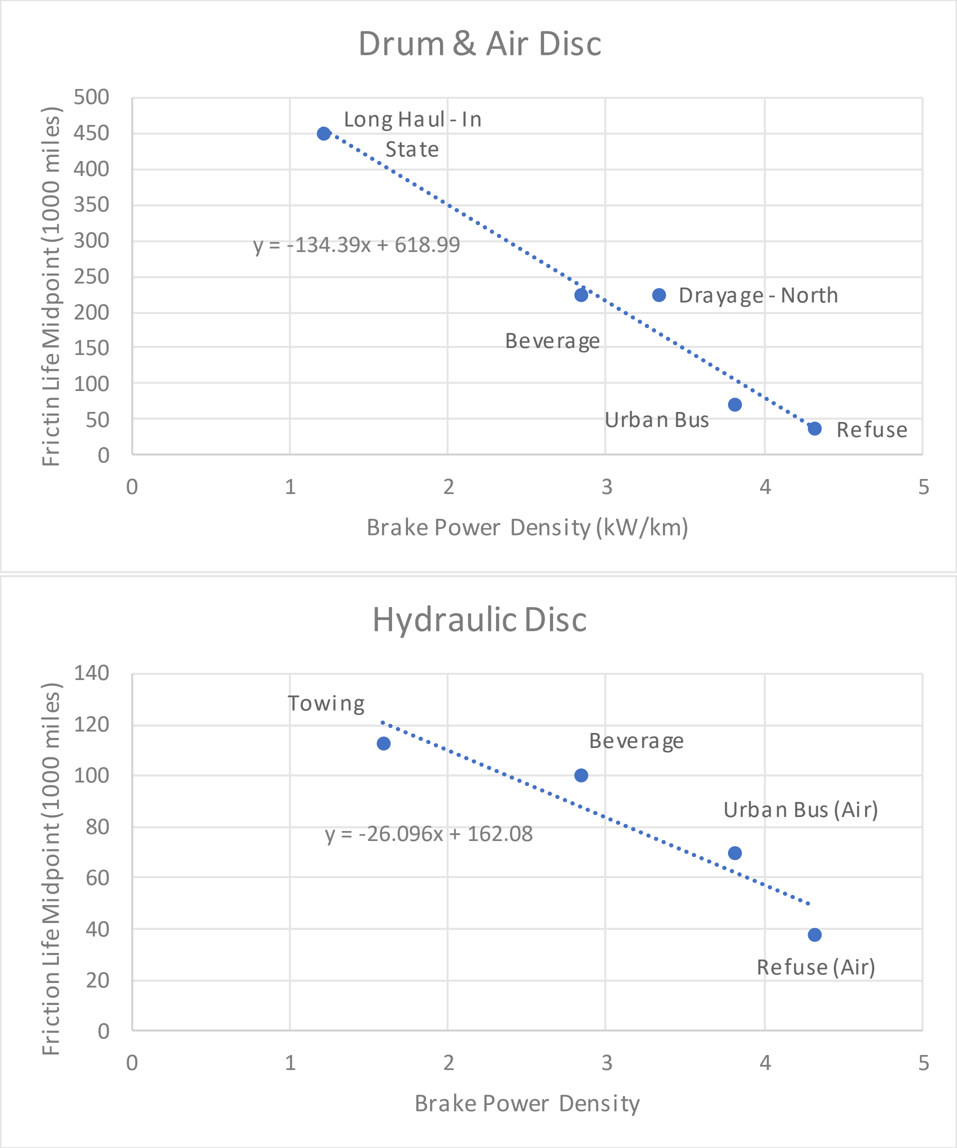


Figure 8. Market Survey Friction Life Estimates vs. Brake Power Density

The regression equations shown in the charts were used to estimate friction life for each EMFAC truck category, as a function of vocation cycle brake power density. These were used to generate vocation-specific friction life, presented in Table 9. Based on input from the suppliers, friction life is assumed the same for OE and aftermarket materials. The life of drum and disc components does depend on OE vs. aftermarket, and is estimated as a multiplier of friction life – 2x for OE components, and 1x for aftermarket components, per the market survey presented in the previous section

With an estimate of friction life, daily wear rate is calculated as (daily VMT / friction life). Daily VMT estimates by EMFAC truck category (2011) were drawn from CARB's EMFAC2017 web database (CARB 2019), based on 2020 calendar year estimates. VMT was desired at the vocation level to account for differences in braking intensity by vocation cycle for the brake wear calculation. In most cases EMFAC categories map to vocation types 1:1, but for Public, Construction and T6 Pickup & Delivery categories one EMFAC VMT value had to be distributed to multiple vocation types. In these cases, the VMT was split evenly across all vocations. Resulting daily VMT estimates from EMFAC, spread across vocations as noted, are shown Table 9. With friction life and daily VMT the wear rate for friction materials can be calculated as (Daily VMT / Friction Life), also shown in Table 9 ("n/a" denotes no market share). Wear rate for drum and disc components, not shown, were estimated in relation to friction material wear rates. Per supplier input, OE component wear rates were estimated to be half that of friction materials, while aftermarket component wear rates were estimated to be the same as those for friction material.

Table 9. VMT, Friction Life, and Wear Rate by Truck Category

EMFAC Category	Vocation Cycle	Brake Power Density (kW/km)	2020 Daily Statewide VMT (Miles)	Drum / Air Disc		Hydraulic Disc	
				Friction Life (Miles)	Wear Rate (Veh/Day)	Friction Life (Miles)	Wear Rate (Veh/Day)
T7 Ag	Agriculture	0.85	13,391	504,619	0.03	n/a	n/a
T7 CAIRP	Long Haul OOS	0.66	8,676,057	530,642	16.35	n/a	n/a
T7 CAIRP Const.	Construction	1.44	262,885	425,115	0.62	n/a	n/a
T7 CAIRP Const.	Cement Mixer	1.89	262,885	364,562	0.72	n/a	n/a
T7 NNOOS	Long Haul OOS	0.66	10,577,441	530,642	19.93	n/a	n/a
T7 NOOS	Long Haul OOS	0.66	3,408,594	530,642	6.42	n/a	n/a
T7 Other Port	Drayage North	3.33	243,037	171,175	1.42	n/a	n/a
T7 Dray - North	Drayage North	3.33	592,647	171,175	3.46	n/a	n/a
T7 Dray - South	Drayage South	1.94	1,960,246	358,799	5.46	n/a	n/a
T7 Public	Freeway Work	2.06	129,003	342,072	0.38	n/a	n/a
T7 Public	Sweeping	1.49	129,003	418,340	0.31	n/a	n/a
T7 Public	Municipal Work	1.87	129,003	367,186	0.35	n/a	n/a
T7 Public	Towing	1.59	129,003	404,867	0.32	n/a	n/a
T7 Single	Local Moving	1.28	2,161,966	446,545	4.84	n/a	n/a
T7 Single Const.	Construction	1.44	652,169	425,115	1.53	n/a	n/a
T7 Single Const.	Cement Mixer	1.89	652,169	364,562	1.79	n/a	n/a
T7 Solid Waste	Refuse	4.32	632,975	38,352	16.50	n/a	n/a
T7 Tractor	Long Haul IS	1.21	9,472,764	456,049	20.77	n/a	n/a
T7 Tract Const.	Construction	1.44	1,075,964	425,115	2.53	n/a	n/a
T7 Utility	Utility	2.19	32,009	324,467	0.10	n/a	n/a
T7 Gas Truck	Local Moving	1.28	17,097	446,545	0.04	n/a	n/a
T6 Ag	Agriculture	1.94	15,310	n/a	n/a	111,567	0.14
T6 PU & Del	Food	0.88	3,609,508	n/a	n/a	139,207	25.93
T6 PU & Del	Beverage	2.85	3,609,508	n/a	n/a	87,765	41.13
T6 PU & Del	Local Moving	1.28	3,609,508	n/a	n/a	128,602	28.07
T6 PU & Del	Airport Shuttle	2.60	1,209,657	269,876	4.48	n/a	n/a
T6 PU & Del	Refuse	4.32	3,609,508	n/a	n/a	49,357	73.13
T6 PU & Del	Urb/School Bus	3.82	2,446,951	105,660	23.16	n/a	n/a
T6 PU & Del	Express Bus	1.50	287,561	416,984	0.69	n/a	n/a
T6 IS Hv const	Construction	1.44	365,978	425,115	0.86	n/a	n/a
T6 IS Hv Const.	Cement Mixer	1.89	365,978	364,562	1.00	n/a	n/a
T6 IS Sm Const.	Construction	1.44	957,205	n/a	n/a	124,442	7.69
T6 IS Sm Const.	Cement Mixer	1.89	957,205	n/a	n/a	112,686	8.49
T6 Public	Freeway Work	2.06	100,532	n/a	n/a	108,320	0.93
T6 Public	Sweeping	1.49	100,532	n/a	n/a	123,126	0.82
T6 Public	Municipal Work	1.87	100,532	n/a	n/a	113,196	0.89
T6 Public	Towing	1.59	100,532	n/a	n/a	120,511	0.83
T6 Utility	Utility	2.19	66,481	n/a	n/a	104,902	0.63
T6 Gas Truck	Local Moving	1.28	2,650,540	n/a	n/a	128,602	20.61

4.b.3 Results

Applying market share (Table 7), wearable mass (Table 8) and wear rate (Table 9) values to Equation 3 produces BWI by EMFAC vehicle category. These are presented in Table 10 for the OE case, ranging from highest to lowest BWI. The highest BWI are in Class 8 long haul vocations, though bus and MD pickup and delivery applications take up many slots in the top 10 due to high braking intensity and friction wear rates. The top 10 categories/vocations account for about 80 percent of total BWI. Using aftermarket wear rates did not change the ranking of BWI, but affected total BWI estimates.

Table 10. BWI Results Ranked by Truck Category

Rank	Weight Category	EMFAC Category	Vocation Cycle	Total BWI (kg)	Percent of Total	Cumulative %
1	Class 8 (T7)	Tractor	Long Haul IS	1,114	13.7%	13.7%
2	Class 8 (T7)	NNOOS	Long Haul OOS	1,069	13.1%	26.8%
3	Class 8 (T7)	CAIRP	Long Haul OOS	877	10.8%	37.6%
4	Class 4-7 (T6)	Pick Up & Delivery	Refuse	875	10.7%	48.3%
5	Class 4-7 (T6)	Pick Up & Delivery	Urb/School Bus	576	7.1%	55.4%
6	Class 4-7 (T6)	Pick Up & Delivery	Beverage	492	6.0%	61.4%
7	Class 8 (T7)	Solid Waste	Refuse	455	5.6%	67.0%
8	Class 8 (T7)	NOOS	Long Haul OOS	345	4.2%	71.2%
9	Class 4-7 (T6)	Pick Up & Delivery	Local Moving	336	4.1%	75.3%
10	Class 4-7 (T6)	Pick Up & Delivery	Food	310	3.8%	79.1%
11	Class 8 (T7)	Dray - South	Drayage South	293	3.6%	82.7%
12	Class 4-7 (T6)	Gasoline Truck	Local Moving	247	3.0%	85.7%
13	Class 8 (T7)	Dray - No	Drayage North	186	2.3%	88.0%
14	Class 8 (T7)	Tractor Construction	Construction	136	1.7%	89.7%
15	Class 8 (T7)	Single	Local Moving	133	1.6%	91.3%
16	Class 4-7 (T6)	Pick Up & Delivery	Airport Shuttle	111	1.4%	92.7%
17	Class 4-7 (T6)	Instate const. small	Cement Mixer	102	1.2%	93.9%
18	Class 4-7 (T6)	Instate const. small	Construction	92	1.1%	95.1%
19	Class 8 (T7)	Other Port	Drayage North	76	0.9%	96.0%
20	Class 8 (T7)	Single Construction	Cement Mixer	49	0.6%	96.6%
21	Class 8 (T7)	Single Construction	Construction	42	0.5%	97.1%
22	Class 8 (T7)	CAIRP Construction	Cement Mixer	39	0.5%	97.6%
23	Class 8 (T7)	CAIRP Construction	Construction	33	0.4%	98.0%
24	Class 4-7 (T6)	Instate heavy const.	Cement Mixer	28	0.3%	98.4%
25	Class 4-7 (T6)	Instate heavy const.	Construction	24	0.3%	98.6%
26	Class 4-7 (T6)	Pick Up & Delivery	Express Bu	17	0.2%	98.9%
27	Class 4-7 (T6)	Public	Freeway Work	11	0.1%	99.0%
28	Class 4-7 (T6)	Public	Municipal Work	11	0.1%	99.1%
29	Class 8 (T7)	Public	Freeway Work	10	0.1%	99.2%
30	Class 4-7 (T6)	Public	Towing	10	0.1%	99.4%
31	Class 4-7 (T6)	Public	Sweeping	10	0.1%	99.5%
32	Class 8 (T7)	Public	Municipal Work	10	0.1%	99.6%
33	Class 8 (T7)	Public	Towing	9	0.1%	99.7%
34	Class 8 (T7)	Public	Sweeping	9	0.1%	99.8%
35	Class 4-7 (T6)	Utility	Utility	8	0.1%	99.9%
36	Class 8 (T7)	Utility	Utility	3	0.0%	99.9%
37	Class 4-7 (T6)	Ag	Agriculture	2	0.0%	100.0%
38	Class 8 (T7)	Ag	Agriculture	1	0.0%	100.0%
39	Class 8 (T7)	Gasoline Truck	Local Moving	1	0.0%	100.0%

The contribution of BWI by brake type is shown in Figure 9. Drum brakes account for about one-half of total BWI in the state, and hydraulic disc about one-third.

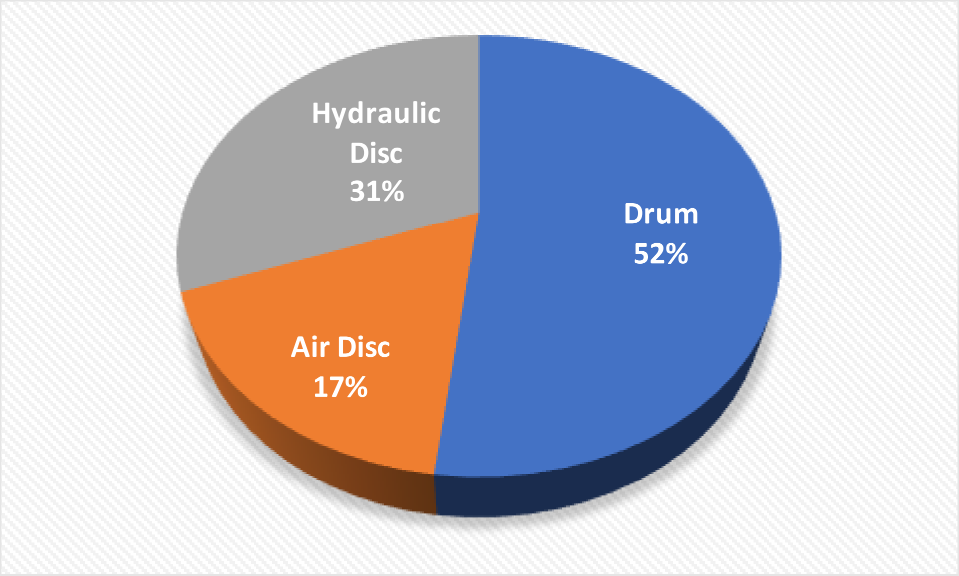


Figure 9. Contribution of Brake Type to Total BWI

These BWI results provide a good foundation for considering the vehicle categories, vocations and brake types that need to be included in dynamometer emissions testing to best represent brake emissions in California. Building on BWI, development of the dynamometer test matrix considered loaded vs. unloaded configurations, and the mix of OE and aftermarket on various truck vocations, as detailed in the following section.

SECTION 5 EMISSIONS TEST MATRIX

Under Task 3, ERG and LINK developed a plan for conducting dynamometer emissions testing. Based on project resources the matrix was constructed assuming 4 dynamometer test days for the LD vehicle and 36 days for HD trucks. This accounted for the time required for hardware changes, PM filter changes, burnish of new friction material, and calibration of dyno cooling settings.

5.a HD vehicle tests

The HD test plan needed to account for several dimensions in attempting to generate emissions data that can be applied to the entire HD truck fleet in California. The broad conclusions from the mass balance analysis were that drum, air disc and hydraulic disc brake configurations all contribute to overall brake wear, as do all three axles types (steer, drive, trailer). To account for all brake configurations and axle types required multiple test fixture setups as they vary in equipment and size, requiring unique hardware installation. Given a set budget of test days, the number of valid emissions tests needed to be determined working backwards from the time required for dynamometer setup and calibration on each brake and axle test fixture. In addition, changing friction material from original equipment (OE) to aftermarket (AM) constituted additional hardware change. Each change in hardware required installation time plus extensive time for burnish to break in the material. Once a test fixture was installed and burnished, a change in test cycle or load condition required additional time to change the PM filter. Accounting for all of this, an emissions test matrix was developed to maximize the coverage of brake wear index (BWI) estimated in the mass balance analysis, and to cover a range of average speed and brake power densities for application in EMFAC.

The proposed vocation cycles were selected based on the following 3 criteria: 1) cover a range of average speed, to facilitate modeling of PM emissions as a function of speed in EMFAC; 2) cover a range of vocation cycle brake power density (defined in the interim report), to allow this metric to be factored into the development of EMFAC emission rates if desired; and 3) cover as much total BWI as possible. Figure 10, showing cycle brake power density vs. cycle average speed, was constructed to aid in assessing these criteria.

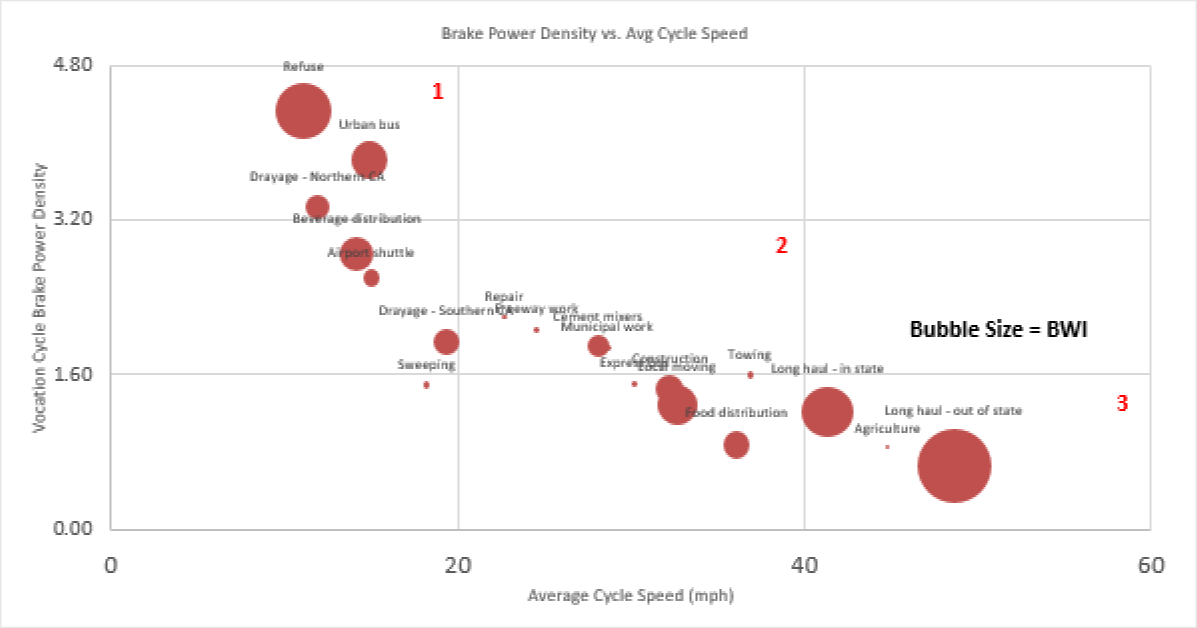


Figure 10. BWI by Cycle Speed and Brake Power Density

As one might expect, brake power density and average cycle speed are well-correlated. The first two criterion (range of operation) only apply to Class 8 trucks, since other vocations are restricted to more local operation and hence low speed. Choosing cycles in the areas labeled 1, 2 and 3 would provide data over a range of both speed and brake power density. Choosing the largest bubbles (BWI) addresses the third criterion. Combining the conclusions from BWI analysis, the proposed set of test fixtures and cycles to be tested is shown in Table 11. Ideally each of these fixtures and cycles would be run with OE and AM friction material, with repeat tests. Additionally, it is desirable to have fully loaded and unloaded tests on the Class 8 fixtures, since (as detailed in the interim report) operation between these modes is roughly 50/50 and brake temperature differences are significant. However, the constraint of 36 test days precludes running this full matrix of tests. Development of the final test matrix required prioritizing which Class 8 test fixtures would be tested at 2 load points (fully loaded and unloaded), and which would receive repeat tests. The choice of fixtures testing on 2 load points was determined by reviewing axle loading in the Task 1 HD test reports provided along with the interim report. For Class 8 loaded vs. unloaded configurations the difference in loading was relatively small for steer axles, so unloaded tests on Class 8 steer axles were deemed unnecessary. BWI was then used to prioritize tests with repeats: the largest BWI test fixtures were Class 8 drive and trailer axles, and Hydraulic disc drive axle.

Table 11. HD Emissions Test Matrix

All tests conducted with original equipment (OE) and aftermarket (AM) friction material

Test Fixture	Cycle 1	Cycle 2	Cycle 3	Loads	Repeat Tests
Class 8 Drum Steer	Drayage N*	Cement	LH OOS**	1	
Class 8 Drum Drive	Drayage N	Cement	LH OOS	2	✓
Class 8 Drum Trailer	Drayage N	Cement	LH OOS	2	✓
Class 8 Disc Steer	Drayage N	Cement	LH OOS	1	
Class 8 Disc Drive	Drayage N	Cement	LH OOS	2	✓
Refuse Truck ADisc Steer	Refuse			1	
Refuse Truck ADisc Drive	Refuse			1	
Urban Bus ADisc Steer	Urban Bus			1	
Urban Bus ADisc Drive	Urban Bus			1	
Hydraulic Disc Steer	Beverage	Local Moving		1	
Hydraulic Disc Drive	Beverage	Local Moving		1	✓

*Northern California Drayage **Long Haul Out-Of-State

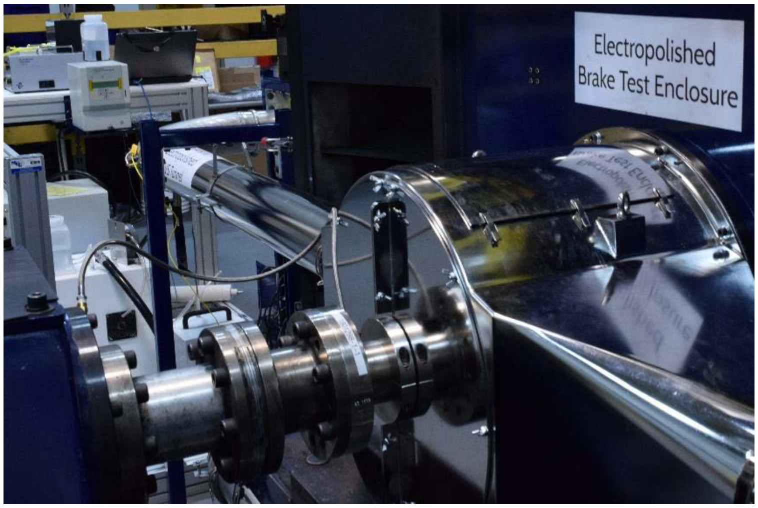
As described in the next section, each of the test fixtures listed in Table 11 above were new components that, once installed on the dynamometer, underwent a burnish procedure to break in the material to normal in-use levels. Akin to “de-greening” of vehicle components for exhaust testing, this process ran the vocation test cycles until stabilization was reached on brake pressure and real-time PM loss. All burnish cycle data is included with the raw test reports that are companion to this report.

