Appendix A

Vehicle and Friction Material Selection Supporting Data

This Appendix includes supporting data for the Representative Test Vehicle and Friction Material Selection section of the report. This table presents the details of the top-25 vehicle analysis including the calculated values for the two brake wear indices (BWI). In the table, VIO indicates vehicles in operation. BWI1 is VIO x total wearable mass, and BWI2 is VIO x total wearable mass x replacement rate.

MAKE	MODEL	MY	Common for bench-marking	Curb wt (kg)	Brake system	VIO	**VIO Rnk**	Total wear mass per vehicle / g	BWI1 = (VIO x total wearable mass) / ton	**BWI1 Rnk**	Repl. Rate (%)	OE/OES mkt share (%)	BWI2 (tons)	**BWI2 Rnk**
TOYOTA	CAMRY (BASE, L, LE)	2009-2016	yes-FA	1460	Disc/ Disc	342992	1	2133	732	1	16%	34.0%	117	1
HONDA	CIVIC LX	2012-2015		1221	Disc/ Drum	140733	5	2322	327	4	14%	34.0%	46	3
NISSAN	ROGUE S	2014-2016		1550	Disc/ Disc	41213	10	1845	76	14	11%	34.0%	8	16
TOYOTA	SIENNA LE	2011-2015		1940	Disc/ Disc	44921	8	2717	122	8	14%	34.0%	17	6
FORD	F150 SPRCREW	2015-2016	yes-FA & RA	2206	Disc/ Disc	32921	17	2895	95	11	11%	90.0%	10	10
TOYOTA	PRIUS REGULAR	2010-2016		1382	Disc/ Disc	241055	2	1749	422	3	2%	34.0%	8	15
TOYOTA	COROLLA L	2014-2016		1265	Disc/ Drum	159154	3	3028	482	2	11%	53.5%	53	2
NISSAN	ALTIMA (BASE, 2.5)	2012-2016	yes-FA	1429	Disc/ Disc	149096	4	1510	225	5	14%	40.7%	32	4
NISSAN	SENTRA S	2013-2016		1277	Disc/ Disc	110629	6	1436	159	7	11%	53.5%	17	5
FORD	F150 SPRCREW	2013-2014	yes-FA	2549	Disc/ Disc	33721	16	2878	97	10	16%	17.0%	16	7
LEXUS	RX 350	2014-2015		1900	Disc/ Disc	43306	9	2707	117	9	11%	34.0%	13	8
CHEVROLET	TAHOE C1500	2007	yes-FA	2462	Disc/ Disc	19517	23	2521	49	18	23%	14.0%	11	9

MAKE	MODEL	MY	Common for bench-marking	Curb wt (kg)	Brake system	VIO	**VIO Rnk**	Total wear mass per vehicle / g	BWI1 = (VIO x total wearable mass) / ton	**BWI1 Rnk**	Repl. Rate (%)	OE/OES mkt share (%)	BWI2 (tons)	**BWI2 Rnk**
TOYOTA	RAV4 XLE	2014-2016		1560	Disc/ Disc	36803	14	2462	91	12	11%	34.0%	10	11
TOYOTA	TACOMA DOUBLE CAB	2015-2016		1975	Disc/ Drum	36052	15	5256	189	6	5%	90.0%	9	12
HONDA	ACCORD LX	2014-2016	yes-FA	1465	Disc/ Disc	52193	7	1598	83	13	11%	53.5%	9	13
DODGE	RAM 1500 ST	2004		2260	Disc/ Disc	19739	22	2180	43	19	21%	5.0%	9	14
HYUNDAI	ELANTRA GLS	2013		1207	Disc/ Disc	30566	18	1649	50	17	16%	17.0%	8	17
HYUNDAI	SONATA (GLS, SE, SPORT)	2013-2015		1486	Disc/ Disc	40117	11	1678	67	15	11%	90.0%	7	18
CHEVROLET	SILVERADO 1500	2014-2015	yes-FA	2240	Disc/ Disc	27578	19	2431	67	16	11%	53.5%	7	19
HONDA	ACCORD EX	2014-2016		1492	Disc/ Disc	39344	12	993	39	21	11%	53.5%	4	20
HONDA	ACCORD SPORT	2014-2015		1468	Disc/ Disc	37332	13	803	30	23	11%	34.0%	3	21
HONDA	CIVIC LX	2016		1276	Disc/ Disc	25782	20	1666	43	20	5%	90.0%	2	22
LEXUS	RX 350	2016		1970	Disc/ Disc	12540	24	2668	33	22	5%	90.0%	2	23
HYUNDAI	SONATA SE	2016		1486	Disc/ Disc	11363	25	1803	20	24	5%	90.0%	1	24
HONDA	ACCORD SPORT	2016		1507	Disc/ Disc	22978	21	803	18	25	5%	90.0%	1	25

Appendix B

Heating and Cooling Matrix for Track Testing

The following table depicts the braking events that made up the ERG heating and cooling matrix conducted by LINK at the test track. Each vehicle was subject to a series of braking snubs to achieve the desired initial temperature. The initial and final speeds, along with the deceleration rate is given for each braking event. The cooling speed, where applicable, refers to the steady-state speed that should be held after the braking event to allow the brakes to cool down below 50°C.

Event #	Initial Front Axle disc temperature, °C	Initial speed, km/h	Final speed, km/h	Cooling speed, km/h	Deceleration, g
1	60	55	0	0	0.10
2	60	55	< 5	55	0.25
3	160	55	< 5	55	0.25
4	160	55	< 5	NA	0.35
Warm-up	open	120	60	55	0.40
5	300-350	55	55	55	-
6	60	55	< 5	NA	0.25
Warm-up	open	120	60	55	0.40
7	300-350	55	55	55	-
8	60	55	< 5	55	0.35
9	60	95	0	0	0.10
10	60	95	< 5	55	0.10
11	60	95	< 5	95	0.25
12	160	95	< 5	95	0.25
13	160	95	< 5	NA	0.35
Warm-up	open	120	60	95	0.40
14	300-350	95	95	95	-
15	60	95	< 5	NA	0.35
Warm-up	open	120	60	95	0.40
16	300-350	95	95	95	-
17	60	95	< 5	95	0.35
18	60	130	0	0	0.10
19	60	130	< 5	55	0.10
20	60	130	< 5	130	0.25
21	160	130	< 5	130	0.10
22	160	130	< 5	NA	0.25
Warm-up	open	120	60	130	0.40
23	300-350	130	130	130	-
24	60	130	< 5	NA	0.35
Warm-up	open	120	60	130	0.40
25	300-350	130	130	130	-
26	60	130	< 5	95	0.35
Warm-up	open	120	60	NA	0.40
post Warm-up	300-350	60	0	0	0.25
27	300-350	0	0	0	-
Warm-up	open	120	60	NA	0.40
Warm-up	300-350	60	0	0	0.25
28	300-350	0	0	0	-

Appendix C

Derivation of the Generalized Coastdown Curve and Road Load Coefficients

The generalized coastdown curve was determined using the EPA-published road load coefficients for the six test vehicles used in this project. EPA publishes these values, including test weight, yearly as a part of new-vehicle exhaust emissions certification.1 The coefficients are used to allow determination of the simulated dynamometer drag force on the vehicle as a function of speed. The published coefficients for the test vehicles used in this work are shown in the following table.