SECTION 6 DYNAMOMETER EMISSIONS TEST SETUP

6.a Preparation

6.a.1 Test fixture

The HD brake dynamometer for PM emissions testing was modified from a standard commercial vehicle development dynamometer at LINK's Dearborn research facility. The dynamometer was upgraded and modified to provide an enclosure for the brake assembly and add ducting for emission sampling. The ducting was electropolished to eliminate surface retention of particles. An airflow nozzle was added to provide temperature control and sample propulsion. Details of LINK's process for HD dyno build-out, preparation and setup are included in Appendix B.



LINK HD Brake Emissions Dyno

The LD emissions measurement was conducted on the same LD dyno with nearly identical setup to that for the CARB LD Study, as documented in Standard et al 2020. The primary difference for this program was the use of two parallel 47 mm Teflon filters to measure PM_{10} and $PM_{2.5}$, rather than the 100S4 PM filter system used in the LD program.

6.a.2 Emissions test setup

PM emissions testing on the dynamometer was conducted for the test matrix outlined in the prior section. For the LD regenerative testing, the track testing provides real-world braking parameters for use in the laboratory testing. For the HD testing, dynamometer parameters were be derived from thermodynamic modeling or direct track testing results, depending on the configuration and cycle being tested. Calibration was conducted for each brake configuration and vocation cycle to ensure brake temperature were within range compared to target temperatures. For each emissions test, LINK compiled a test report to document filter-based emissons, real-time emissions, vehicle parameters (vehicle weight and, test inertia, vehicle description, brake size, part numbers, etc.), brake temperatures, brake torque, and dyno parameters. The reports also include like data for the burnish procedure which proceeded all emissions tests. The remaining description of the test layout is from Standard et. al 2020, with modifications as necessary to convey updates for the HD system.

The dynamometer test setup elements included the following:

- Software controls (ProLINK Duty Cycle Program) with capability to recreate speed and brake deceleration profiles derived from the driving schedules measured on the vehicle during the proving ground measurements.
- Measurement, control, and data storage for speed, torque (deceleration), brake pressure, and friction coefficient during braking at 200-1000 Hz; brake temperatures at 50 Hz.
- Measurement and data storage for speed, torque, brake pressure, and brake temperatures at 10 Hz in-between brake events.
- Constant velocity sampling system with fixed cooling and sampling airflow during a given test.
- Ability to adjust cooling airflow prior to the test to reflect the cooling rates established for the project.
- Cooling air with climatic environmental controls to provide stable (20 ± 5) °C and (50 + 10) % relative humidity; this helps ensuring a stable set of conditions when the particles enter the sampling train (between the aspiration position and the actual instrument).
- Adapt a constant velocity sampling system, cooling air climatic environmental controls, and instrument cluster as described in this section.

Similar to the CARB LD program, PM measurement was conducted with gravimetric filters supplemented with instruments to collect real-time measurement of particle mass, number, and size. A key difference from the CARB LD program was that the 100S4 filter setup used in the LD program and initially proposed for Caltrans was replaced with two separate 47mm Teflon filters. This allowed more frequent filter switching, enabling direct emission measurement of PM_{10} and $PM_{2.5}$ on each individual vocation cycle. 250 teflon filters were shipped in batched from the Haagen-Smit Laboratory in El Monte, CA directly to LINK's Dearborn test facilities.

The real-time instruments were the same as used for the CARB LD study, and details of instrument specifications and calibrations are found in this study. A short summary of the instruments in below, with improvements made between the CARB LD and Caltrans studies noted in bold.

TSI QCM MOUDI 140. The Model 140 Quartz Crystal Microbalance (QCM) MOUDI is designed to perform continuous, real-time size-segregated mass concentration measurements of particles smaller than 2.5 µm. The system uses six cutpoint stages at 960, 510, 305, 156, 74 and 45 nm and operates at a 10 L/min inlet flow rate. **Based on input from the CARB LD study results, the QCM was improved to report 10 second average results vs. 60 second average results.**

TSI CPC. The 3790A Condensation Particle Counter (CPC) is a full-flow design PM particle counter that has a particle size lower detection limit of 23 nm. The unit is designed to linearly respond to particle concentrations from 1 to 10,000 particles/cm3 and can operate continuously taking 10Hz measurements. TSI indicates a counting accuracy of ± 10%. The PMP has specified the use of this unit as the baseline for brake particle counting without the use of a catalytic stripper or other volatile particle removal

(VPR) device. No VPR device was used in this program.

TSI APS. The 3321 Aerodynamic Particle Sizer (APS) measures the aerodynamic size of particles between 0.5 ‐ 20 μm. The system operates using time-of-flight aerodynamic sizing to determine the particle’s behavior while airborne and is unaffected by index of refraction or Mie scattering. The unit also measures light-scattering intensity in the equivalent optical size range of 0.37 to 20 μm. The system offers continuous sampling at 1 Hz.

TSI EEPS. The 3090 Engine Exhaust Particle Sizer (EEPS) is a spectrometer that measures the size distribution of particle emissions from 5.6 to 560 nm continuously at up to 10 Hz. The EEPS provides outputs of size distribution in the above range as well as particle number concentrations down to 200 particles/cm3.

A schema TSI Inc. measurement system used in this work are depicted in Figure 11**Error! Reference source not found.**. The systems are shown along with their component names as well as their particle measurement size range, along with whether they measure mass or count (#).

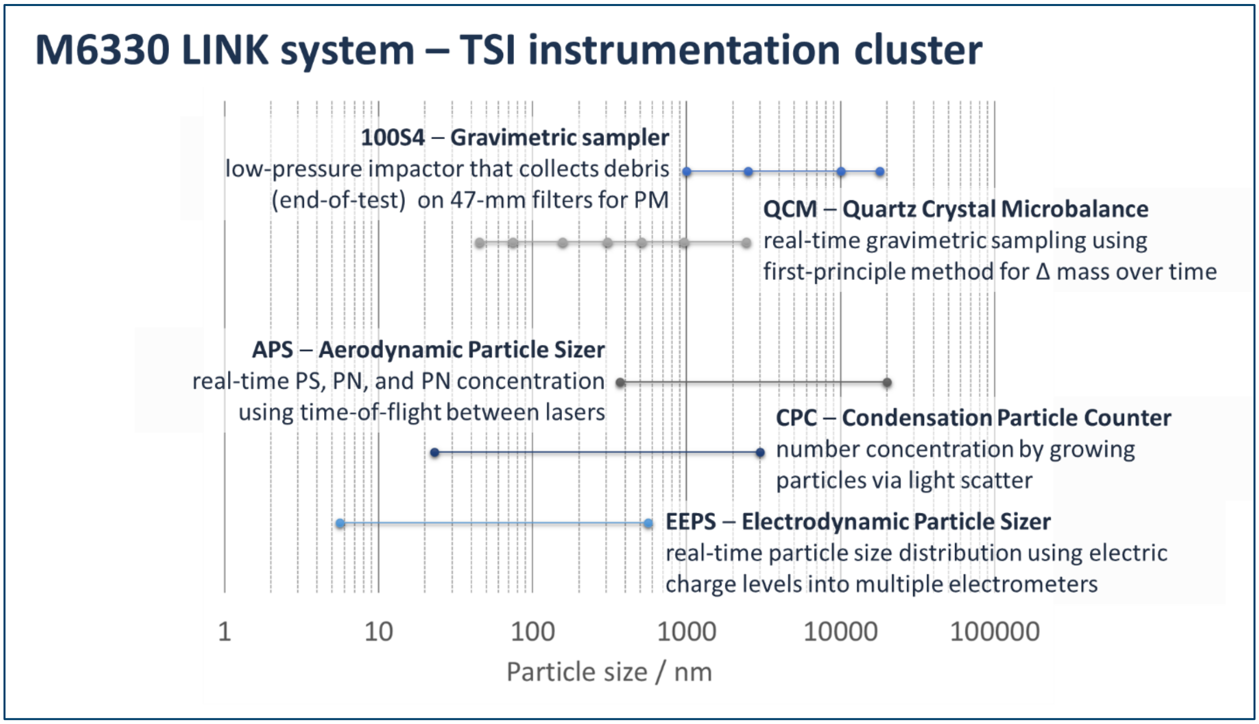


Figure 11. TSI Inc. Particulate Sampling Equipment Ranges

A schematic of the system layout is shown in **Error! Reference source not found.**. The layout employs round ducting in stainless steel, with internal electropolished finish, with minimal constrictions and with at least 8 diameters without disturbances prior to brake emissions sampling and prior to measuring the cooling airflow (standard pitot tube). This item follows the U.S. EPA method 1A regarding sampling and airflow measurement positions.

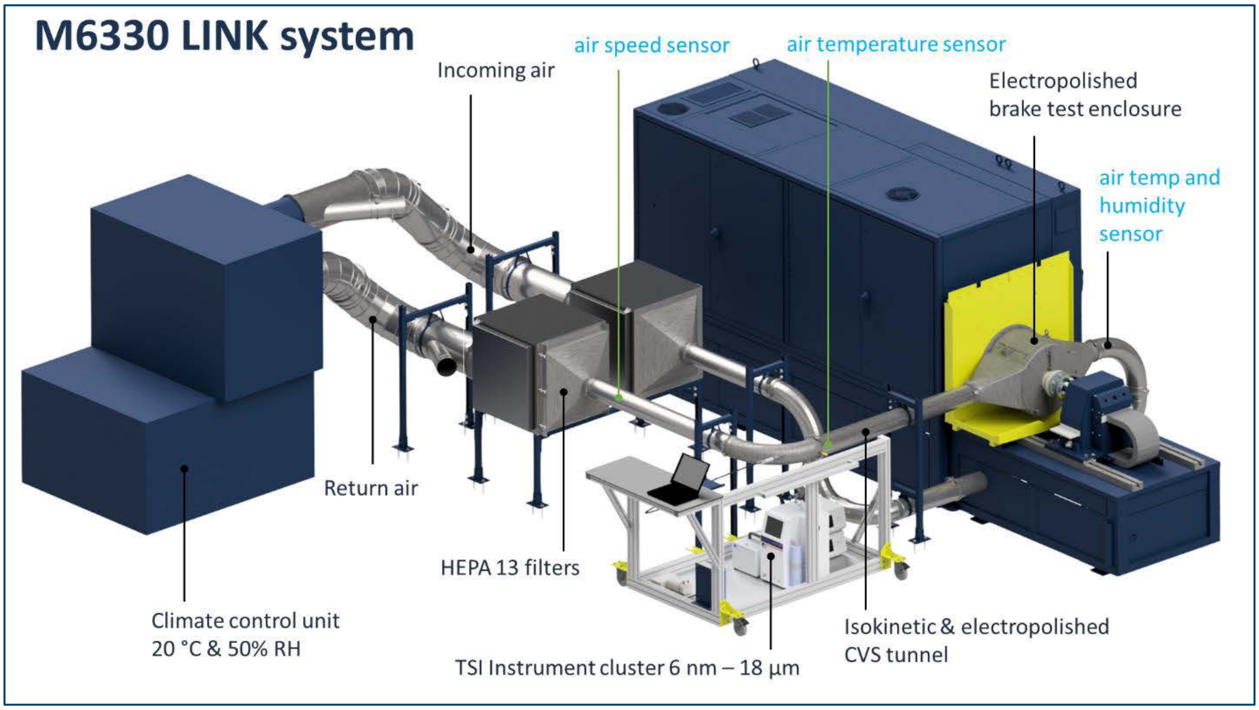


Figure 12. LINK Brake PM Test Setup

Elements of the layout include:

- Low background noise at approximately five times below the average measurements during the tests.
- Design layout to minimize aerodynamic losses (bends, constrictions, turbophoretic, gravitational deposition, diffusion, and aspiration at the nozzle).
- Isokinetic sampling within 10% maximum deviation (for instruments measuring above 1 µm) to avoid skewing the particle size distribution data.
- A transport time of less than 5 seconds to minimize potential changes in size distribution due to coagulation. In addition, the short transport time will allow the particle size distribution to be closer to the actual distribution as-generated by the friction surface.

The emissions sample line setup is detailed in Figure 13; as noted, this differs from the CARB LD study in the use of two parallel teflon filters in place of a 100S4.

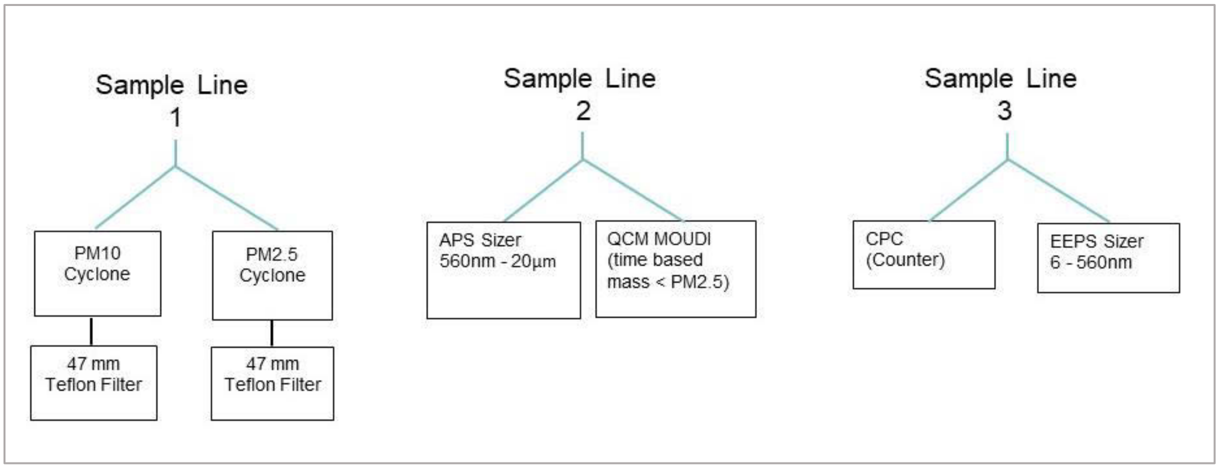


Figure 13. Sample Line Setup

SECTION 7 HEAVY DUTY VEHICLE EMISSIONS TESTING

7.a.1 Brake and friction material parts

Though specific brake parts were identified for testing in the market survey conducted for Task 2, the COVID shutdowns that began in Spring 2020 required several mid-course corrections. Brake suppliers were unable to locate all parts through normal distribution channels, requiring alternatives to be quickly identified and procured. Two brake suppliers, Meritor and Bendix, stepped up to provide parts in kind to keep the project on schedule. An additional work-around was required to address incorrectly sized original equipment friction material for the bus that arrived from Europe and could not be returned in a timely manner. In this case, refuse truck friction material was used for the bus testing. The final parts matrix used for testing is shown in Table 12.

Table 12. Brake Parts Tested

Vehicle Type	Axle	Brake Type	Parts	Rotor/Drum Part Number	Pad/Shoe Part Number
Class 8	Trailer	Drum	OE	66864B	Mer. MA212 D4707
Class 8	Steer	Disc	OE	10083924	Mer. EX225+L D1370
Class 8	Steer	Disc	OE Rot & AM Pads	10083924	AMPM1370BA
Class 8	Drive	Disc	OE	10083924	Mer. EX225+L D1370
Class 8	Steer	Drum	OE	10014756	Mer. MA1201 D4720
Class 8	Steer	Drum	OE Rot & AM Pads	10014756	KT4720QBA202R
Refuse	Steer	Disc	OE	Mer. 23-123642-002	Mer. EX225+H D1311
Refuse	Steer	Disc	AM	AMP2219N	AMPM1311BA
Refuse	Drive	Disc	OE	Mer. 23-123642-002	Mer. EX225+H D1311
Refuse	Drive	Disc	AM	AMP2219N	AMPM1311BA
Class 8	Trailer	Drum	OE Dru & AM Shoe	66864B	KT4707QBA202R

Bus	Drive	Disc	Refuse OE	Mer. 23-123642-002	Mer. EX225+H D1311
Bus	Drive	Disc	OE Rot & AM Pads	Scania T-Brake	K109249
Bus	Steer	Disc	OE Rot & AM Pads	Scania T-Brake	K109249
Bus	Steer	Disc	Refuse OE	Mer. 23-123642-002	Mer. EX225+H D1311
Class 8	Drive	Disc	OE Rot & AM Pads	10083924	AMPM1370BA
MHDV	Drive	Disc	OE	Mer. 23-123458-002	Mer. MA707 D769
MHDV	Drive	Disc	OE Rot & AM Pads	Mer. 23-123458-002	E11107690
MHDV	Steer	Disc	OE	Mer. 23-123458-002	Mer. MA707 D769
MHDV	Steer	Disc	OE Rot & AM Pads	Mer. 23-123458-002	E11107690
Class 8	Drive	Drum	OE	1009830	Mer. MA2001 D4707
Class 8	Drive	Drum	OE Dru & AM Shoe	1009830	KT4707QBA202R

7.a.2 Coastdown coefficients

The effect of vehicle coastdown - the deceleration caused by tire rolling resistance, aerodynamics, engine braking, and vehicle friction – is important to account for as it defines where braking is required. Assuming all deceleration requires braking overestimates the amount of braking and hence emissions. To account for this, for HD vehicles coastdown coefficients were adapted from Ates and Matthews 2012,which conducted coastdown tests on a number of heavy duty truck configurations which overlapped with the vehicle types being run in the brake PM programs. For the Tesla, coastdown coefficients determined by the manufacturer and submitted to EPA for emissions testing were used.

Table 13. HD Coastdown Coefficients

Brake Test Vehicle Type	A (N)	B (N/kph)	C (N/kph^2)	Test Weight (kg)
Class 8 Loaded	1,985.45	21.023	0.2538	36,746
Class 8 Unloaded	580.61	15.332	0.2930	13,045
Class 6	687.54	26.387	0.0502	12,603
Refuse	1,082.43	28.93	0.0848	20,276
Bus	847.40	25.514	0.1336	16,465

7.a.3 Temperature calibration

All configurations were run on the HD dynamometer to determine cooling setting necessary to match real-world temperature conditions. The targets for this calibration were 1 Hz brake temperature measured during from track testing conducted in Task 1, where the same cycles were tested (Drayage, Refuse, Urban Bus, and Beverage); or modeled temperatures estimated by the HD brake temperature model for cycles that were not tested directly on the track (Cement, Local Moving, Long Haul Out-of-State). For most configurations, trial-and-error was conducted to get the best match; coastdown coefficients were introduced to improve matches, air flow was varied between low (7.5 kph) or high (70 kph), and in some cases dyno load was reduced to achieve acceptable temperatures. Temperature tolerance criteria established by the Particle Measurement Protocol (PMP) based on the CARB LD study were used to judge calibration match, though the variation in HD temperatures is expected to be greater than for LD due to the wider variety of truck, brake and airflow configurations. The following LD PMP temperature acceptability criteria were therefore considered guidelines rather than actual rules (Barbossa, H. 1720) in judging the temperature match over each cycle, configuration, axle, and loading scenario:

- Average 1Hz temperature within ±10 ℃ of target
- Peak temperature within ±25 ℃ of target
- Initial Brake Temperature (IBT) within ±15 ℃ of target
- Final Brake Temperature (FBT) within ±25 ℃ of target

Calibration results are shown in Table 14 along with the airflow settings used to achieve the calibration. In limited cases, the target temperatures simply could not be reached on the dynamometer.

Table 14. HD Dyno Temperature Calibration Results

Vehicle	Brake	Axle	Vocation	Track (PG) /Model (M)	Avg 1 Hz (±10 C)	IBT (±15 C)	FBT (±25 C)	Peak (±25 C)	Airspeed (km/h)
Class 8 Tractor	Disc	Drive	Drayage	PG	-6	10	13	3	70
Class 8 Tractor	Drum	Steer	Drayage	PG	7	12	18	23	70
Class 8 Trailer	Drum	Trailer	Drayage	PG	-24	-4	-7	-38	7.5
Class 8 Tractor	Disc	Drive	LH OOS	M	0	0	0	0	70
Class 8 Tractor	Drum	Steer	LH OOS	M	1	0	4	25	70
Class 8 Trailer	Drum	Trailer	LH OOS	M	-6	0	-9	-9	7.5
Class 8 Tractor	Disc	Drive	Cement	M	-1	-3	10	1	70
Class 8 Tractor	Drum	Steer	Cement	M	4	6	18	6	70
Class 8 Trailer	Drum	Trailer	Cement	M	-10	5	2	-22	7.5
Motorcoach	Disc	Steer	Urban Bus	PG	-17	-18	-28	-23	7.5
Motorcoach	Disc	Drive	Urban Bus	PG	-7	-9	-27	-21	7.5
Refuse	Disc	Steer	Refuse	PG	-16	-16	-2	-10	7.5
Refuse	Disc	Drive	Refuse	PG	-25	-31	-17	-21	70

7.a.4 Emissions instrumentation calibration

7.b Emission testing

7.b.1 Final testing protocol and order

Testing was conducted at LINK's Dearborn test facility in October-November 2020 according to the protocol shown in Table 15. Included in the text matrix are burnish procedures (break-ins when new configurations installed on dynamometer), and tests for tunnel blanks. In the course of burnish testing, it was discovered that brake pressure stabilized after 200 braking events, well before the formal burnish cycle was complete. To conserve dynamometer time, the procedure was shortened to 200 braking events. Vocation cycles were run for a minimum of 2 hours

Table 15. HD Test Protocols

Air disc/drum brake
Burnish (200 stops at 250 °F and 200 stops at 500 °F)
Resink pad/shoe
Re-run 50 stops at 500 °F
Vocation cycles (1 for Bus/Refuse, 3 for Class 8)
Intermittent tunnel blank tests
Hydraulic disc brake
Burnish SAE J2684 (500 snubs at 393 °F)
Resink shoe
Re-run 50 stops at 500 °F
Run vocations (2 for Class 6)
Intermittent tunnel blank tests

SECTION 8 HEAVY DUTY VEHICLE EMISSIONS RESULTS

8.a Heavy Duty Vehicles

8.a.1 Operational parameters

Brake temperatures (rotor and pad) and brake torque averages across brake configuration, axle and test type are summarized in **Error! Reference source not found.**. These follow expected trends in terms of brake intensive, loading, and brake type, as observed in earlier track testing. That is, brake temperature are a function of braking power, braking density, and loading. Because the brake temperature were calibrated to track testing, these data serve as more of a quality assurance check to confirm that replication of temperature son the dynamometer reflect expected trends.

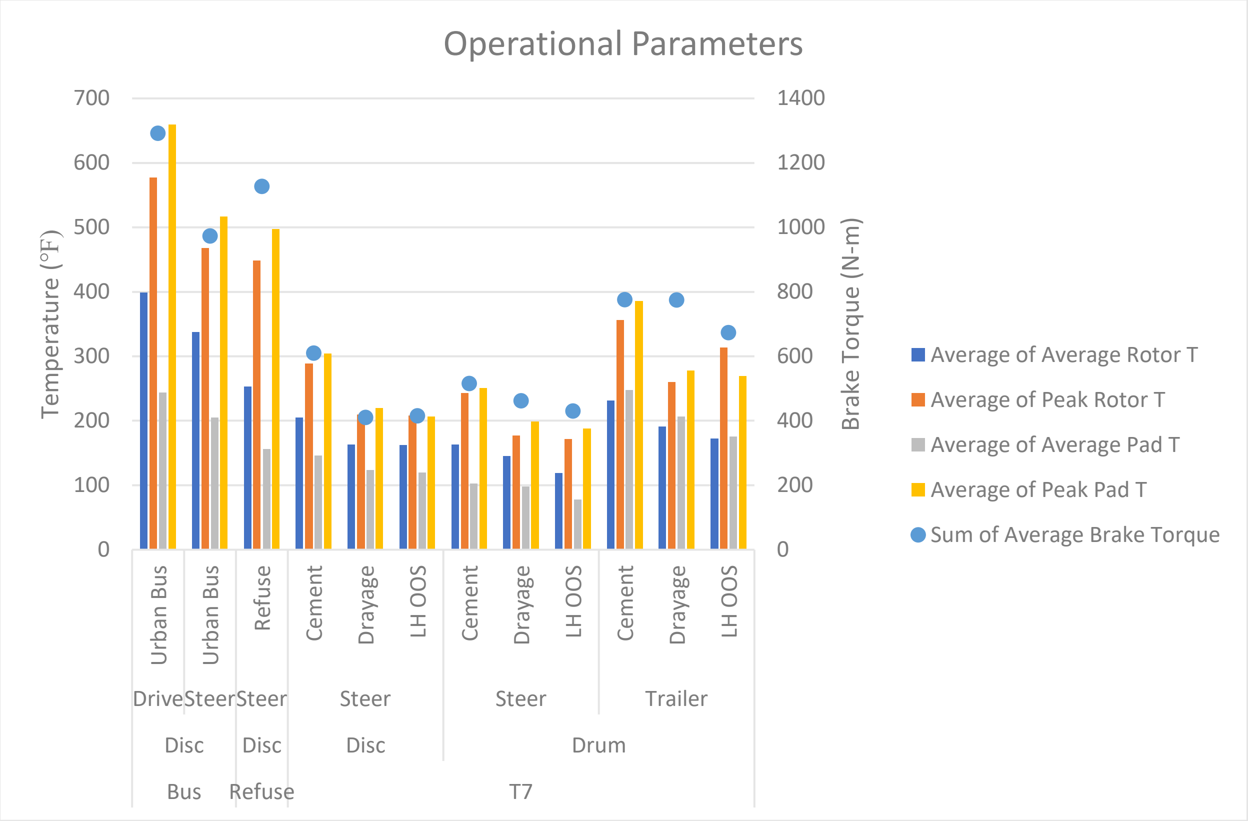


Figure 14. HD Operational Parameters

8.a.2 *Statistical Analysis of Filter Data*

A statistical analysis was conducted on individual wheel PM_{10} results to determine where data could be grouped for analysis, and what factors were important to break out for modeling. The initial focus of this analysis was to determine if there was any statistical difference in the OE and AM tests, as visual inspection showed no trend. Grouping these would in effect create a replicate test for every configuration, axle, loading and vocation cycle.

Parameters of the statistical analysis are as follows:

- Independent variable: PM_{10} mg/mi
- Dependent variables: Brake, Axle, Load, Equipment, Cycle, Flow
- Categorical variable coding:
  - BRAKE: 0=Disc, 1=Drum
  - STEER: 0=No, 1=Yes
  - DRIVE: 0=No, 1=Yes [Both 0 = Trailer]
  - LOAD: 0=Unloaded, 1= Fully Loaded
  - EQUIPMENT: 0=Original, 1=Aftermarket

- DRAYAGE: 0=No, 1=Yes
- CEMENT: 0=No, 1=Yes [Both 0 = Long Haul]
- FLOW: 0=7.5 kph, 1=70 kph

The ANOVA result for all Class 8 trucks, and drum brakes only, showed significance ($p < 0.05$) for load, cycle and flow. Brake, axle and original vs. aftermarket equipment were not significant, an important finding with respect the treatment of OE and AM data for the emissions analysis.

8.a.3 Filter Results By Configuration and Axle

PM_{10} results from the teflon filters for individual wheels are shown in this section. PM_{10} results are shown split by $PM_{2.5}$ (from separate filter), and $PM_{2.5-10}$, the difference in the mass of both filters. The sum of these is total PM_{10}.

Class 8 Trucks

The average of individual wheel results for the Class 8 (T7) tractor-trailer configurations are shown in **Error! Reference source not found.** for disc brakes and **Error! Reference source not found.** for drum brakes. These are all full-load tests (80,000 lbs). The trailer was only tested as drum brake, based on market survey estimating that 90 percent of trailer brakes are drum. The large differences in drive and steer axle emissions for the two brake types are believed to be influenced by difference in air flow used for brake cooling, which affected drum brake emissions as discussed later in the section.

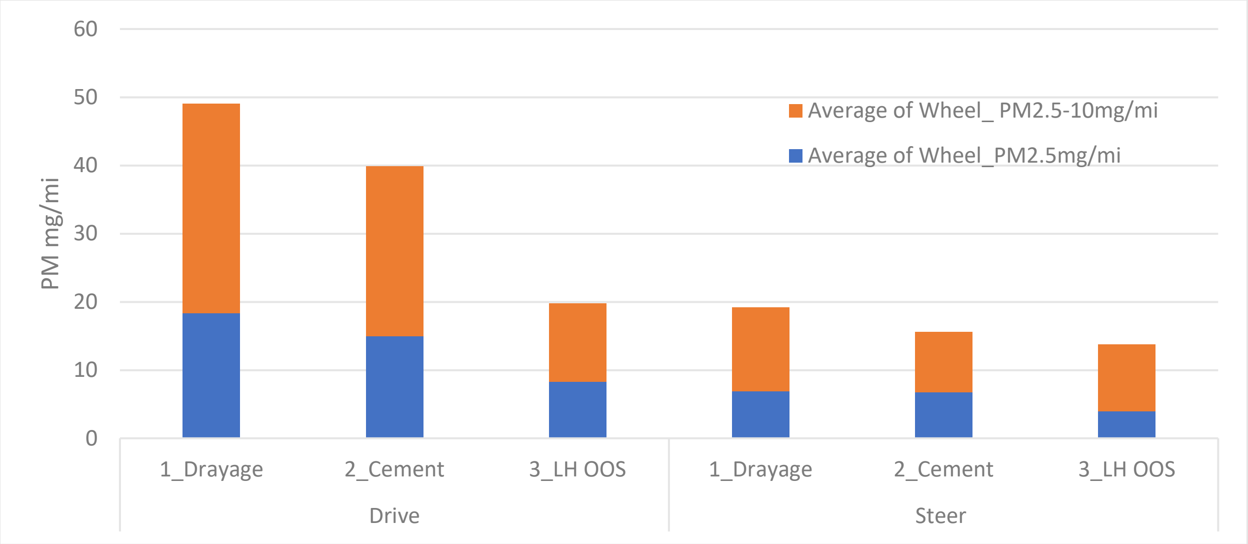


Figure 15. Loaded Class 8 Disc Brake Individual Wheel Means

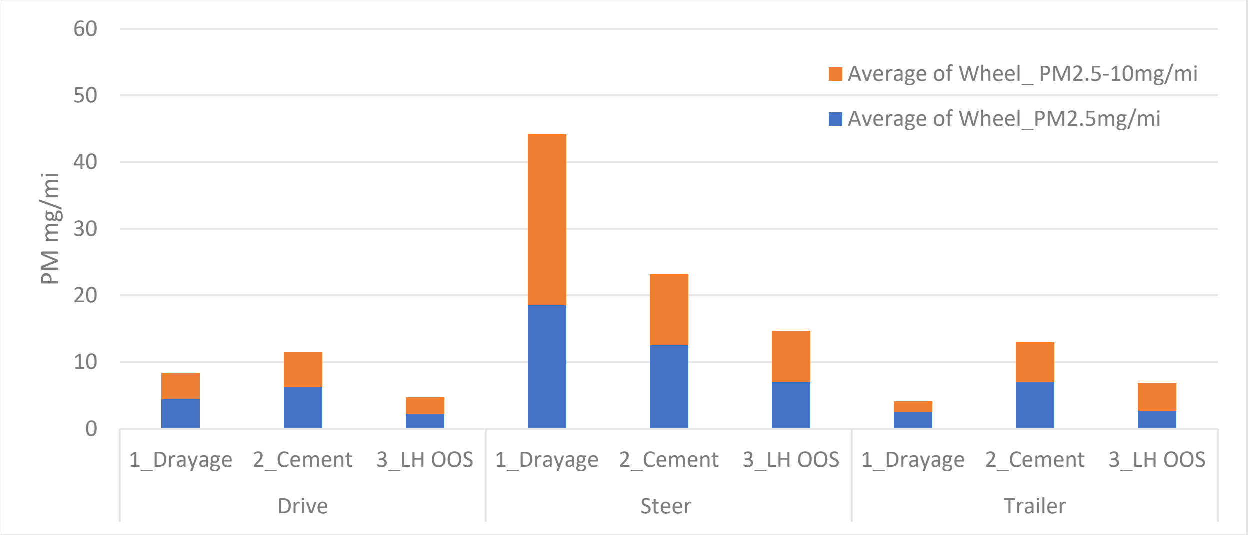


Figure 16. Loaded Class 8 Drum Brake Individual Wheel Means

Other Trucks

The average of individual wheel results for the Class 6 Medium-Duty (T6) with hydraulic disc brakes, bus with air disc brakes, and simulated refuse truck with air disc brakes are shown in **Error! Reference source not found.**. The refuse truck shows highest emissions, followed by the bus, reflective of the braking-intensive duty cycles. T6 hydraulic disc brake emission is relatively low by comparison.

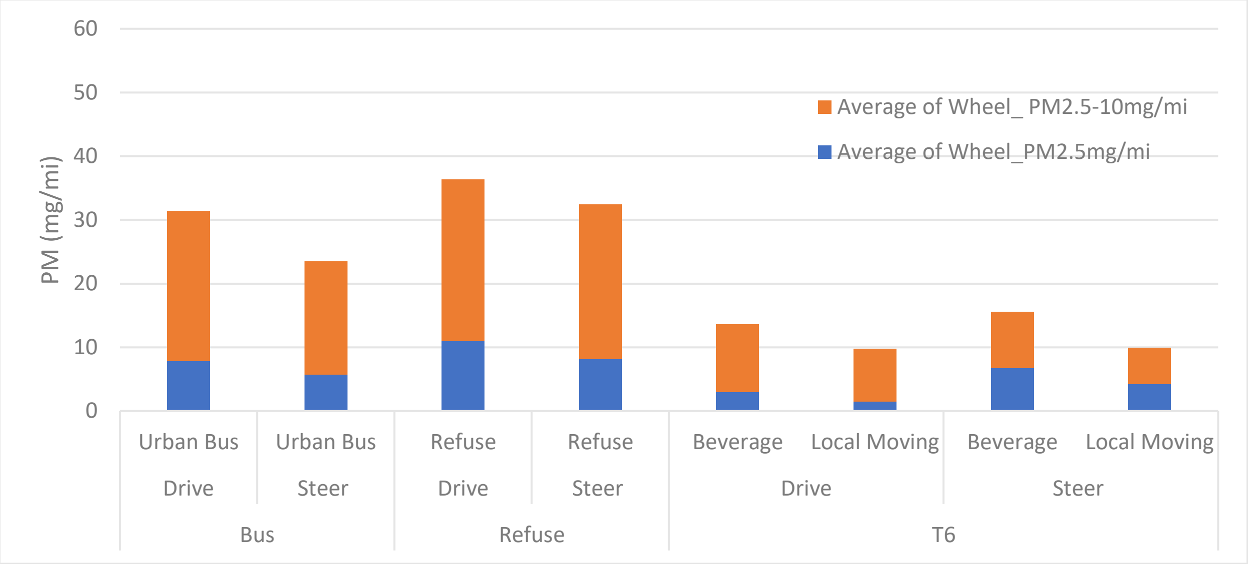


Figure 17. Medium Duty (T6), Bus, Refuse Truck individual Wheel Means

8.a.4 Effect of Load

A subset of Class 8 configurations was run on the dynamometer to simulate full payload loading (80,000 lbs GVWR) and no payload loading (37,000 lbs GVWR, i.e. an empty trailer). A comparison of these emissions is shown in Figure 18**Error! Reference source not found.**. On average the unloaded test are 50 percent less than loaded tests.

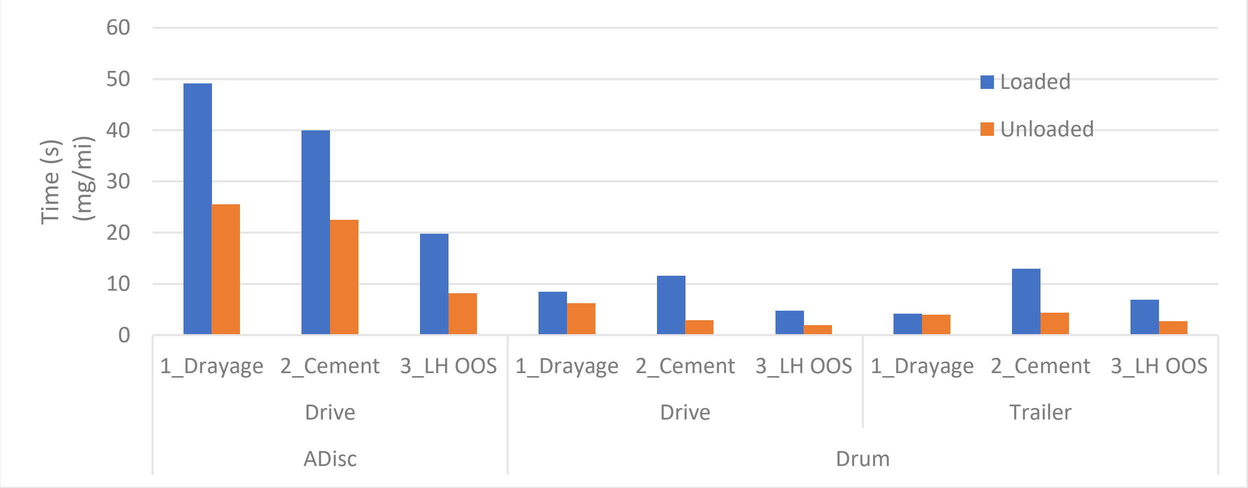


Figure 18. Loaded vs. Unloaded Class 8 Individual Wheel Means

8.a.5 Effect of Air Flow Rate

As discussed previously, air flow on brake housing was varied in an attempt to better calibrate with real-world brake temperatures. In the course of testing drum brake results appeared to be influenced by whether a high (70 kph) or low (7.5 kph) air flow was applied to a test. To confirm this, additional tests were conducted to allow paired comparison of the same test with two different flows. The results of high and low flow tests are shown in Figure 19**Error! Reference source not found.**. Tests with high flow rate were substantially higher than those with low flow rate. When comparing low flow and high flow tests, the high flow did reduce brake temperatures by about 10 degrees C (adjusting for initial temperature), which is within variability observed on the track due to differences in ambient temperature and wind direction. As discussed in the next section, two options for EMFAC emission rates were developed and presented to Caltrans and CARB. Option 1 used data from the T7 drum tests at the intended flow rate - some high, some low - and did not attempt to account for the large difference in drum emissions caused by differences in flow rate. We considered this the "temperature driven" option since the flow rates were established to best match the target brake temperatures from track testing. Option 2 did account for the effect of different flow rates on the drum brakes, by setting drum brake emissions as the average of 7.5 kph and 70 kph airflow tests across the entire sample of drum tests (pooling steer/drive/trailer and OE/AM into one sample). It should be noted the flow effect was only pronounced for drum brakes, not disc brakes, which will be open to the atmosphere and insensitive to airflow.

In reality the amount of PM escaping a drum brake will depend on a number of factors - e.g., truck speed, wind direction, aerodynamic flow, bumpy roads etc. - that cannot all be accounted for on a dyno. The difference in drum brake emissions for the high and low air flow conditions speaks to this degree of variability. A recommendation for future dynamometer testing is to consider flow rate in the design of the program in light of these real-world factors.

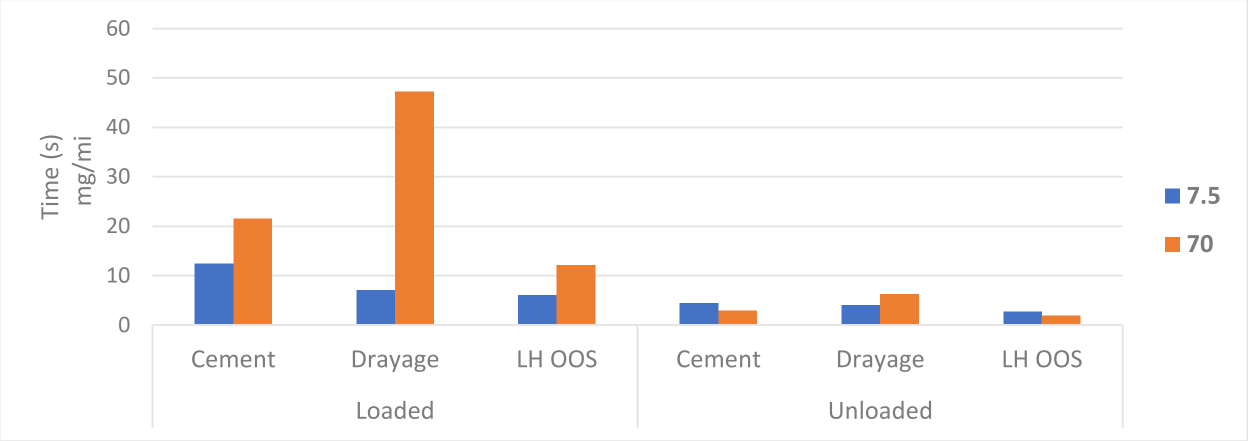


Figure 19. Class 8 Drum Brake Results with High and Low Air Flow

8.a.6 *Test Repeatability*

The number of repeat tests were planned to be limited initially, and the use of repeat tests to diagnose the flow issue resulted in fewer repeats than planned. All repeats were conducted on Class 8 trailer, with paired tests shown in Figure 20**Error! Reference source not found.**. The absolute difference in tests range from 0.6 – 5.2 mg/mi PM_{10}. As shown the range in percent change between repeat tests was -58 percent to +533 percent.

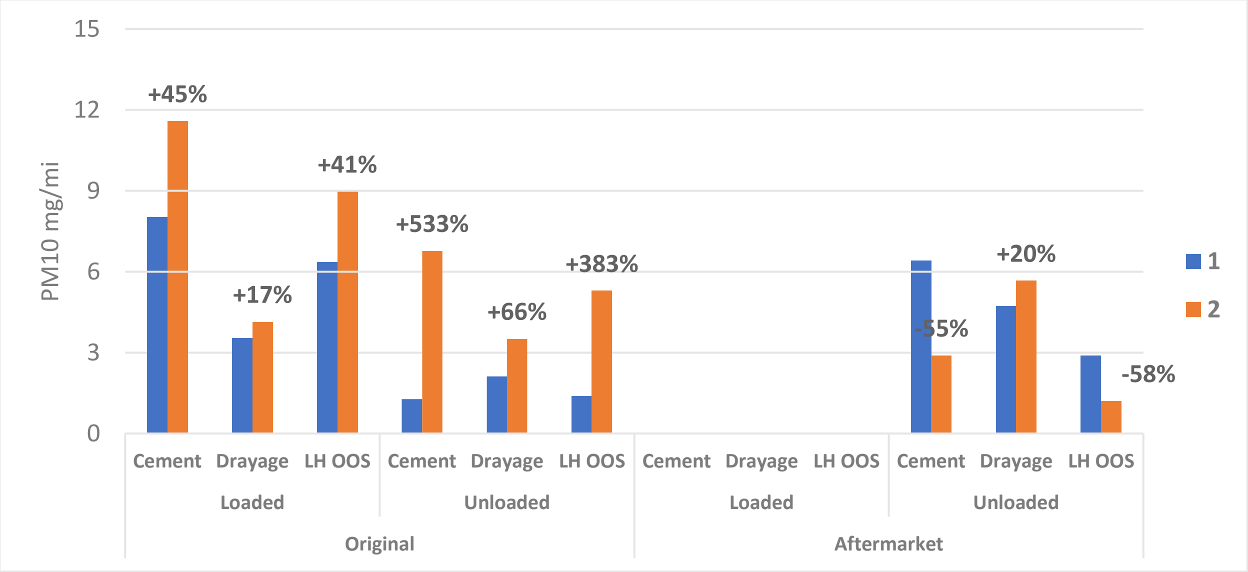


Figure 20. Repeat Test Results

8.a.7 Real-time results

The HD test matrix was developed with multiple vocation cycles with a spread of average speed and braking intensities, in order to allow EMFAC rates and speed correction factors to be developed directly from gravimetric filter data. The development of HD EMFAC rates therefore did not rely on real-time data as was the case for the CARB LD study, which used real-time data to apportion filter data collected on the LD test cycle to assess the impact of vehicle speed and develop LD speed correction factors. This difference in test matrix design shifted emphasis for the HD study away from real-time data. That said, the real-time data collected in the HD program offers a wealth of data for further analysis of HD brake PM mass, number and size as they relate to braking activity real-time. All of the individual test reports provided by LINK include time traces of the real-time data including brake temperature, torque, PM mass (via QCM), number and size (via APS and EEPS) both the emission test cycles and burnish cycles (see Appendix C for example traces for the urban bus test). The test reports also summarize event-based particle count and mass vs. brake temperature, kinetic energy, and speed; as well as particle size distributions (Figure 21). This provides arguably the most robust set of brake PM data ever collected on HD vehicles. A full analysis of these data is beyond the scope of developing EMFAC emission rates that were the focus of this project. A review of these data, as indicated in the bus data example presented here, confirms that particle number and mass are influenced by three closely related variables of braking energy, braking vehicle speed, and brake temperature. It is our hope that the emission research community takes full advantage of this groundbreaking new dataset to conduct a deeper investigation into the size, number and mass of brake particles and their relationship with vehicle dynamics, brake configuration and composition.