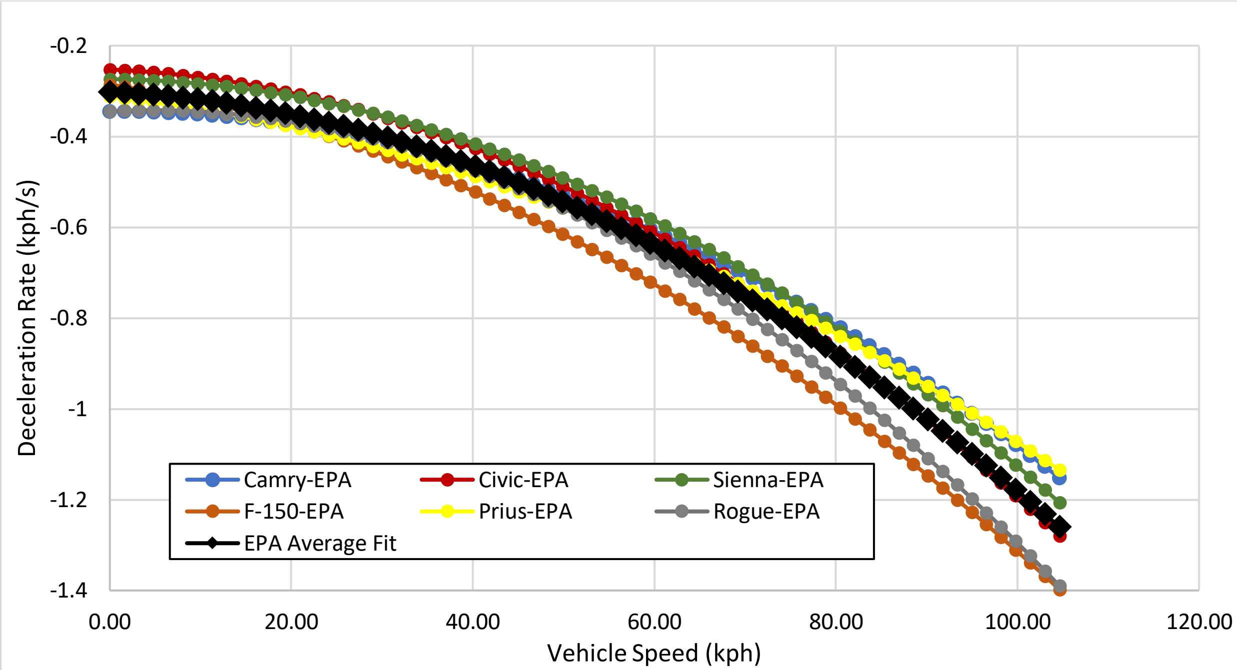
	Target Coef. A (lbf)	Target Coef. B (lbf/mph)	Target Coef. C (lbf/mph**2)	Weight, lbs
Toyota Camry	35.941	-0.01201	0.020084	3670
Honda Civic	21.290	0.11890	0.018670	2970
Toyota Sienna	37.384	0.03816	0.029553	4810
Ford F-150	46.83	0.7658	0.03132	5770
Toyota Prius	31.145	0.35285	0.013956	3510
Nissan Rogue	35.59	-0.1577	0.028	3640

The EPA target coefficients are the target that the vehicle will experience as a function of speed. For this project, the force was not the parameter of interest as the main focus was on the vehicle deceleration rate. Using the weight and the road load force curve, ERG determined the expected deceleration rate as a function of speed for the six vehicles. ERG performed a polynomial curve fit to the average (by speed) of the deceleration rates for the six vehicles. The calculated coastdown deceleration rates as a function of speed are presented for the six test vehicles in the following figure. The larger black curve represents a fit to the average of the six vehicles and forms the basis of the generalized coastdown curve. The generalized coastdown curve used in this work was:

$$\Delta V = -7.931\text{x}10^{-5}\bullet V^2 - 8.558\text{x}10^{-4}\bullet V - 0.3023$$

where ΔV has units of kph/s and V has units of kph.

[1] https://www.epa.gov/compliance-and-fuel-economy-data/annual-certification-data-vehicles-engines-and-equipment



The following table presents the actual inertia values used by LINK when programming tests of each vehicle/axle combination into the dynamometer control software:

Vehicle	Front Inertia (kg•m^2)	Rear Inertia (kg•m^2)
Camry ETW	79.8	28.6
Civic ETW	55.1	19.8
F-150 ETW	161.0	58.6
F-150 HLW	184.3	67.0
Prius ETW	53.0	26.5
Rogue ETW	85.9	30.8
Rogue HLW	95.9	34.4
Sienna ETW	98.0	47.5
Sienna HLW	113.2	54.9

Appendix D

The ERG Vector Collinearity Cycle Building Approach

This section references two past reports in which ERG described the use of the vector collinearity method to build up a cycle from a larger in-use dataset. The process required further refinement for use in 17RD016 because of the temperature requirements and that temperature could not be directly controlled on the brake dynamometer (as the temperature is a function of only speed, braking intensity, and time).

The first reference was included as a footnote in ERG's proposal for this project. This reference is *Roadway-Specific Driving Schedules for Heavy-Duty Vehicles*, an ERG report to EPA, August 15, 2003. Section 5 of that document includes the description of the implementation of the vector method. This report is available at: http://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P100LWCT.TXT

The next reference is presented as an excerpt, and is from *Development of NONROAD Load Factors, Emission Factors, Duty Cycles, and Activity Estimates*, an ERG report to EPA, February 12, 2013. In this reference, the term microtrip is the equivalent to the brake event in Project 17RD016 (meaning it is the building block taken from the larger dataset and used to build up the new cycle). The section describing the technique reads as follows:

In 1995 we developed a technique for creating duty cycles based on the microtrip concept. Since then, we have built engine dynamometer cycles (load and RPM vs. time) for wheeled loaders[2] and telescoping boom excavators,[4] and chassis dynamometer cycles (speed vs. time) for drayage trucks, heavy-duty trucks[3], dump trucks, and Bangkok cars and motorcycles. In most cases we also collected the data used to build those duty cycles. In addition, many of the cycles built were actually used to make dynamometer measurements of the emissions of engines and POEs.

The idea of a duty cycle is that it contains the essence of actual operating behavior. To make a representative cycle practical, it should be no longer than needed. A key challenge for the cycle builder is to compress the dataset collected on each type of construction equipment to produce a reasonably short cycle while maintaining the essence of the engine operating behavior. Such a short cycle can then be used to characterize engine operation to estimate engine emissions for a type of construction equipment during typical operation for that type of equipment.

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[2] T.H. DeFries, G.F. Baker, B. Limsakul, M.A. Sabisch, P. Henson, S. Kishan, "ERG Contributions to the Texas Department of Transportation Evaluation of PuriNOx Diesel Fuel," prepared for R.D. Matthews, University of Texas at Austin, prepared by Eastern Research Group, TxDOT-030218, February 18, 2003.
[3] T.H. DeFries, S. Kishan, B. Limsakul, M.J. Hebets, "Roadway-Specific Driving Schedules for Heavy-Duty Vehicles," prepared for U.S. Environmental Protection Agency, prepared by Eastern Research Group, EPA-030815, August 15, 2003.

Representative cycles can be built using different methodologies. The methodology we have chosen for this study is to use pieces of real engine operation, called microtrips, from the data collected on construction equipment, which when connected together can be expected to have similar emissions behavior to the same type of equipment in normal operation. The cycle is built around parameters of equipment operation and usage that are known to be important to exhaust emissions. By building up a duty cycle from snippets (microtrips) of actual engine operation such that the characteristics of the cycle in some way matches the characteristics of a database of typical engine operation, it can be inferred that the emissions behavior of the engine over the cycle will be similar to the emissions behavior of the engine in a particular type of construction equipment.

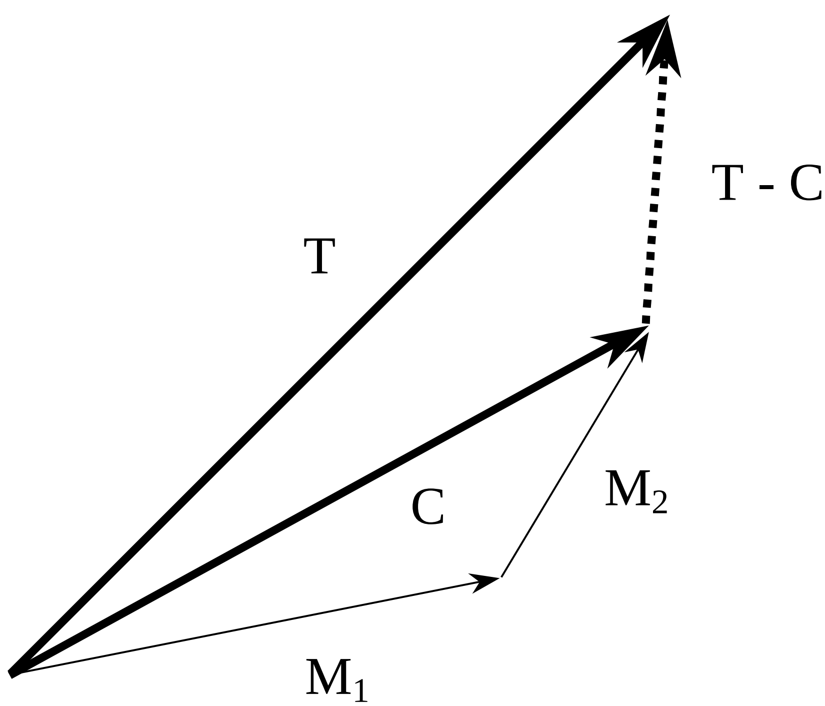
The cycle is created by selecting and combining microtrips taken from the dataset of actual engine operation for each type of construction equipment. Two or more variables are used to define and select microtrips for the cycle. This cycle-building introduction uses relative mass fuel rate and relative RPM as the two variables used to define engine operation. To identify specific segments of equipment operation for inclusion in the cycle, the entire activity dataset is converted to a set of microtrips. Typically, a microtrip is defined as a contiguous time trace of engine operation that is an all-non-idle period or that is an all-idle period.