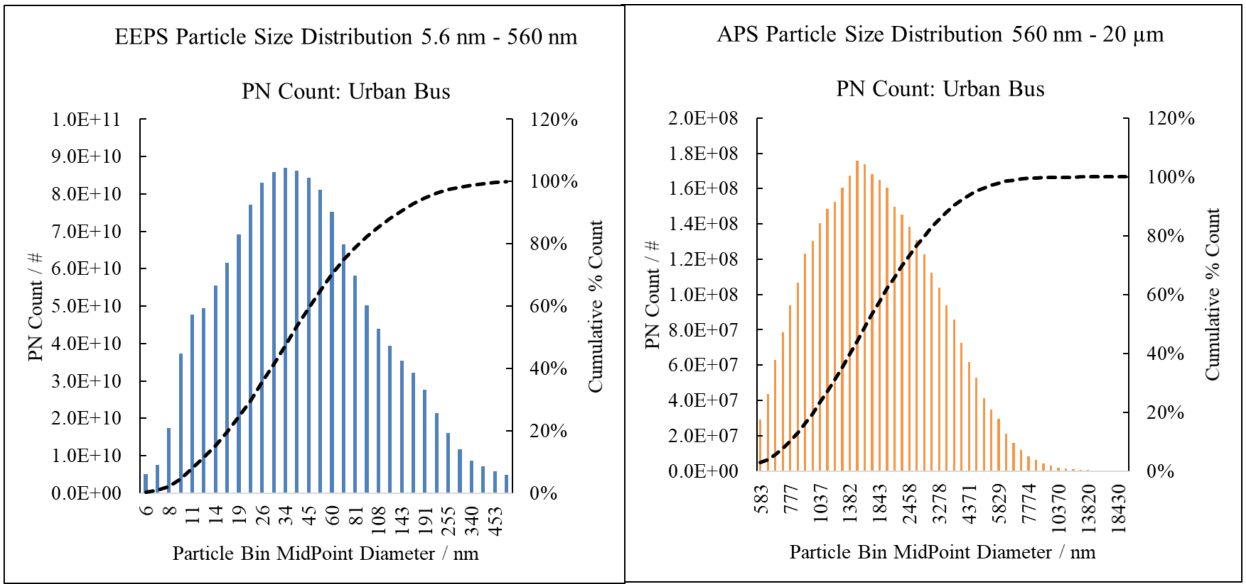


Figure 21. Real-Time Data Sample: Particle Size Distribution for Urban Bus Drive Axle

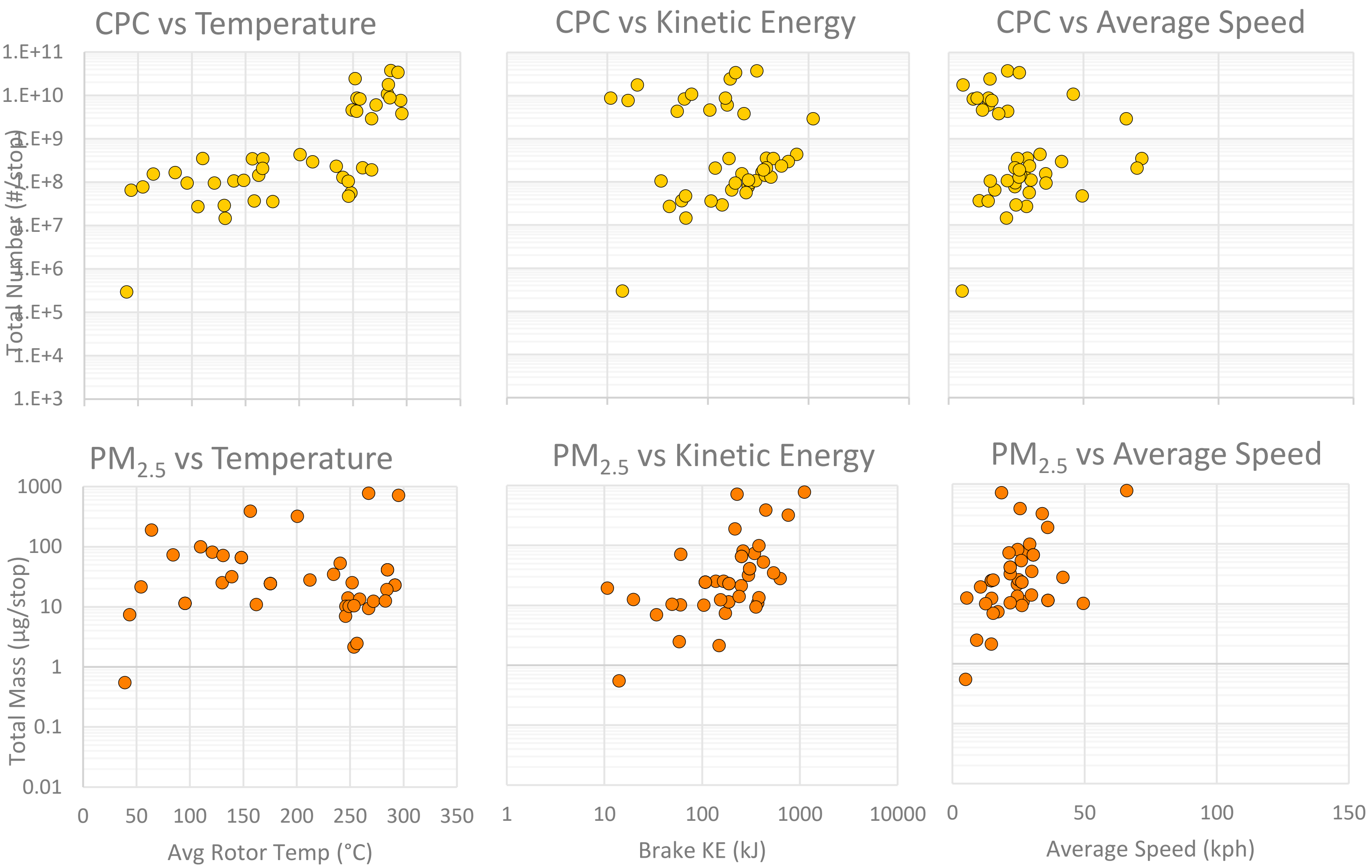


Figure 22. Real-Time Data Sample: Event-Based PN & PM for Urban Bus Drive Axle

SECTION 9 DEVELOPMENT OF HEAVY DUTY VEHICLE EMFAC RATES

9.a EMFAC Brake PM categories

EMFAC2017 categories for HD brake PM were retained for EMFAC20211: T7, T6, Solid Waste (Refuse), and Bus, which encompasses multiple categories of Motorcoach, School Bus, Urban Bus, and Other Bus. In the mold of exhaust emissions, the EMFAC20211 structure for HD brake PM_{10} was established with a “zero mile level” (ZML), which serves as an overall average emission rate prior to deterioration; speed correction factor (SCF), which adjusts the ZML as a function of average vehicle speed; and deterioration rates (DR), which account for degradation in emissions performance over time. $PM_{2.5}$ is then estimated via an aggregate factor expressed as fraction of PM_{10}. This section describes the process for aggregating individual wheel test results measured on dynamometer as described in Section 11 into the EMFAC20211 rates.

9.b Converting gravimetric filter results to emission inventory

For HD trucks, raw filter results from single wheel dynamometer testing where transformed to full vehicle EMFAC emission rates over several steps of processing. ZMLs in EMFAC are expressed as grams per vehicle-mile travelled (grams/mile). Transforming single wheel dynamometer results to representative full-truck gram/mile rates required accounting for load, axle, and speed factors designed into the emission test matrix, primarily for T7 trucks. The factors accounting for in rolling up single-wheel ZML include:

- The mix of loaded and unloaded operation (T7 trucks only);
- The number of steer, drive, and (if applicable) trailer brakes per truck;
- The fraction of particles dispersing to the environment vs. residing within brake housing (airborne fraction);
- The mix of drum and air disc brakes by model year range; (T7 trucks only);
- Differences in PM emissions from original and aftermarket friction material, which would form the basis of deterioration rates
- Vocation cycle results

Analysis of each of these items is discussed in the following sections.

9.b.1 Weighting Loaded/Unloaded Conditions

The test configuration produced both loaded and unloaded emission factors (EFs) for a single brake. Prior to incorporating EFs into EMFAC, the loaded vs. unloaded EFs required aggregation to reflect to an average loading condition and multiplying single-brake EFs by the average number of brakes on a truck.

The loaded condition depicts driving while the cargo area is full, whereas the unloaded condition means the cargo area is empty, such as when a truck is on the way to a pickup or after dropping off. The EMFAC model considers brake-wear EFs as corresponding to the overall loading condition that includes braking while sometimes loaded, sometimes unloaded. As discussed earlier, WIM data published in Hernandez 2017 informed the inclusion of fully loaded and unloaded test points for Class 8 trucks. For weighting these test points into a single representative emission factor for California, the California Vehicle Inventory and Use Survey (CA-VIUS) provides a more representative dataset to generate statewide weighting factors for loading and scaling factors for full trucks.

The CA-VIUS replaces the California portion of the national VIUS that supported a broad range of vehicle analyses for planning and policy until its discontinuation in 2002 (Jeong et. al 2016). Conducted over the period 2016-2018, the CA-VIUS is both recent and specific to activity in California. The CA-VIUS sampled 14,789 unique vehicles to represent the nearly 760,000 heavy-duty trucks operating in California in 2018. The advantages of applying CA-VIUS for this work is that the survey database contains truck weighting factors that represent the sample's contribution to the total California heavy-duty diesel truck population.

Seven (7) data fields of the CA-VIUS database in the table below provided the information to develop the weighting factor to combine unloaded and loaded truck test data for T7 trucks (Table 16. First, the gross vehicle weight data field was filtered to include only Class 8 trucks (greater than 33,000 lbs.). Next, weighted annual VMT multiplied by weight was divided into the four categories Deadheading Bobtail, Deadheading Empty, Partially Loaded, and Fully Loaded.

Table 16. CA-VIUS Data Fields Used to Determine Load Weighting

CA-VIUS Data Field	Description of Values
Gross Vehicle Weight of Truck	Class 3 (10,001-14,000 lbs.)
	Class 4 (14,001-16,000 lbs.)
	Class 5 (16,001-19,500 lbs.)
	Class 6 (19,501-26,000 lbs.)
	Class 7 (26,001-33,000 lbs.)
	Class 8 (> 33,000 lbs.)
AnnualVMT	Best estimate of total miles during the last 12 months
DeadheadingBobtail (% of AnnualVMT)	Percent Deadheading (traveling empty to make a pickup or returning empty): Empty Bobtail.
DeadheadingEmpty (% of AnnualVMT)	Percent Deadheading (traveling empty to make a pickup or
PartiallyLoaded (% of AnnualVMT)	Percent Partially loaded based on weight or volume - CARRYING products, materials or other cargo.
FullyLoaded (% of AnnualVMT)	Percent Fully loaded based on weight or volume -
Weight	Survey Expansion Factor

Equation 5 shows the calculation of the unloaded and loaded percent for T7 trucks.

Equation 5. Loaded & Unloaded Fractions

$$\text{Unloaded fraction} = [\, VMT_{DHB} + VMT_{DHE} + 0.5\,(VMT_{PL})] \,/\, VMT_{TOTAL} = 0.273$$
$$\text{Loaded fraction} = [\, 0.5\,(VMT_{PL}) + VMT_{FL}] \,/\, VMT_{TOTAL} = 0.727$$

Where:

Unloaded fraction = fraction of T7 trucks that operate at 0% load
Loaded fraction = fraction of T7 trucks that operate at 100% load

VMT_{DHB} *= annual vehicle-miles traveled while deadheading bobtail (no trailer)*
VMT_{DHE} *= annual vehicle-miles traveled while deadheading empty (empty trailer)*
VMT_{PL} *= annual vehicle-miles traveled while partially loaded*
VMT_{FL} *= annual vehicle-miles traveled while fully loaded*
$VMT_{TOTAL} = VMT_{DHB} + VMT_{DHE} + VMT_{PL} + VMT_{FL}$

9.b.2 Axles per Truck

The number of brakes per truck depends on the number of axles on the average truck. The CA-VIUS database fields "Number of Axles Truck" and "Trailer Axles" were used to determine the number of brakes on the T7 and Hydraulic brake test configurations. ERG summed weighted annual VMT by each of the above axle count categories for T7 trucks (Class 8). For the Hydraulic brake test configuration, weighted annual VMT from the T6 trucks (Class 4-7) were included. There is some uncertainty in the number of axles for the CA-VIUS categories of "More than five axles" and "Other" (under "Number of Axles Truck") and for "Three or more axles" (under "Trailer Axles). We assumed 6 axles for both "More than five axles" and "Other" categories, and 3 axles for "Three or more axles."

Equation 6 shows the calculation of the number of trailer axle brakes per T7 truck using a VMT-weighted average from Class 8 trucks in the CA-VIUS (4.16). Equation 7 shows the calculation of the number of drive axle brakes for an average truck with hydraulic brakes using pooled Class 4-7 trucks in the CA-VIUS (2.12). Trucks with hydraulic brakes were assumed to be single unit

Equation 6. Trailer Axle Brakes per Class 8 Truck

$$\text{Trailer Axle Brakes per Truck} = 2 \times \left[\frac{\sum_{TA}(VMT_{TA} \times AxleCount)}{VMT_{TOTAL}}\right] = 4.16$$

Where:

2 = two brakes per axle
Σ_{TA} *= summation over "Trailer Axles" categories*
VMT_{TA} *= annual vehicle-miles traveled for the particular "Trailer Axles" category*
AxleCount = the number of axles (0 to 3) for the particular "Trailer Axles" category
VMT_{TOTAL} *= annual vehicle-miles traveled, totaled across all "Trailer Axles" categories*

Equation 7. Drive Axle Brakes per Class 4-7 Truck

$$\text{Drive Axle Brakes per Truck} = 2 \times \left[\frac{\sum_{NTA}(VMT_{NTA} \times AxleCount)}{VMT_{TOTAL}} - 1\right] = 2.21$$

Where:

2 = two brakes per axle
Σ_{NTA} *= summation over "Number of Axles on Truck" categories*
VMT_{NTA} *= annual vehicle-miles traveled for the particular "Number of Axles on Truck" category*
AxleCount = the number of axles (2 to 6) for the particular "Number of Axles on Truck" category
VMT_{TOTAL} *= annual vehicle-miles traveled, totaled across all "Number of Axles on Truck" categories*
1 = one steer axle assumed

9.b.3 Airborne Fraction

Airborne fraction is the amount of total brake mass shed from the pad during brake events and become airborne, versus becoming trapped in brake housing or adhering to wheel, brake or vehicle body. This is exacerbated for drum brakes prominent on T7 trucks, with fraction material enclosed by the drum with limited pathways to the outside environment. Accounting for these factors and older brake wear studies, EMFAC2017 estimated an airborne fraction of 0.5. Estimates in the literature vary widely on either side, dependent on physical test configuration and airflow realism (Hagino et al 2016; Sanders et al 2003).

For this study the dynamometer configuration was set up with the full brake fixture intact, including shoes and drums, and direct air flow for temperature control and PM sampling. This setup mimicked real-world retention of brake material in the drum housing. The amount of PM sampled with this setup was thus judged to adequately represent real-world condition given the variability expected under real-world conditions. Similarly, PM sample from disc brakes would reflect real-world conditions this configuration does not have a means for trapping particles. For this reason an additional airborne fraction correction factor was judged not needed. PM mass emissions were used for modeling as collected (airborne fraction of 1.0).

9.b.4 T7 Drum vs. Disc by Model Year

The only model year dependence developed for the EMFAC2021 rates is for T7 trucks, to account for the shift from drum brakes to disc brakes for Class 8 trucks. Reduced Stopping Distance rules put forth by the U.S. Department of Transportation (NHTSA 2009) precipitated a shift to disc brakes for Class 8 heavy-duty trucks, for improved brake performance and durability required under the rule. The shift has been gradual however, with the supplier market survey conducted for this project estimating market penetration of 85 percent drum vs. 15 percent disc. While in the market survey brake suppliers did confirm a continued shift to disc brakes, specific market penetration projections were not available. Trade literature suggests Class 8 tractor configurations are being deployed steer-only disc brakes, or steer and drive disc brakes (as tested for track testing). Trailers are likely to continue employing drum brakes however, as legacy trailers can continue to be coupled with disc tractors. Though the penetration of disc is projected to increase, T7 trucks will employ both disc and drum well into the future. To capture this, EMFAC2021 T7 emission rates assumed the following penetration:

Table 17. T7 Drum vs. Disc by Model Year Range

	Pre 2010	2010 2025	Post 2025
Drum	100%	85%	50%
Disc	0%	15%	50%

9.b.5 Original Equipment vs. Aftermarket

The entire HD test matrix of vehicle types, brake configurations, load and vocation cycles was run with original equipment friction material and then repeated with aftermarket friction material. This was done to represent the prevalence of aftermarket friction material on the road given long truck life, and to account for possible degradation in brake PM emissions between original and aftermarket equipment, as observed with LD vehicles. As discussed in the previous section, however, emissions with aftermarket friction material test did not exhibit a clear trend versus their original equipment counterparts, and t-test confirmed no statistical difference between the samples. Though this finding differed from LD vehicles, this is consistent with market trends. In the U.S. the majority of commercial vehicle brake components are supplied by only a few companies, who provide both original and aftermarket parts. The friction material formulations do not vary significantly between original and aftermarket, unlike the light vehicle market where a large number of aftermarket-only suppliers produces many varieties of pad.

Because the original and aftermarket configurations did not demonstrate different emissions, these tests were grouped in the development of EMFAC emission rates (ZML and SCFs). The implication of this is that deterioration rates (DRs) will be zero; the ZML reflects average emission rates over the full life of HD vehicles.

9.b.6 Vocation Cycle Weightings

As discussed in Section 3, vocation cycles were chosen for T6 and T7 trucks to represent a range of speed and braking intensity. Vocation-specific results were weighted together based on statewide mix of speeds to estimate ZML, and as detailed in the next section, were then used to calculate speed correction factors.

Speed weightings were derived using the EMFAC distribution of speeds by truck class, expressed as 5 mph speed bins with speed midpoints ranging from 5-90 mph. To ensure a mix of all vocation cycles tested, the EMFAC speed fraction for each 5 mph speed bin was assigned to the vocation cycle with highest representation in that bin. The result is illustrated in Table 18, which shows the average speed and speed bins most represented by each cycle.

Table 18. Vocation Cycle Weightings for ZML

Class	Vocation	Average Speed (mph)	Speed Bins with Highest Representation	Weighting
T7	Drayage N	11.9	5-35mph	0.18
	Cement	28.1	40-55 mph	0.24
	Long Haul OOS	48.6	60-90 mph	0.57
T6	Beverage	14.2	5-30 mph	0.27
	Local Moving	32.6	35-90 mph	0.73

9.c Zero Mile Levels

With no deterioration rate, ZMLs are the representative statewide average emission rate for the full life of a given truck. Combining the steps and weighting factors described in Section 9.b The process of transforming individual wheel results to full truck ZMLs by EMFAC truck category is shown schematically in Table 19 for PM_{10}.

Table 19. Schematic Process for Producing ZML from Individual Wheel Result

EMFAC Brake Wear Truck Class	Test Data	→ Pre-Process →				PM_{10} ZML (g/mi)
	Individual Wheel PM_{10} Filter Result	**Wheels Per Truck**	**Load Weighting**	**Configuration Weighting$_{my}$**	**Cycle Weighting**	
T7	Class 8 Drum Steer	2	0.73 Loaded 0.27 Unloaded	Table 11	Table 12	**Pre MY 2010: 0.096** **MY 2010-2025: 0.106** **MY 2026+: 0.129**
	Class 8 Drum Drive	4				
	Class 8 Drum Trailer	4.16				
	Class 8 Disc Steer	2	0.73 Loaded 0.27 Unloaded			
	Class 8 Disc Drive	4				
	Class 8 Drum Trailer	4.16				
Refuse	Refuse Truck ADisc Steer	2	n/a	n/a	n/a	**0.210**
	Refuse Truck ADisc Drive	4				
Bus	Urban Bus ADisc Steer	2			n/a	**0.110**
	Urban Bus ADisc Drive	2				
T6	Hydraulic Disc Steer	2			Table 12	**0.047**
	Hydraulic Disc Drive	2.21				

9.d Speed Correction Factors (SCF)

Speed correction factors allow estimation of brake wear for each of the specific EMFAC speed bins, and are expressed relative to ZMLs in Table 19. To estimate the SCFs, full truck emission rates calculated as described for each vocation cycle were mapped to speed bins based on closest cycle average speed. Emissions for speed bins between the average speeds of two vocation cycles were interpolated based on bin midpoint speed. This is shown schematically in Table 20. The SCF by speed bin is calculated as speed-based emission rate divided by ZML.

Table 20. Speed Correction Factors

Speed Bin	Mapped T7 Vocation (Avg MPH)	T7 SCF	Mapped T6 Vocation (Avg MPH)	T6 SCF
5	Drayage (11.9)	1.43	Beverage (14.2)	1.31
10		1.43	*Interpolated*	1.31
15	*Interpolated*	1.41		1.31
20		1.38		1.29
25		1.35		1.06
30	Cement (28.1)	1.33		0.94
35	*Interpolated*	1.12		0.88

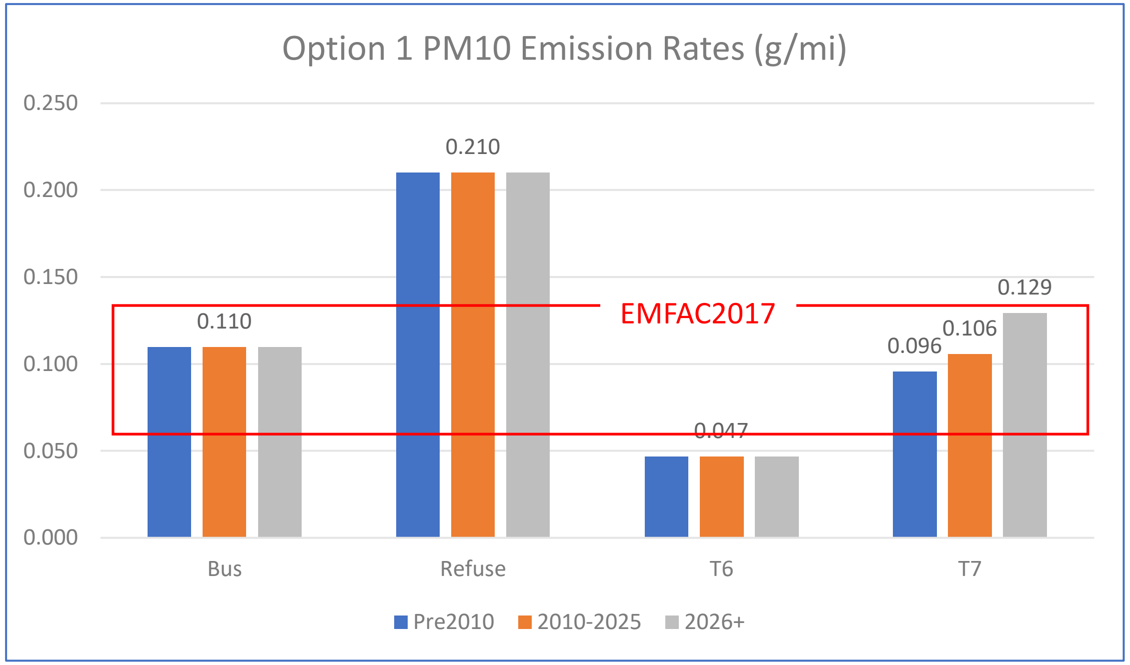
40		0.98		0.88
45		0.83		0.88
50	Long Haul OOS (48.6)	0.72		0.88
55		0.72		0.88
60		0.72		0.88
65		0.72		0.88
70		0.72		0.88
75		0.72		0.88
80		0.72		0.88
85		0.72		0.88
90		0.72		0.88

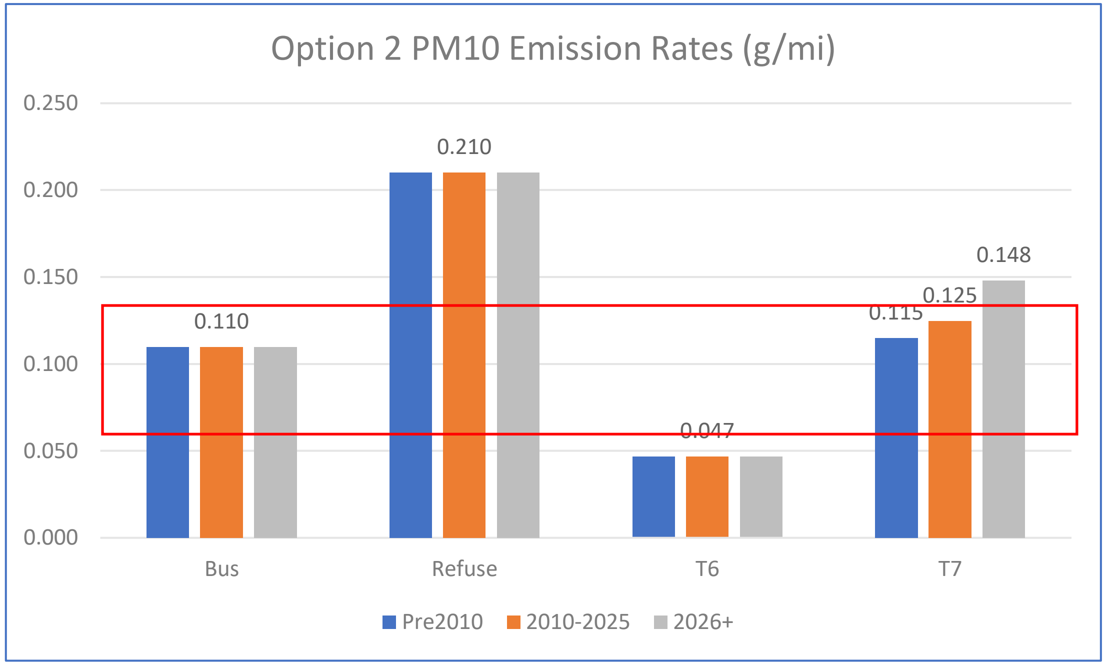
9.e PM$_{2.5}$ Fractions

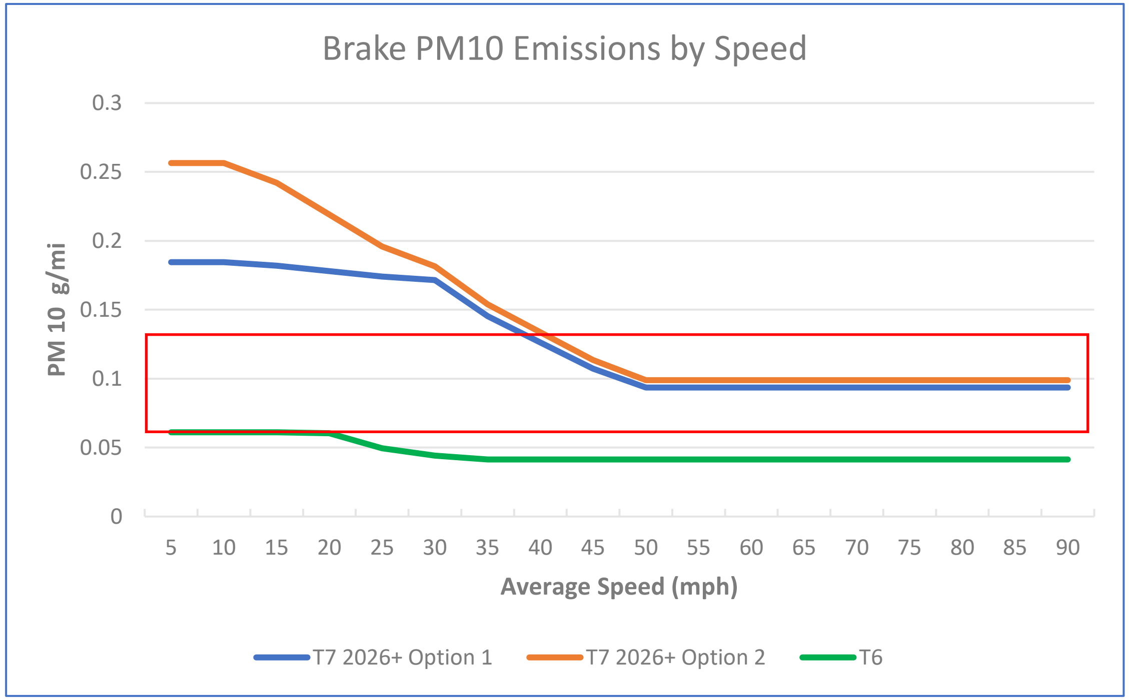
PM$_{2.5}$ is estimated in EMFAC by applying a mass fraction to PM$_{10}$. EMFAC uses a single mass fraction for HD brake wear, requiring calculation of aggregate ZML across truck categories. PM$_{2.5}$ ZMLs were first calculated with PM$_{2.5}$ filter values using the method outlined in Table 19. Aggregate HD PM$_{10}$ and PM$_{2.5}$ ZMLs were then calculated as a weighted average of truck category ZMLs using EMFAC VMT fraction for T7 (0.42), T6 (0.27), Refuse (0.18) and Bus (0.13) categories. PM$_{2.5}$ fraction was then calculated as aggregate HD PM$_{2.5}$ ZML divided by aggregate HD PM$_{10}$ ZML. The result was 0.35, which matches the EMFAC2017 PM$_{2.5}$ fraction for brake wear.