To use the microtrip cycle development approach, all of the microtrips in the dataset need to have all of their second-by-second observations binned in terms of relative mass fuel rate and relative RPM. While the size of the bins is arbitrary, bins in general need to be narrow enough to resolve important emissions effects. On the other hand, from a practical perspective, the number of bins needs to be small so that the program that selects microtrips can run in a reasonable amount of time.

Selecting microtrips for the cycle is based on a strategy of minimizing the difference between a cycle vector **C** representing operation in the candidate cycle and a target vector **T** representing operation in the activity database. As microtrips are added to the kernel of the candidate cycle, the difference between the two vectors **C** and **T** tends to become smaller and smaller. The build-up process ends when the cycle developer decides that the two vectors are substantially the same and the duration of the cycle that has been built up is acceptably short. The multi-dimensional space that these vectors are in will be described shortly, but first let us consider how the build-up process works for developing a cycle.

The goal of building the cycle is to select microtrips such that when their vectors $\mathbf{M_i}$ are added together, the vector **C** of the resulting cycle is as similar as possible to the target vector **T** of the activity database. Figure A3-1 shows the hypothetical situation of the vectors after two microtrips have been used to create a cycle. In this hypothetical example, the first microtrip was selected from the activity database for the case as the one whose vector $\mathbf{M_1}$ was closest to the target vector **T** for the database. Then, a second microtrip is searched for such that when its vector $\mathbf{M_2}$ is added to $\mathbf{M_1}$ to create the resultant vector **C** shown in Figure A3-1, the distance between the tips of **C** and **T** is minimized. This distance is the length of the vector **T-C** as denoted in the figure by the dashed vector. As microtrips are added to create the built-up cycle represented by **C**, the length of **T-C** is calculated after each additional microtrip is added to the cycle to follow the progress of the build-up process. It should be noted that the order of the microtrips in the final cycle is unimportant from the point of view of the selection of the microtrips. The reason for this is that the resultant **C** is independent of the order in which the microtrip vectors $\mathbf{M_i}$ are added together.

Figure A3-1. Vector Description of Comparing Target and Cycle Activity



It should also be noted that we are forcing microtrips to be added to the candidate cycle. This is done even if the addition of the best incremental microtrip causes the length of **T-C** to increase in some instances. Generally, as the cycle is built up there will be a decrease in the length of **T-C**. After several microtrips have been added, the length of **T-C** may increase slightly. Later, with the addition of more microtrips, a "discovery" will be made that will produce a relatively abrupt decrease in the length of **T-C** so that the accumulated cycle will be substantially better than the cycle was much earlier in the build-up process.

All of the vectors used above to describe the build-up process are based on representations of the cumulative frequency distributions of observations in relative mass fuel rate / relative RPM space. This statement requires some explanation. A segment of operation, whether it is a microtrip, a piece of a duty cycle, or the entire activity database can be described as a frequency distribution. The distribution consists of combinations of the two variables: relative mass fuel rate and relative RPM. The continuous values for these variables were converted into frequency distributions through the use of bins. Each one-second observation in the database was placed in a particular relative mass fuel rate / relative RPM bin. The cumulative frequency distribution is made up of the number of observations that fall “below” the current bin for each of the two-binned variables. The binning criteria for the variables will be described in Section 5.2. To help the reader understand the process, we will present a numerical example in one dimension and another example in two dimensions to demonstrate how the comparison of the vectors **T** and **C** works.