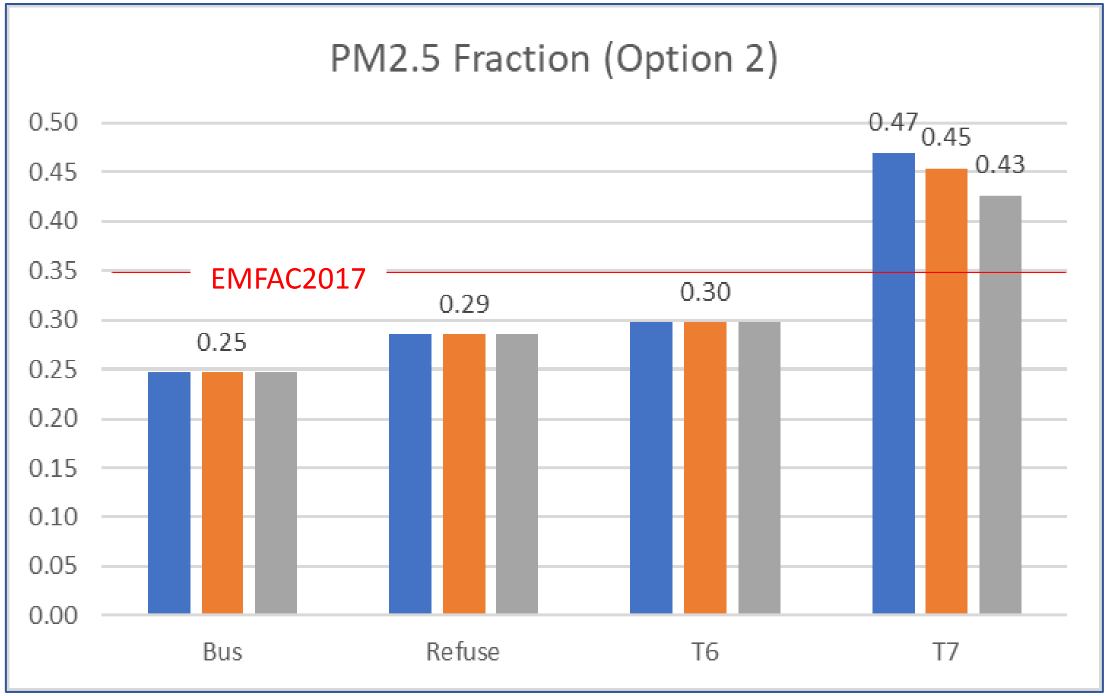
9.f Full Vehicle EMFAC Rate and SCF Options

The figures shown on the next page are the final rates developed for EMFAC20211, by truck class and model year range. Option 1 uses data from the T7 drum tests at the intended flow rate, while Option 2 does account for the effect of different flow rates on the drum brakes. Though the differences in individual wheel results for drum brakes is large, the weighted full truck difference in Option 1 vs Option 2 is confined to T7 trucks, and is within 20 percent. The main difference occurs at low speeds, as shown in the SCF chart. The model year effect for T7 is due to increasing penetration of disc brakes over time, assuming 50/50 disc/drum by model year 2026. The speed-based emissions for other model year groups follow similar trend as shown here. Superimposed on the rate charts is the range of EMFAC2017 emission rates and SCF. Refuse trucks are well above the EMFAC2017 values, buses are within the range, and T6s are below the range. The EMFAC2017 rates for recent and future model year T7s are at the lower end of the depicted range (0.063 g/mi), so the updated rates are much higher; overall we expect these results to increase the HD brake PM inventory projections in California.


Option 1 PM10 Emission Rates (g/mi)


Option 2 PM10 Emission Rates (g/mi)


Brake PM10 Emissions by Speed


PM2.5 Fraction (Option 2)

PART II: LIGHT-DUTY REGENERATIVE TESTING (TESLA MODEL 3)

SECTION 10 TESLA BRAKE TEMPERATURE MEASUREMENT

As part of the CARB LD study ERG and LINK undertook an extensive effort to generate a realistic dynamometer test cycle that is representative of real-world braking kinetics and temperatures for cars and light trucks in California. This effort began with evaluation of existing drive schedules including those used in EMFAC for estimating emissions over a range of speeds (UCC cycles), and the WLTP brake cycles. From this, a custom drive schedule known as the California Brake Cycle (CBDC) was developed that specifically represents braking activity on light-duty vehicles in California (Stanard 2019). This driving cycle was used for LD track testing in this project, and will be used for dynamometer emissions testing in Task 4.

To fill the LD vehicle test slot, ERG proposed two options: 1) choose the “next vehicle down” from the regenerative braking market share analysis conducted for the CARB LD Study, likely a conventional hybrid with high sales in California such as the Hyundai Sonata; or 2) choose a full electric vehicle in order to ensure this growing market segment was represented in EMFAC. Caltrans, in consultation with CARB, chose to test a full EV, to understand how a vehicle with high regenerative braking behaves under realistic braking conditions. Analysis of 2018 EV sales figures in the U.S., of which California sales constitute the majority showed that the Tesla Model 3 was by far the highest selling EV, outpacing sales of the second-selling vehicle (Toyota Prius Prime) by a factor of 5 (Green Tech Media 2019). A Tesla Model 3 was subsequently targeted for testing. Within Tesla Model 3 there are both rear-wheel drive (RWD) and all-wheel drive (AWD) configurations, with options for standard, mid and long-range performance. Each of these vary by weight and will thus have implications for brake temperature performance; some are already out of production, e.g. RWD mid- and long-range. Though it required a delay in vehicle procurement, Caltrans and CARB desired a long range AWD configuration, as it was thought to represent a more common application of the Model 3 in California.

LINK procured a Tesla Model 3 AWD from a Detroit area rental agency in September 2019. Testing was conducted at the Michigan Technical Resource Park proving ground near Detroit. Details on the testing are provided in LINK’s test report. To maintain consistency with the track testing conducted on vehicles as part of the CARB LD Study, the test plan included an 8-hour burnish followed by testing on the ERG California cycle developed in the CARB LD study. LINK also ran a WLTP cycle and heating/cooling matrices in keeping with the CARB LD study track testing protocol.

The Tesla Model 3 brake temperature data for the ERG California Cycle is shown in Figure 23. During a project meeting LINK reported that in initial testing on the WLTP, the regenerative braking was aggressive, to the extent that friction braking was hardly invoked on the cycle. While the ERG California cycle did require more friction braking, Figure 23 shows that brake temperatures on the Tesla are generally much lower than conventional vehicle testing in the CARB LD Study.

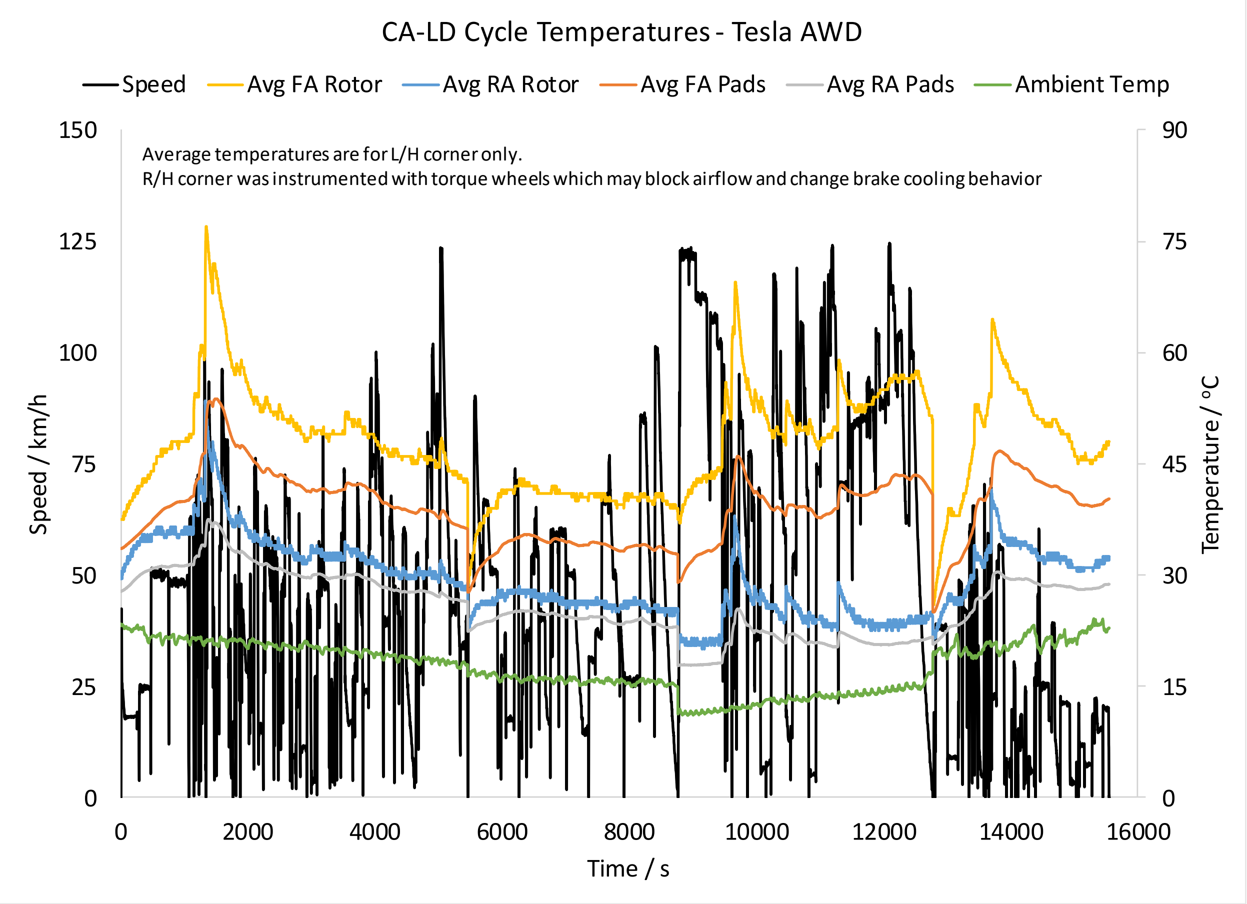


Figure 23. Tesla Model 3 Brake Temperatures on ERG California Cycle

The ERG California cycle will be used for Task 4 emissions testing on the Tesla Model 3. Temperature modeling is therefore not required for the Tesla, as temperatures collected directly in Task 1 can be used to inform dynamometer cooling settings. As discussed in the next section, temperature modeling was required for HD trucks since Task 4 will likely test vocation cycles or loadings not tested directly on the track.

SECTION 11 TESLA EMISSIONS TESTING & RESULTS

Track testing on a Tesla Model 3 confirmed that brake activity levels (and hence wear) are relatively low. From this, we expect brake PM to be low on the Tesla, and that original equipment friction material will be in use for the majority of a Tesla's life. In order to free up test slots for additional HD testing, we propose to test the Tesla Model 3 on original equipment friction material only, resulting in 4 test days to the Tesla: front and rear axle, with repeat tests. The Tesla will be run on the same test protocol used in the CARB LD Study, centered on the CBDC cycle, following the same burnish procedure employed for the LD study and recommended in that study for regenerative brake vehicles. The LD test matrix was simply to run the front and rear axle configurations twice.

The emission setup from the CARB LD study was replicated to conducted testing on the Tesla. Tests were conducted in December 2020, and full test reports included as part of deliverable for this project. An example of real-time data collected for one of the tests (Front Axle test 1) is shown in Appendix C; overall, the aggressive regenerative strategy limited engagement of the vehicle's disc brakes.

11.a Filter Results

Figure 24 shows the average brake torque for each of the 4 Tesla tests compared to the other regenerative braking vehicle tested in the CARB LD study, a Toyota Prius. As shown, brake torques were between 5-10 N-m for the Tesla, compared to Prius averages of 20 N-m for the rear axle, and 55 N-m for the front axle. This difference translated to lower emissions for the Tesla, shown in Figure 25. PM_{10} emission rates on the CBDC cycle ranges from 0.20 to 0.47 mg/mi, or a full vehicle estimate of 1.42 mg/mi. This is about 44 percent of the Prius' full vehicle emissions level. The $PM_{2.5}$ fraction based on filter data collected for the Tesla was relatively high however, at 70 percent.

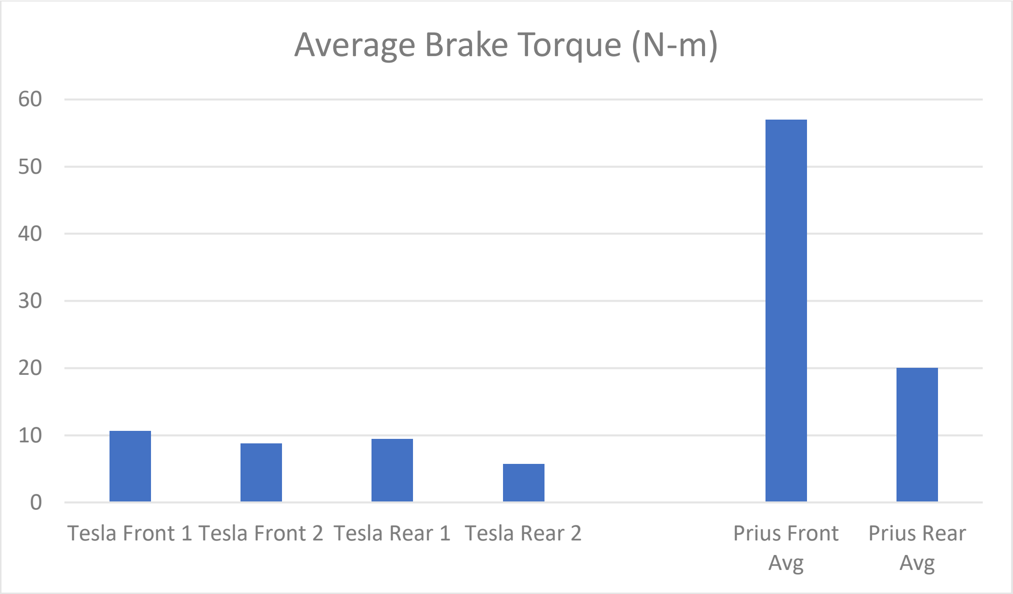


Figure 24. Tesla Model 3 Brake Torque

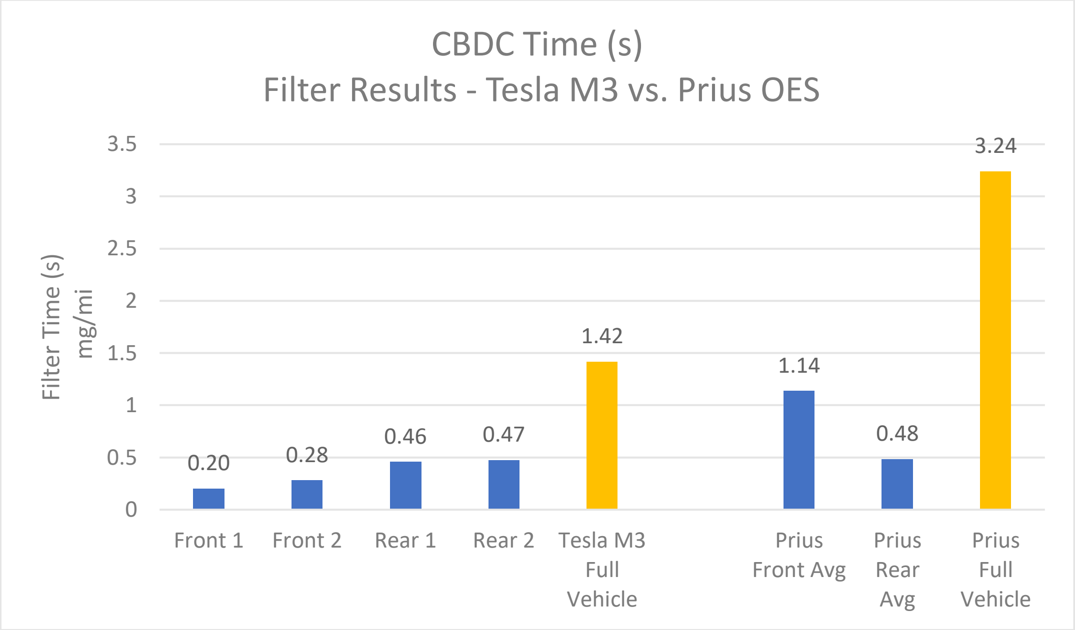


Figure 25. Tesla Model 3 PM_{10} Emissions

11.b Speed Analysis

Speed correction factors needed by EMFAC were developed specifically for regenerative braking vehicles based on the Prius, as documented in the CARB LD study. To compare whether the Prius SCFs are representative of the Tesla Model 3, a direct comparison was made for emissions based on speed between the Tesla and the Prius. As detailed in the LD study, two methods were used to assess the impact of average speed on brake emissions. “Method 1” compared emissions based on average speed of three different components of the CBDC with microtrips falling in average speed ranges of 0-21 kph, 21-69 kph and above 69 kph. Figure 26 shows emissions by these speed bins, replicating “Method 1” SCF analysis from CARB LD Study. This comparison shows that the Tesla appears consistent with Prius, including the trend or the highest emissions being in the mid-speed range.

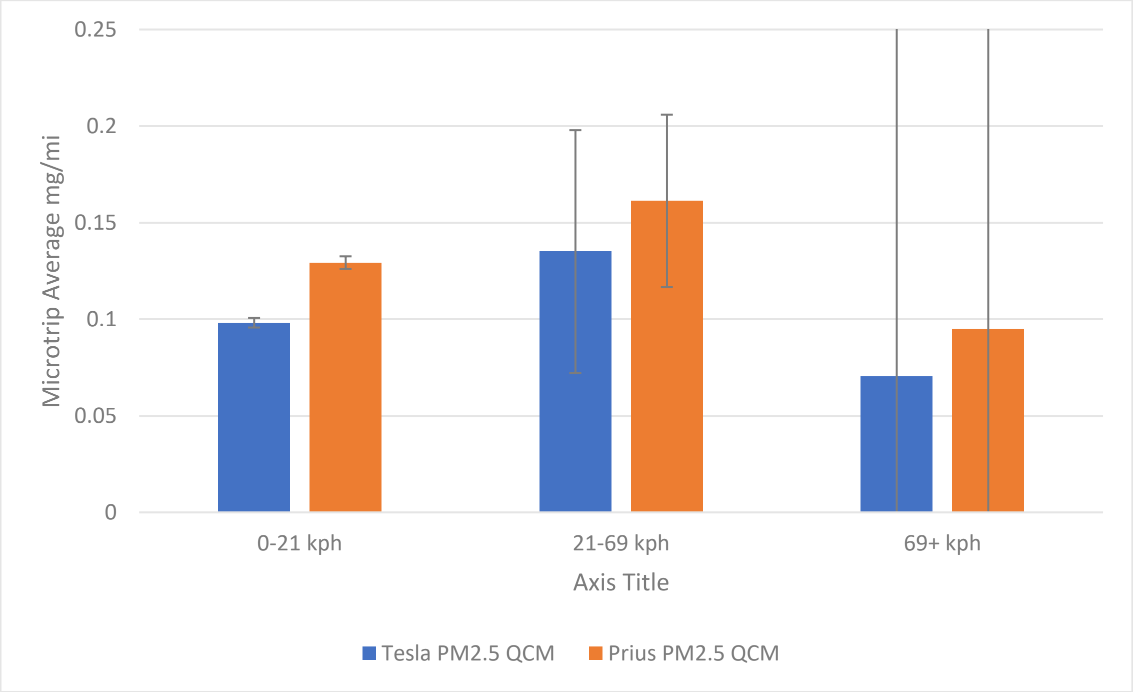


Figure 26. Speed-Based Emissions for Tesla and Prius (Method 1)

The “Method 2” approach analyzed real-time QCM data aggregated into 60 second intervals (the sampling resolution of the QCM system in the CARB LD study) grouped into 5 average speed ranges. The bins were sized in 15 mph increments in this analysis. The QCM sampling resolution was improved from 60 seconds to 10 seconds between the CARB LD study and this study; for direct comparison between the Tesla and prior Prius analysis, the averaging window was kept at 60 seconds, but the higher resolution of the underlying QCM data on the Tesla is apparent. As shown in Figure 27, the general trend of the Tesla and Prius mirror Method 1, with the highest emissions in the mid speed range. However, with Method 2 the Tesla has a more prominent peak vs. the Prius. We attribute this to the higher resolution of the QCM data collected on the Tesla (10 seconds).

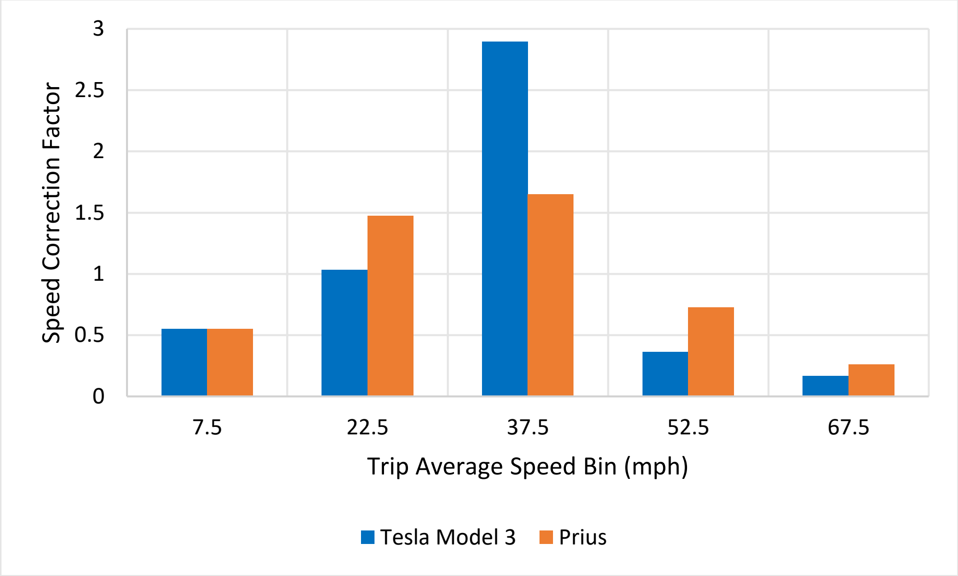


Figure 27. Method 2 PM_{10} Speed Correction Factors

SECTION 12 CONCLUSIONS & FUTURE RECOMMENDATIONS

Caltrans Project No. 65A0703 “Brake Wear in Particulate Matter Emission Modeling” has produced a robust set filter and real-time PM emissions data from a range of HD vehicles and a light-duty EV in real-world operation. These data were collected on a new HD brake emissions dynamometer setup developed by LINK, following on their work to build out a LD test setup in the prior CARB LD study. Over the course of this project real-world brake activity and temperature were measured, a new HD brake temperature model developed, and insights gained into the relationship of brake PM to brake type, vehicle loading, duty cycle, and equipment type. In total this project represents a significant advancement in the study of particle emissions from vehicle braking, and the data collected provides a robust source to continue studying this issue for years to come.

Track testing conducted on four heavy-duty vehicles and one trailer found that bus and refuse trucks had highest overall brake temperatures, with the bus maxing out over 500 °F, and median temperatures above 350 °F. The Class 8 tractor-trailer configuration had relatively lower temperatures, with comparable temperatures between the drum and disc configurations on these trucks. These data were used to adapt and update a heavy-duty truck brake temperature model published in the 1980s by the University of Michigan, with good agreement between predicted and observed temperature traces by axle type.

A market share and brake wear mass balance analysis provided a ranking of daily brake component and friction material wear in California by truck category, vocation, and brake type. The highest wear amounts are for Class 8 long haul vocations, though bus and MD pickup and delivery applications were also found to be major contributors due to high braking intensity and friction wear rates. The top 10 categories/vocations account for about 80 percent of total estimated wear. Overall, drum brakes account for about one-half of total brake wear mass in the state, and hydraulic discs about one-third.

From these early tasks, ERG and LINK developed a matrix of brake dynamometer tests to best quantify the effects that affect braking emissions in California within allotted test days as dictated by project scope. To cover the types of brakes on trucks in California, three brake types were tested – drum, air disc, and hydraulic disc. Steer, drive, and (for Class 8 trucks) trailer axles were tested to reflect difference in loading and components. The vocation cycles were selected to cover a range of average speed, to facilitate modeling of PM emissions as a function of speed in EMFAC2021, and to cover a range of vocation cycle brake power density. Development of the final test matrix required prioritizing which Class 8 test fixtures would be tested at 2 load points (fully loaded and unloaded), and which would receive repeat tests. All tests were conducted with original equipment and aftermarket equipment, to gauge the potential for deterioration with parts replacement.

For heavy duty trucks, key findings from the study were that brake type, duty cycle, axle type and truck loading have a significant influence on brake PM emissions. No significant effect appeared for aftermarket friction material versus original equipment. This is a reflection of homogony between suppliers of original and aftermarket brake parts, which differs from the industry for light-duty vehicle brake components. On an individual wheel basis, the highest PM emissions were from air disc brakes on a fully loaded Class 8 truck on a low speed (drayage truck) duty cycle, at nearly 50 mg/mile. Rolled up to a full truck estimate, refuse trucks has the highest per-mile emissions at 210 mg/mile, over twice the EMFAC2017 emission rate. Class 8 trucks in the future, with a projected split of drum and disc brakes, are projected to emit about 130-150 mg/mile, over twice the EMFAC2017 estimate of 63 mg/mile.

Testing on a Tesla Model 3 with aggressive regenerative braking found relatively low brake torques and temperatures, and by far the lowest PM_{10} emissions of any LD tested in the CARB LD study. However, relatively a relative high $PM_{2.5}$ fraction put the Tesla on par with the other regenerative braking vehicle in the CARB LD study sample, a Toyota Prius.

With many first in this test program, many lessons learned can help inform future brake projects. A significantly uncertainty that was difficult to capture within the scope of this program is the air dynamics that influence brake temperature and (for drum brakes) the amount of particle loss from drum housings. Additional uncertainties such as wind direction, effect of truck aerodynamic improvements (e.g. fairings), and road roughness could not be assessed. Real-world brake temperatures were characterized with track testing on vocation cycles, but like many HD truck surveys, a more robust dataset of real-world temperatures over different environmental and driving conditions will help inform real-world brake emissions statewide. Replicating this on a brake dynamometer through controlled air flows can help to represent real-world conditions as more is learned about them.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support of Caltrans for this project, under the guidance of project manager Simon Bisrat. Sonya Collier, Seungju Yoon, Sara Forestieri, Qi Yao and Jeff Long of CARB have provided invaluable technical input. CARB's Haagen-Smit Laboratory staff Inna Dzhema and Oliver Chang facilitated the handling and shipment of in-kind Teflon filters to LINK. Sandeep Kishan and Alan Stanard of ERG have provided management support and assistance to align this project with the CARB LD study. Jerry Lawruk, Mark Hunt, Brian Nycek, Josh Bautell, Trent Fagrell and Aaron Voisard of LINK conducted HD track testing. Quinn O'Hare and Brian Nyack of LINK supported emission dynamometer testing and Tesla track testing. Federal Mogul and ArvinMeritor provided estimate and insight for the HD market survey. ArvinMeritor and Bendix provided in-kind parts for testing when COVID shutdowns threatened supply chains for purchased parts.

REFERENCES

ARB 2019. EMFAC2017 Web Database (https://www.arb.ca.gov/emfac/2017/), accessed October 15 2019

Ates, M. and Mathews, R. 2012. *Coastdown Coefficient Analysis of Heavy-Duty Vehicles and Application to the Examination of the Effects of Grade and Other Parameters on Fuel Consumption.* Society of Automotive Engineers (SAE) Paper 2012-01-2051

Boriboonsomsin et al. 2017. *Collection of Activity Data from On-Road Heavy Duty Vehicles*, Final Report for CARB Agreement 13-301, May 2017

California Vehicle Inventory and Use Survey (CA-VIUS) data provided to ERG by California Dept. of Transportation, November 2018

EPA 2014. *Brake and Tire Wear Emissions from On-Road Vehicles in MOVES 2014* EPA Report EPA 420-R-14-013 December 2014

Fancher et al 1986. *A Factbook of the Mechanical Properties of the Components for Single-Unit and Articulated Heavy Trucks* UMTRI Report 86-12 December 1986

Green Tech Media 2019. *U.S. Electric Vehicle Sales Increased by 81% in 2018* Web article (https://www.greentechmedia.com/articles/read/us-electric-vehicle-sales-increase-by-81-in-2018) accessed May 15 2019

Hernandez 2017. *Estimation of Average Payloads from Weigh-in-Motion (WIM) Data,* TRR 2017

Jeong et al 2016. *California Vehicle Inventory and Use Survey: Pilot Study Insights* Transportation Research Record Journal of the Transportation Research Board 2547(1):32-40 DOI: 10.3141/2547-06 January 2016

NHTSA 2009. U.S. Department of Transportation National Highway Transportation Safety Agency, Reduced Stopping Distance Final Rule, 49 CFR Part 571 Docket No. NHTSA–2009-0083

Stanard et al. 2019. *Analysis of Activity Data and Generation of Representative Test Cycle* Interim Report for CARB Project 17RD016, September 2019

Stanard et al. 2020. *Brake and Tire Wear Emissions*, Report for CARB Project 17RD016, May 2020

APPENDICES

Appendix A: Heavy duty brake temperature model results

Appendix B: Heavy duty brake emissions dynamometer configuration (LINK engineering)

Appendix C: Real-time PM data samples (full data in test reports)