Suppose we wanted to compare a candidate cycle with the database using a single POE operation variable that was monitored second-by-second in the collection of data for the activity database. The single variable might be engine load. In this hypothetical example, we have 35,900 one-second observations of engine load in the target activity database and 68 one-second observations in the cycle. The first step in comparing **T** and **C** is to bin the observations of load in the target data and in the cycle data. TableTable A3-1 shows the binning of the hypothetical data in Columns 2 and 3. Note that the number of observations in the target data in Column 2 is much higher than the number of observations in the cycle data in Column 3. This is a consequence of the activity database containing all of the observations for all microtrips and the cycle having just one microtrip. The frequency counts in Columns 2 and 3 are then converted to cumulative frequency counts in Columns 4 and 5. This is done to provide proximity information for the microtrip searching algorithm. In other words, we wanted the algorithm to be able to select a microtrip even if the observations for a given microtrip were not in exactly the same bins as the target but did have observations at least in a nearby bin. The use of the cumulative distributions helps ensure that proximity information is available.

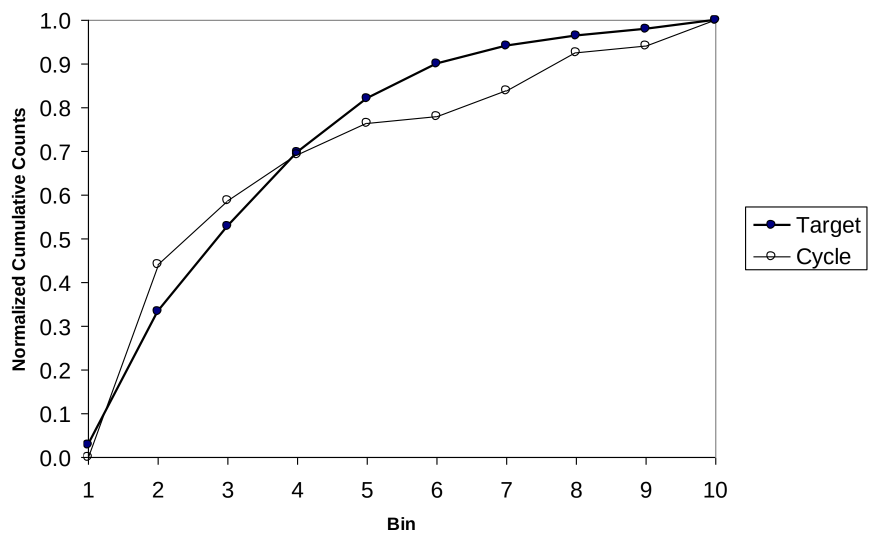
Table A3-1. Comparison of Cycle and Target Vectors for a Hypothetical One-Dimensional Example

	Counts		Cumulative Counts		Vector (Normalized Cumulative Counts)		Square of Difference
Bin	Target	Cycle	Target	Cycle	T	C	T-C
1	1000	0	1000	0	0.028	0.000	0.001
2	11000	30	12000	30	0.334	0.441	0.011
3	7000	10	19000	40	0.529	0.588	0.003
4	6000	7	25000	47	0.696	0.691	0.000
5	4500	5	29500	52	0.822	0.765	0.003
6	2800	1	32300	53	0.900	0.779	0.014
7	1500	4	33800	57	0.942	0.838	0.011
8	800	6	34600	63	0.964	0.926	0.001
9	600	1	35200	64	0.981	0.941	0.002
10	700	4	35900	68	1.000	1.000	0.000
				Sum of Squares	6.139	5.657	0.047
				Vector Length	2.478	2.379	0.217

A comparison of the cumulative counts for the target and cycle information in Columns 4 and 5 shows that if we used these counts to create the **T** and **C** vectors, the lengths of the vectors would be greatly different simply because the target vector, which is made up of the 10 elements in Column 4, would be a much longer vector then the cycle vector, which is made up of the 10 elements in Column 5. Accordingly, we normalize the target and cycle cumulative counts in 4 and 5 to produce the target vector elements and the cycle vector elements as the fractional values between 0 and 1 shown in Columns 6 and 7.