Provided separately: LINK test reports and raw test data

APPENDIX A: HEAVY DUTY BRAKE TEMPERATURE MODEL RESULTS

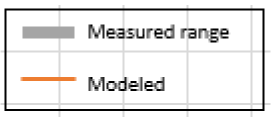


Figure A-1. Unloaded Class 8 Drum-Drum Beverage Cycle

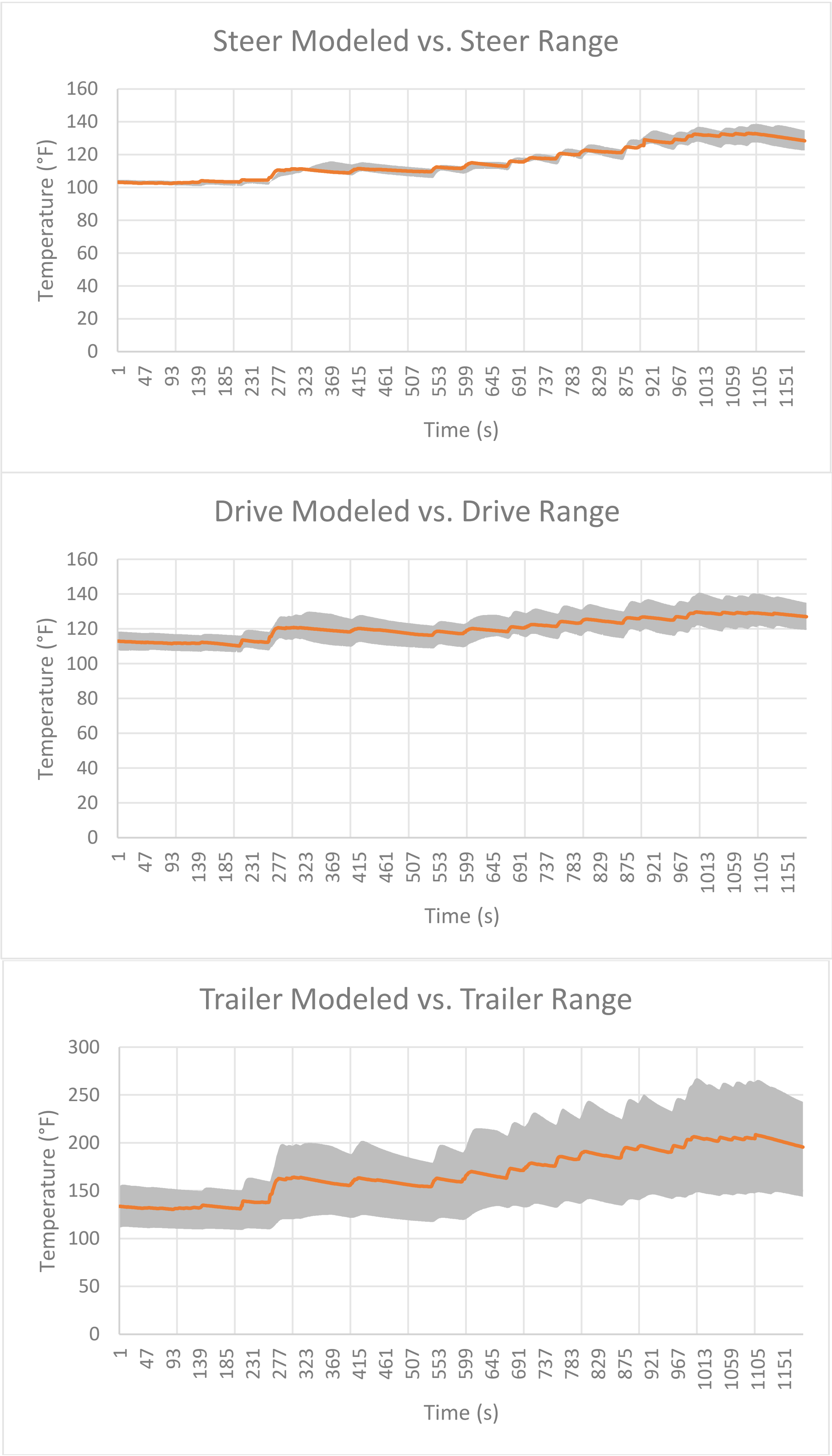


Figure A-2. Loaded Class 8 Drum-Drum Drayage Cycle

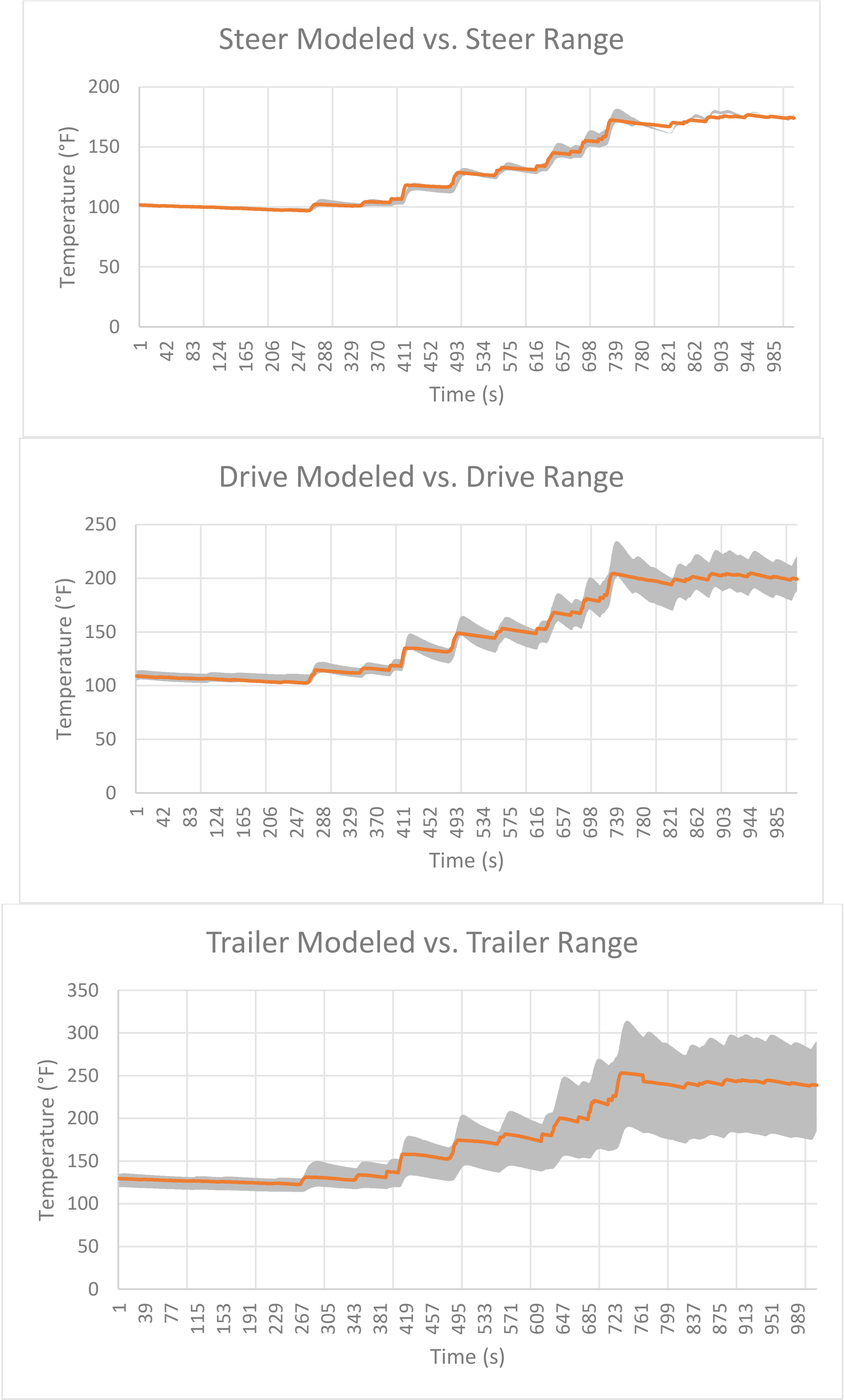


Figure A-3. Unloaded Class 8 Drum-Drum Drayage Cycle

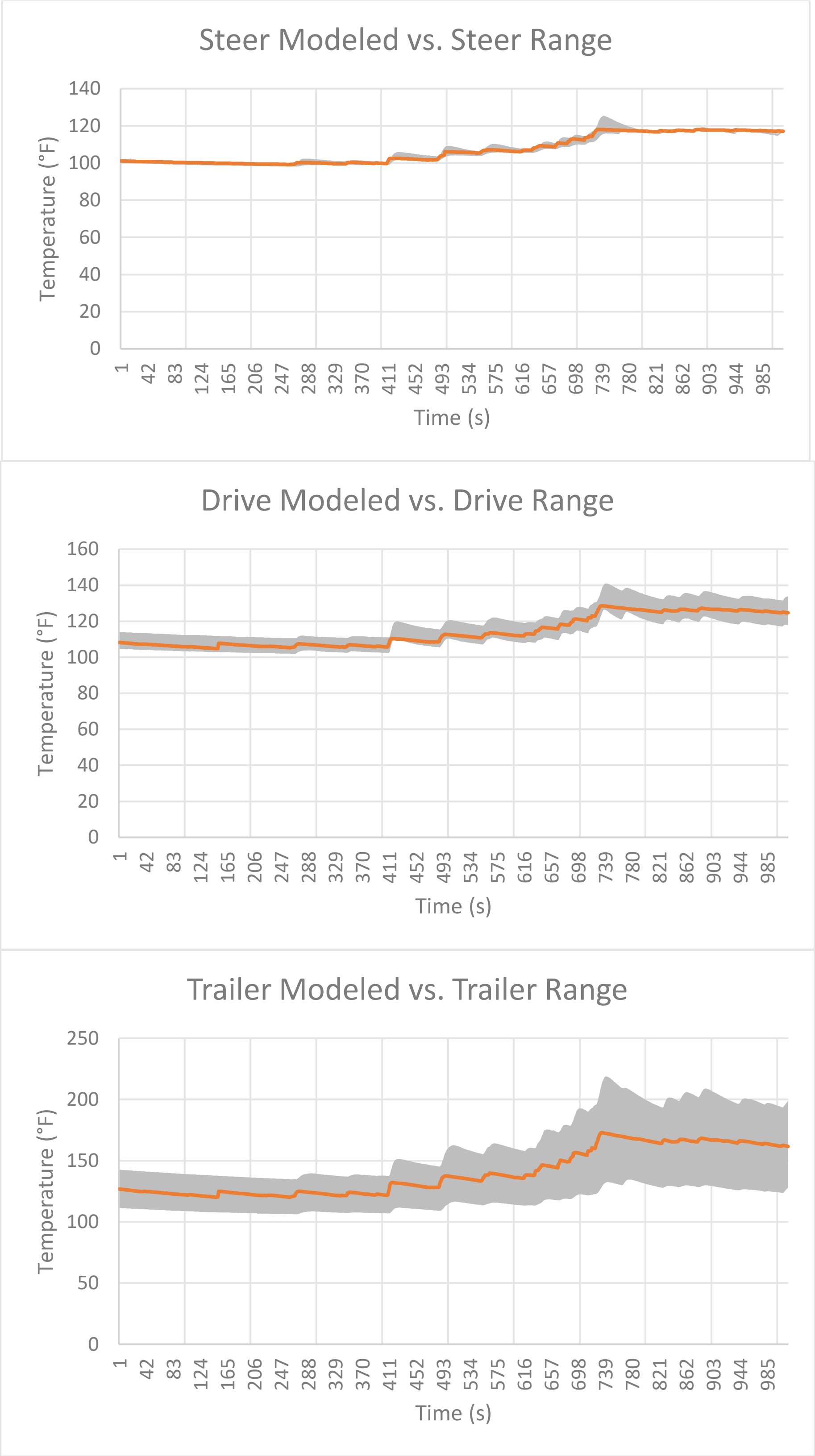


Figure A-4. Loaded Class 8 Disc-Drum Beverage Cycle

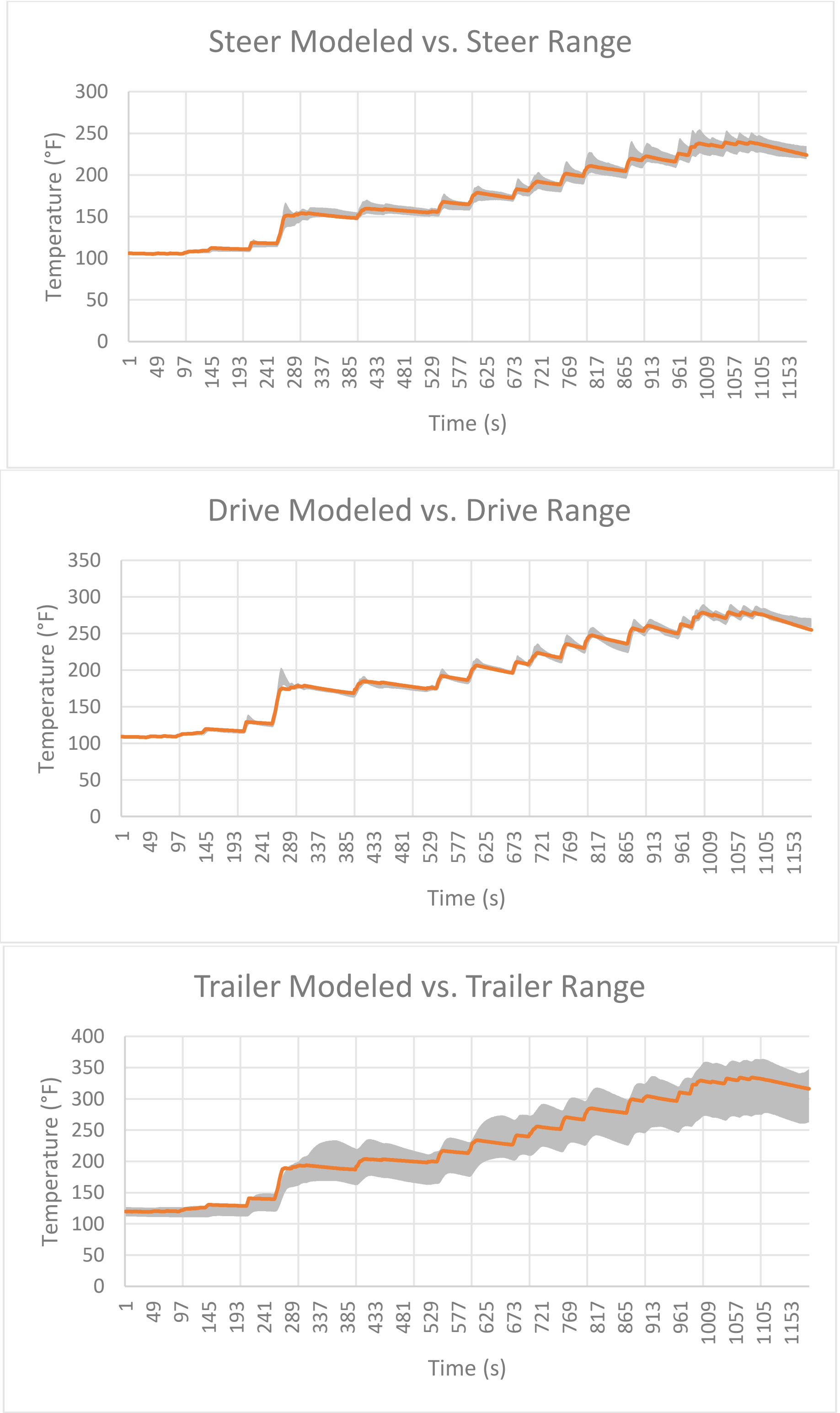


Figure A-5. Loaded Class 8 Disc-Drum Long Haul Cycle

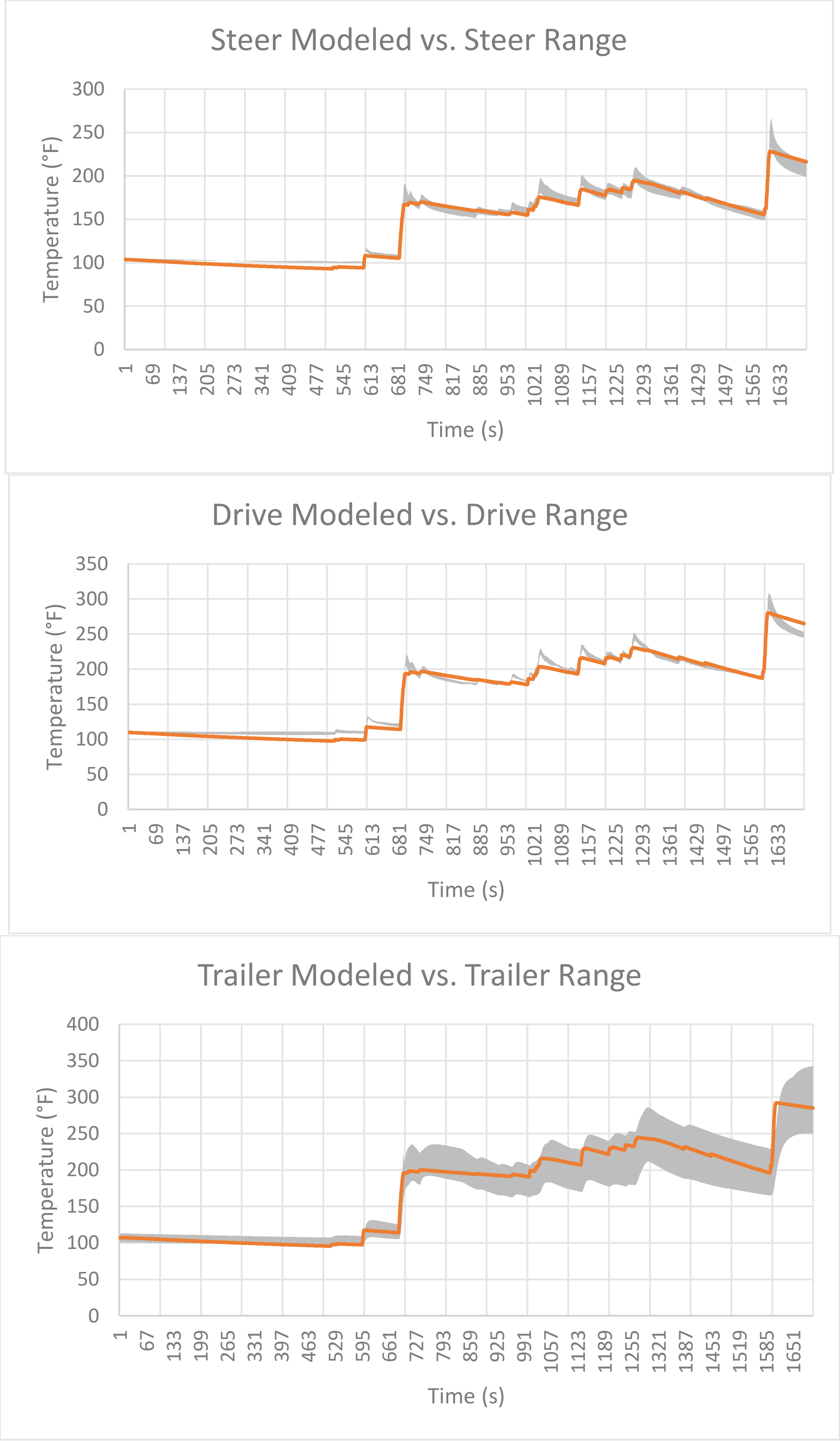
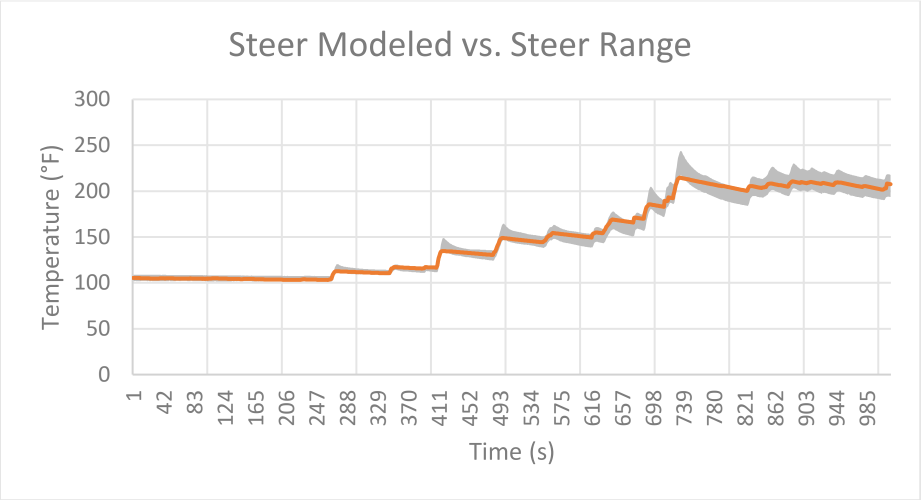
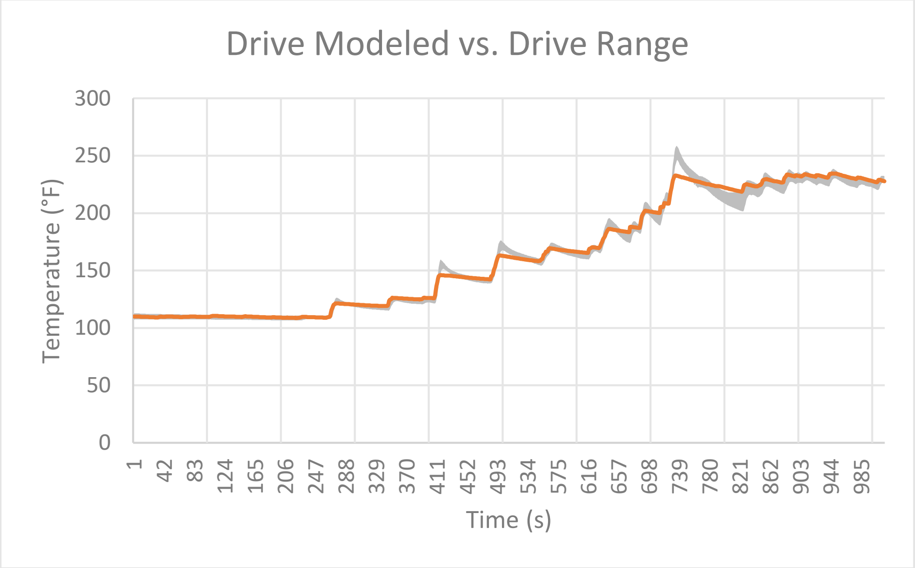


Figure A-6. Loaded Class 8 Disc-Drum Drayage Cycle





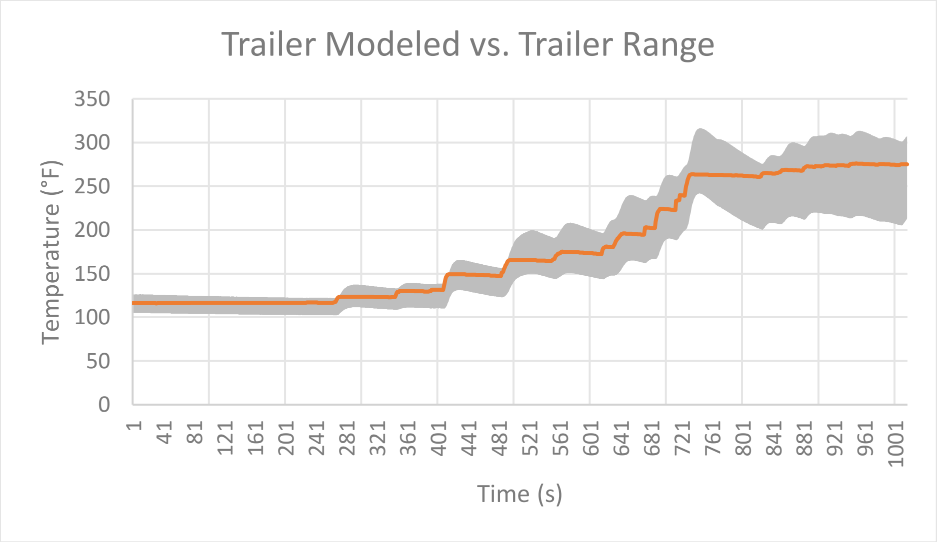
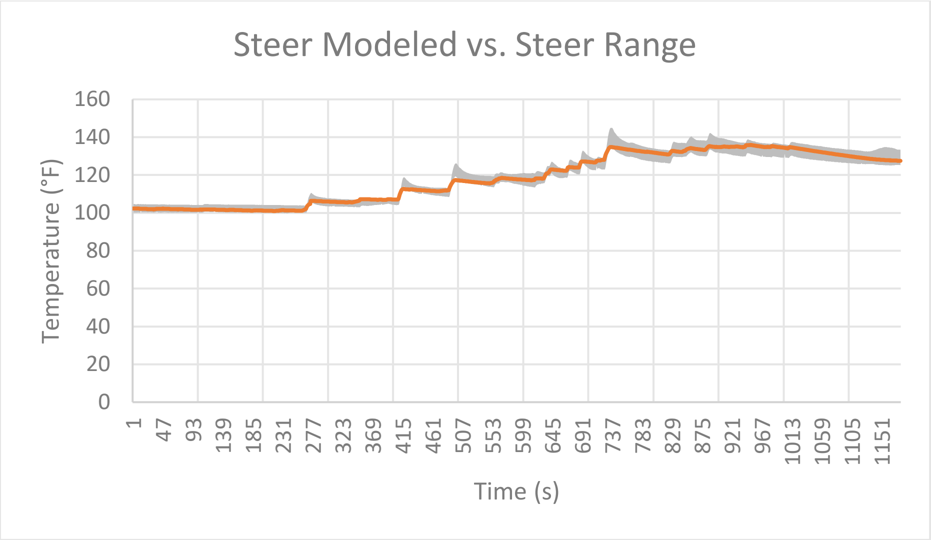
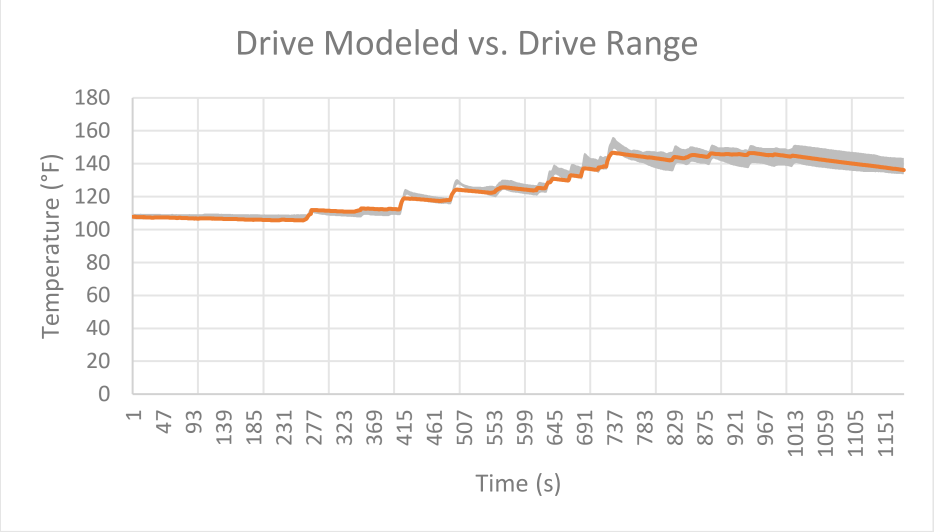


Figure A-7. Unloaded Class 8 Disc-Drum Drayage Cycle





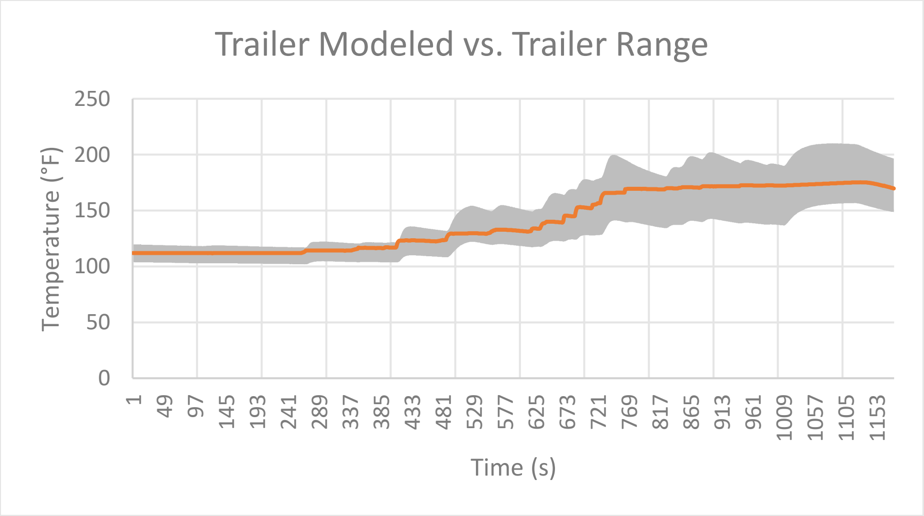


Figure A-8. Refuse Truck Refuse Cycle

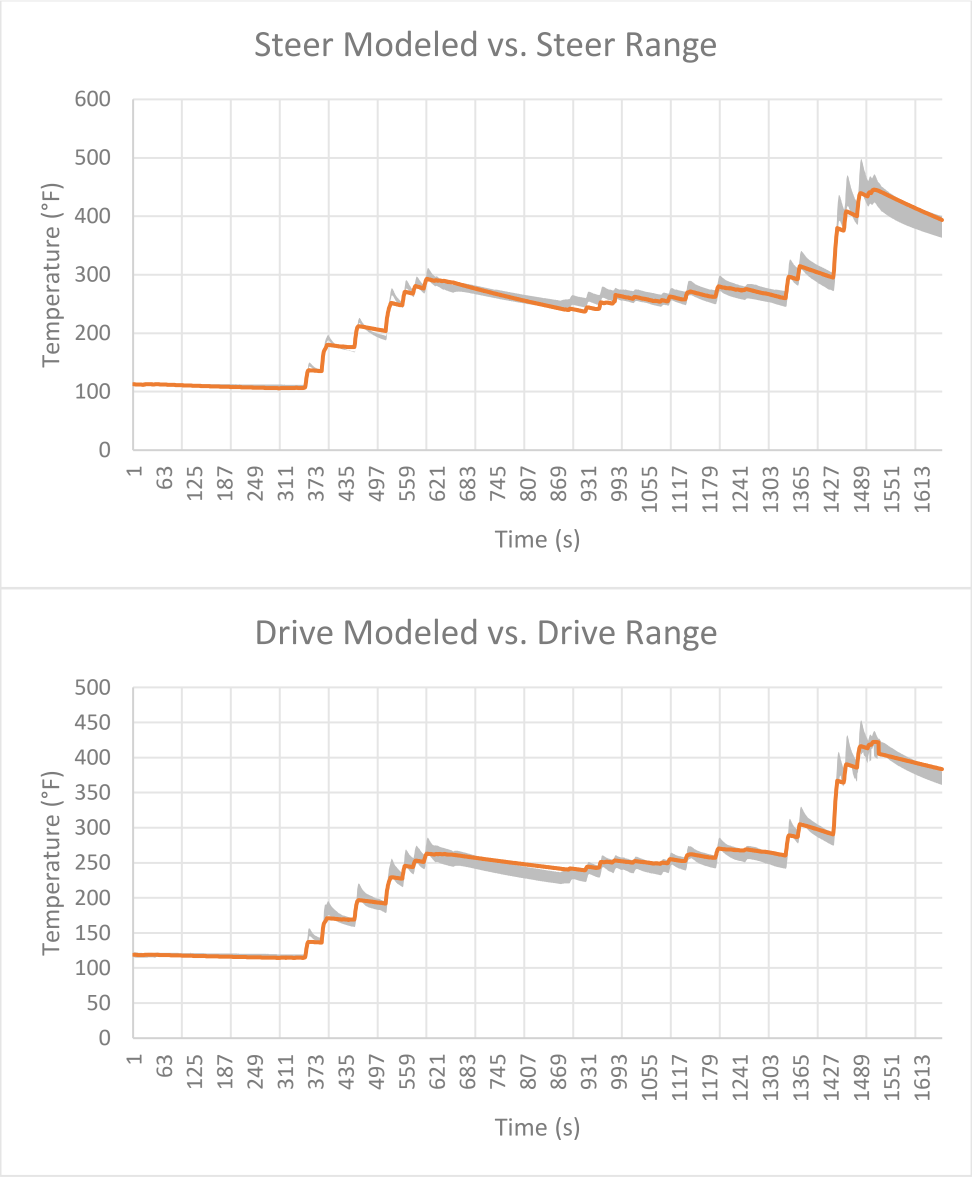
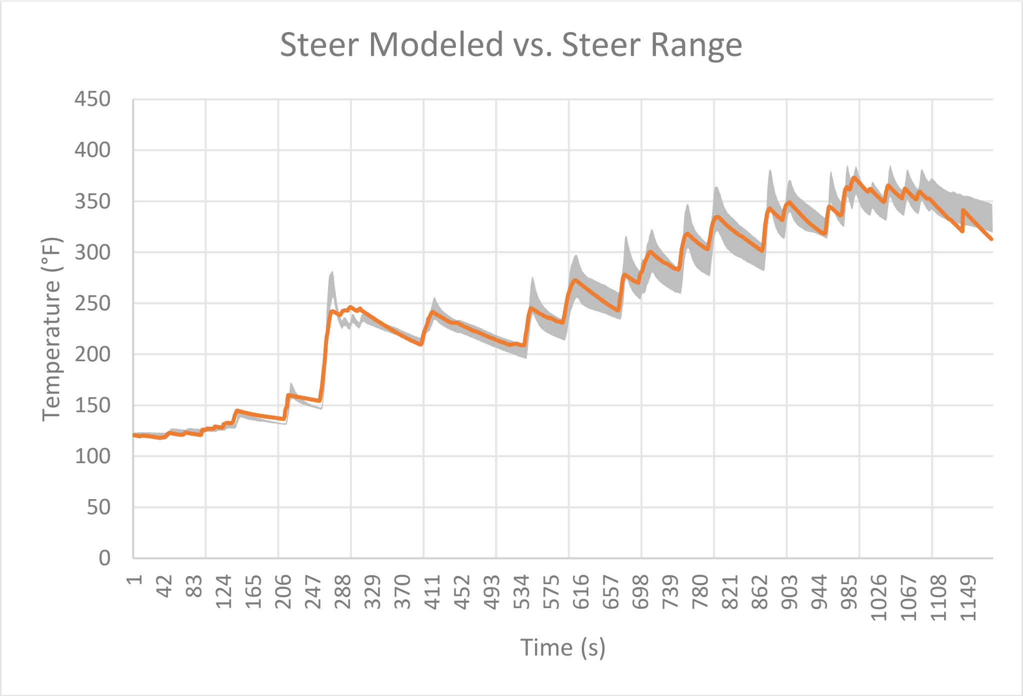


Figure A-9. Class 6 Hydraulic Disc Beverage Cycle



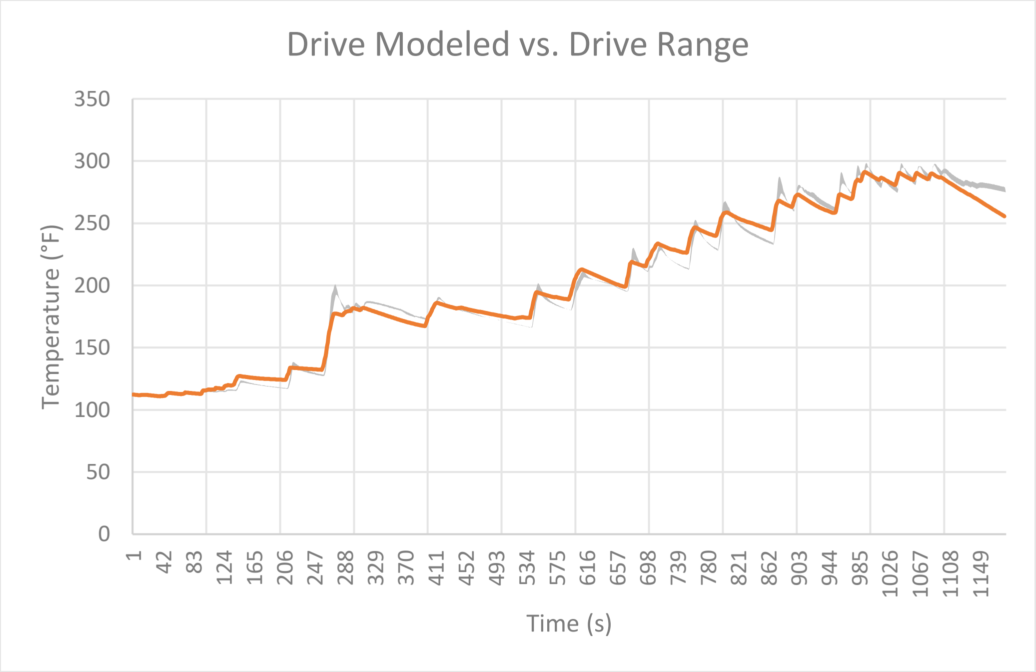


Figure A-10. Loaded Class 6 Hydraulic Disc Towing Cycle

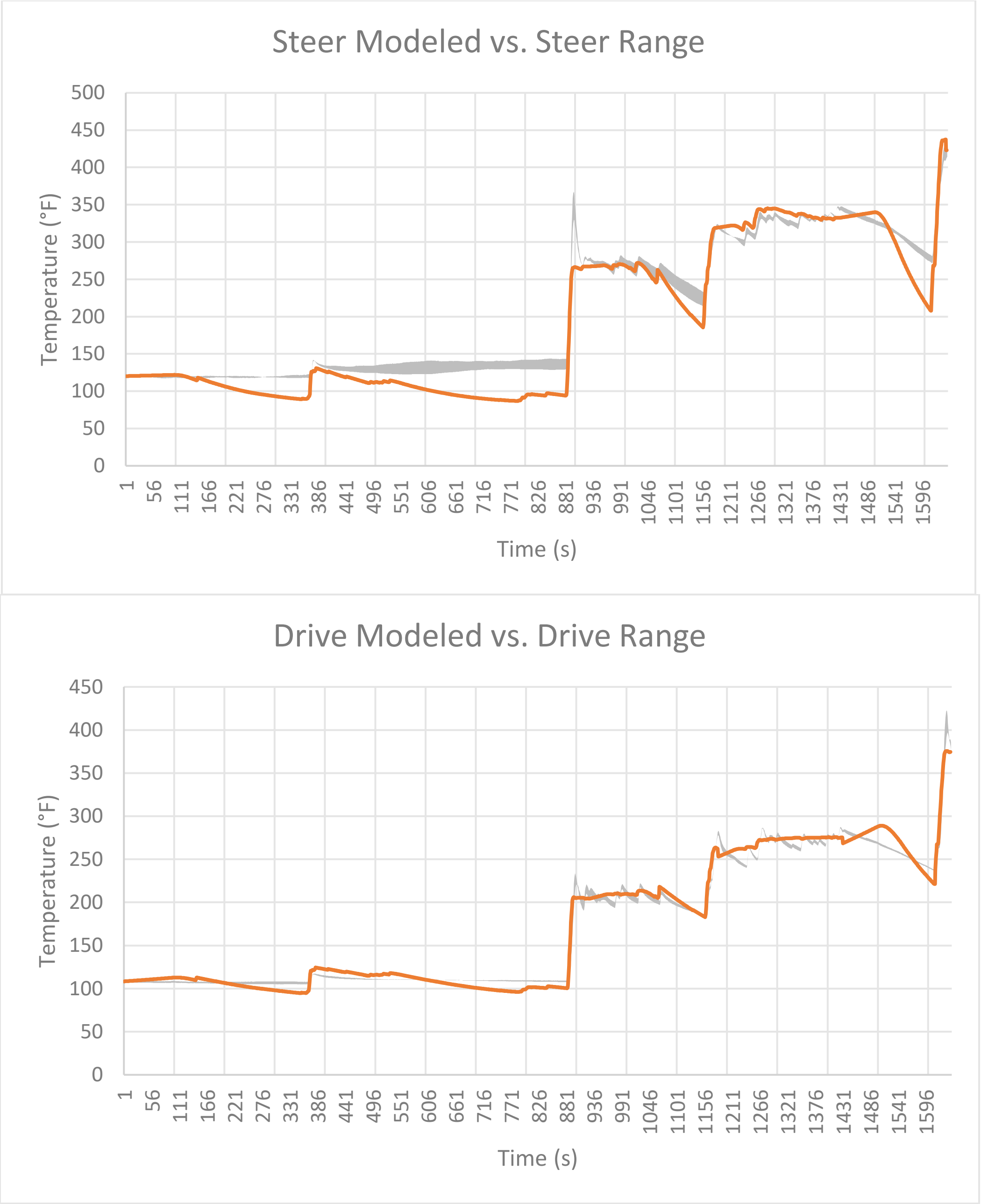
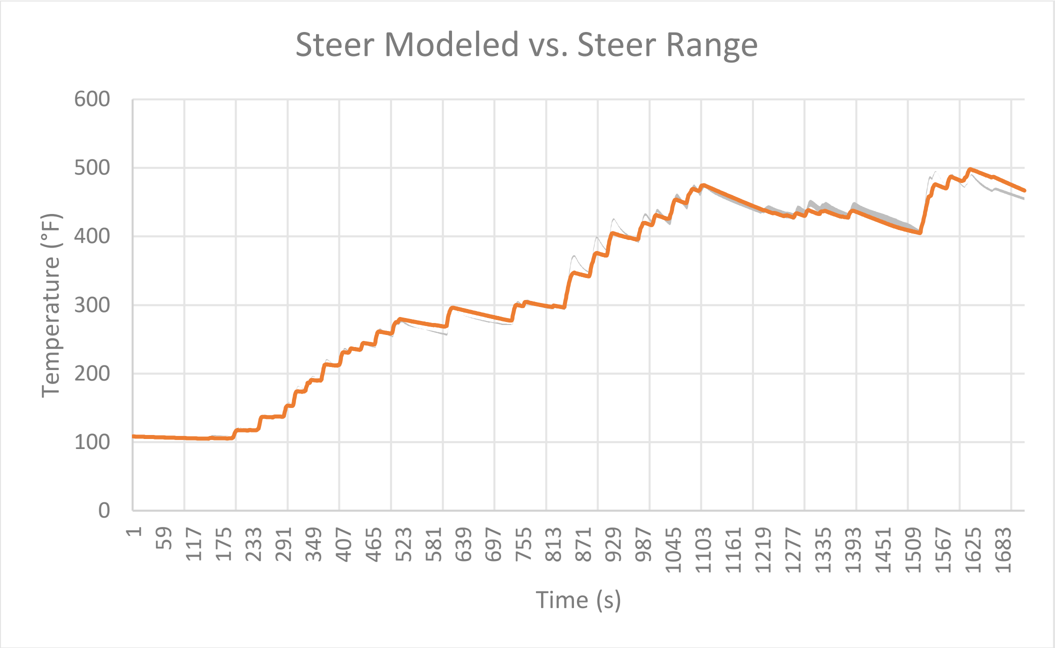
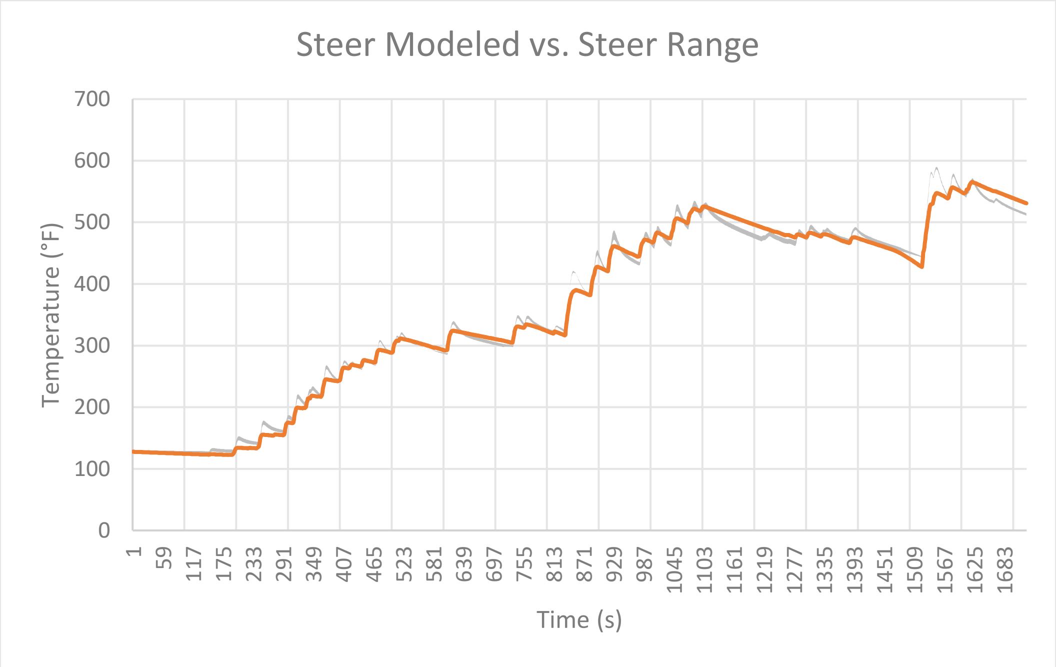


Figure A-11. Loaded Air Disc Urban Bus Cycle





APPENDIX B: HEAVY DUTY BRAKE EMISSIONS DYNAMOMETER CONFIGURATION (LINK ENGINEERING)

Link Engineering Company
401 Southfield Road
Dearborn, Michigan 48120

Adaptation of a CV-Brake Dynamometer to Measure Brake Emissions

LINK's Commercial Vehicle Brake Dynamometer can test a wide variety of standard test procedures, such as the FMVSS121/TP 121D, SAE J2115, EN standards, city traffic, mountain descent routes, performance wear, durability, and thermal capacity. The legacy dynamometer uses a large box-shaped enclosure to fit disc and drum brake assemblies of medium trucks and commercial vehicles. An externally-operated blower provides the cooling air via large duct connections. Figure 1 shows the pre-adapted dynamometer with the standard enclosure and the two airflow ducts for routine testing.

Fig 1: CV dynamometer before starting the conversion

Highlights of System Upgrades for CalTrans Brake Emissions Testing

LINK can execute several upgrades on the CV-Brake Dynamometer, which are described briefly in the below steps:

Step 1 – Fabricate an aerodynamic enclosure and attach it to the dynamometer (see Figure 2). This enclosure replaces the original box enclosure and is electropolished for ultrafine surface finish.

Step 2 – Disconnect the original air ducts and install new, clean ducts for emissions testing. Figure 3 shows the duct connections to the enclosure. The large inlet duct provides uniform airflow across the brake assembly inside the enclosure.

Step 3 - The return duct line or the constant volume sampling (CVS) tunnel as shown in Figure 3 connects to the enclosure's exit. This was used previously on the LD dynamometer for the CARB LD brake wear project 17RD016. The CVS tunnel is also electropolished.

Step 4 – Conditioning airflow to specific air temperature and humidity is crucial for brake emissions testing. The setup achieves this by connecting the test system with a dedicated climatic conditioning unit (CCU). Also, filtering inlet airflow is essential for minimal background emissions and their influence on actual measurements by including HEPA 13 filters and air prefilters. Figure 4 shows a work-in-progress snapshot taken at the time while connecting the ducts to the CCU.

Step 5 – Equip new hardware to the dynamometer for testing hydraulic as well as air brake assemblies for commercial vehicle applications according to the project's test plan. See Figure 5 for an example of brake assembly.

Step 6 – Install the dynamometer control programs to simulate all the drive cycles specified for each vehicle vocation.

Step 7 - Complete all electrical work and software integration to connect the instruments to the dynamometer master controller (ProLINK). ProLINK collects brake emissions data in real-time from various instruments, see Figure 6, in sync with the brake data (pressure, speed, torque, and temperatures).

Fig 2: Aerodynamic brake enclosure exit (using a gentle transition angle to reduce transport losses)

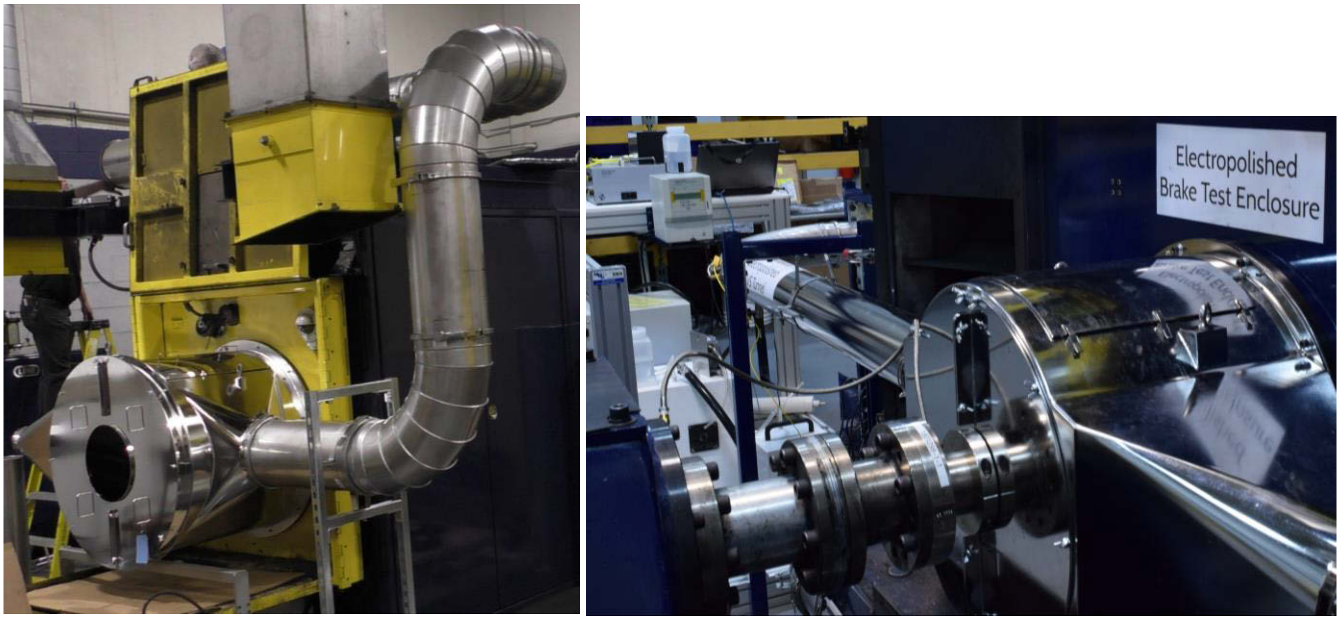


Fig 3: Inlet duct (left) and return duct (right) with air moving in the right-to-left direction

Fig 4: Assembling duct connections to the CCU

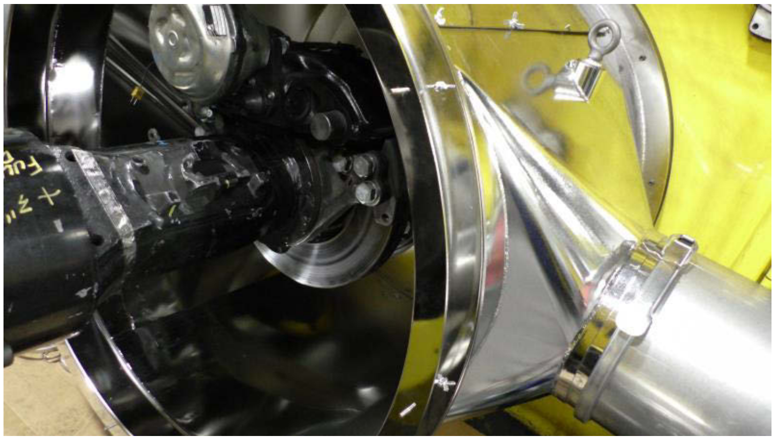


Fig 5: Air disc brake assembly mounted inside the enclosure

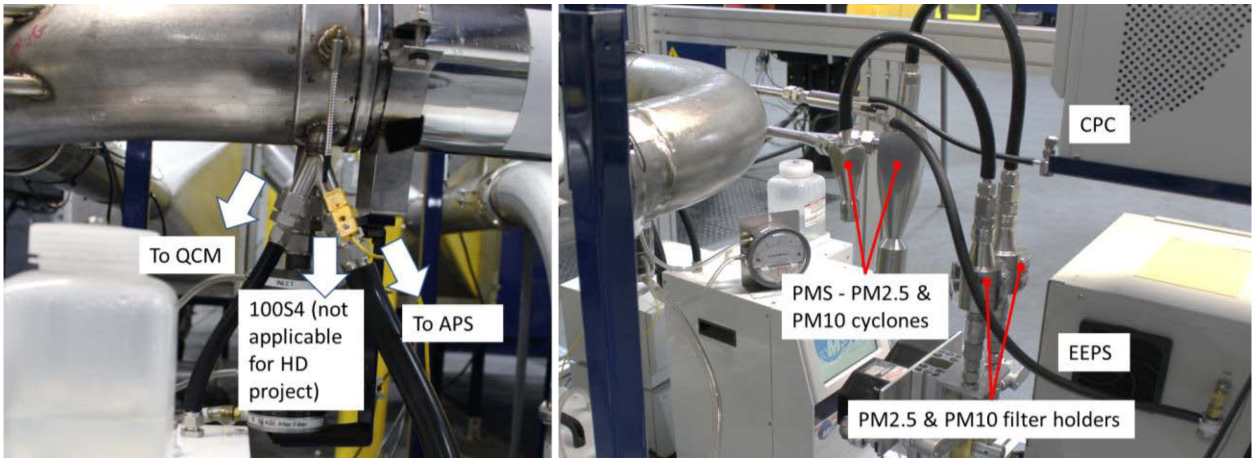
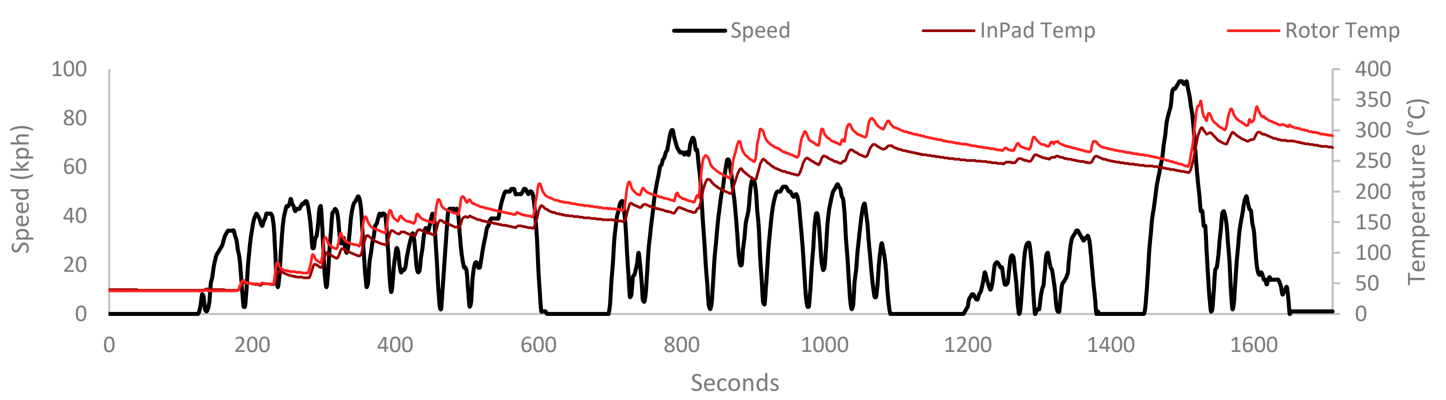


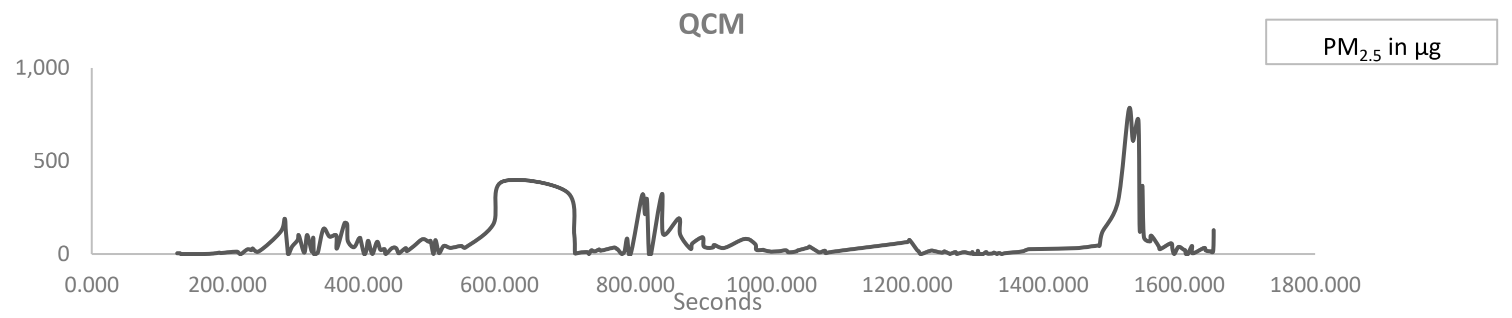
Fig 6: Instrumenting connections to measure HD brake particulates; shows the sampling train with connections to various PM instruments

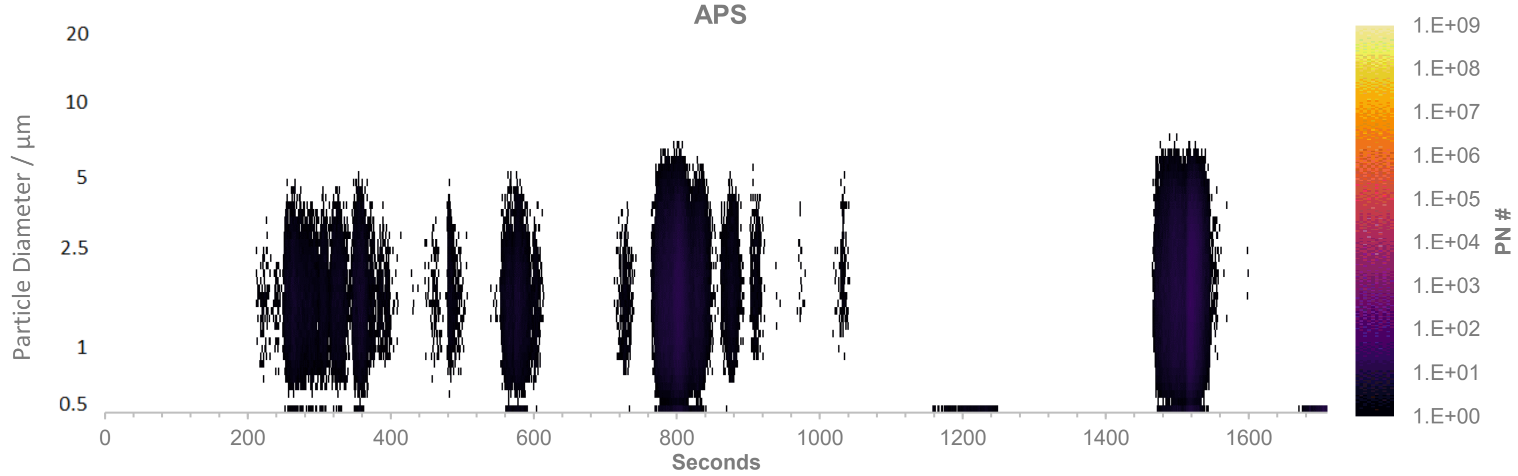
APPENDIX C: REAL-TIME PM DATA SAMPLES (FULL DATA IN TEST REPORTS)

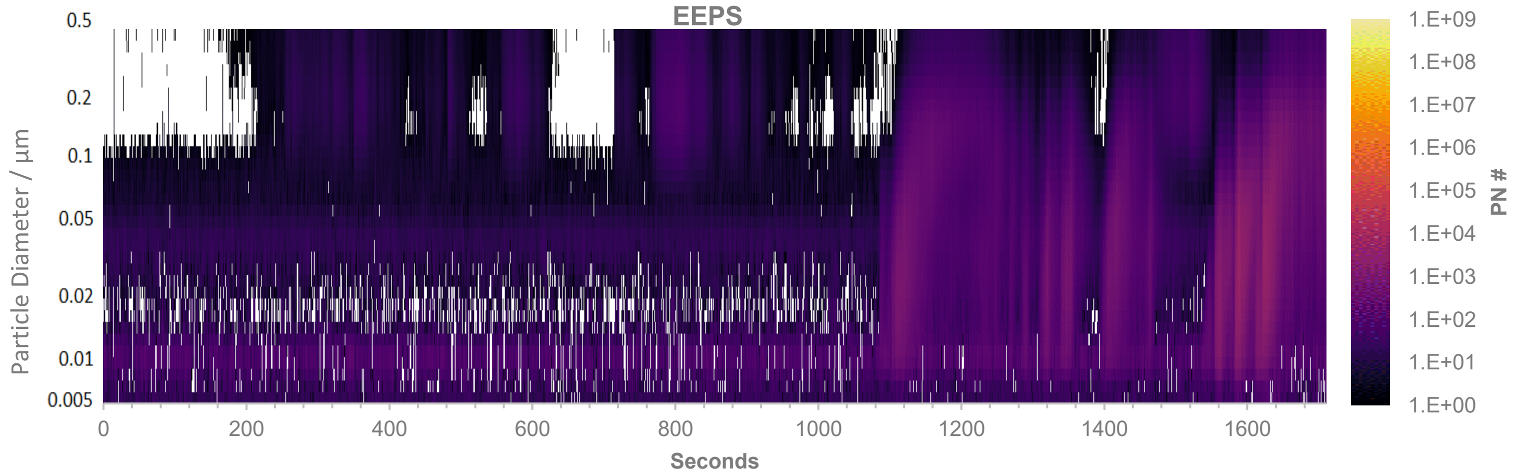
Sample Real-Time Data: Bus Drive OE

Urban Bus









Sample Real-Time Data: Tesla Front Axle

CBDC Cycle