The values in Columns 6 and 7 become the elements of the **T** and **C** vectors, which are in 10-dimensional space. A visualization of the elements of these vectors is provided in Figure A3-2. This figure shows the normalized cumulative counts of the target and cycle from Columns 6 and 7 as a function of the bin number. What we want to do in developing the cycle is select microtrips so that the curve for the cycle is as close as possible to the curve for the target in this figure. The way we do this is to minimize the sums of the squares of the differences between the value for the corresponding elements of the target and cycle vectors. This corresponds to the square of the length of **T**-**C**. TableA3-1 shows the calculated length of **T**, **C**, and **T**-**C**. These lengths can be determined from the values of the elements for **T** and **C** in Columns 6 and 7 using the standard relationship for determining the length of a vector when its elements are known.

Figure A3-2. Visual Comparison of Vector Elements



Extension of the one-dimensional example shown in TableA3-1 and Figure A3-1 to multiple dimensions is demonstrated by the spreadsheet calculations shown in Table A3-2. In this example, 100 matrix elements are used. The table shows 10 rows which might be relative mass fuel rate and 10 columns which might be relative RPM. The left side of Table A3-2 shows the calculations for the target matrix and the right side shows the calculations for the cycle matrix. In Tables a) and b), the second-by-second observations of the target and cycle data are binned. The numbers in each bin represent the frequency of observations that meet the criteria for those bins. In Tables c) and d), the counts in the Tables a) and b) are accumulated across each row. Then, in Tables e) and f), the accumulated frequencies in Tables c) and d) are accumulated down each column. This produces a field of frequencies on a cumulative basis that run from a low value in the upper left corner of each matrix to a high number in the lower right corner of each matrix. The value in the lower right hand corner of Tables e) and f) is equal to the total number of observations in the target or cycle matrix. These total observation numbers in the lower right hand corner of e) and f) are used to normalize all of the frequencies in Tables e) and f) to arrive at the normalized cumulative matrices in g) and h). The values in g) and h) are then used to calculate the square of the differences in each corresponding matrix element to produce the values in Table i). The value in Table j) is just the summation of all of the elements of Table i) and represents the square of the length of the **T**-**C** vector. This is the value that we attempt to minimize when selecting microtrips for the cycle. Note that the counts in a) and b) did not need to be in corresponding bins for this comparison process to work. The use of cumulative distributions permitted the two matrices to be compared successfully.

Extension of the technique to more than two dimensions can be made by analogy.

Table A3-2. Comparison of Cycle and Target Matrices for a Hypothetical Two-Dimensional Example

Target Activity Matrix

a) Count the second-by-second observations in each bin.

	A	B	C	D	E	F	G	H	I	J
1	2									
2		1								
3		2		5						
4			5		3		2	1		
5		5		9	1			2	9	3
6			2			4	1			
7										
8			6			1				
9		1								
10										

Cycle Activity Matrix

b) Count the second-by-second observations in each bin.

	A	B	C	D	E	F	G	H	I	J
1										
2		1								
3				4						
4		4				3		1		
5								4	1	
6				8						2
7					3					
8							1			
9	1	5								
10										

c) Accumulate the above frequencies across each row

1	2	2	2	2	2	2	2	2	2	2
2	0	1	1	1	1	1	1	1	1	1
3	0	2	2	7	7	7	7	7	7	7
4	0	0	5	5	8	8	10	11	11	11
5	0	5	5	14	15	15	15	17	26	29
6	0	0	2	2	2	6	7	7	7	7
7	0	0	0	0	0	0	0	0	0	0
8	0	0	6	6	6	7	7	7	7	7
9	0	1	1	1	1	1	1	1	1	1
10	0	0	0	0	0	0	0	0	0	0

d) Accumulate the above frequencies across each row

0	0	0	0	0	0	0	0	0	0
0	1	1	1	1	1	1	1	1	1
0	0	0	4	4	4	4	4	4	4
0	4	4	4	4	7	7	8	8	8
0	0	0	0	0	0	0	4	5	5
0	0	0	8	8	8	8	8	8	10
0	0	0	0	3	3	3	3	3	3
0	0	0	0	0	0	1	1	1	1
1	6	6	6	6	6	6	6	6	6
0	0	0	0	0	0	0	0	0	0

e) Accumulate the above frequencies down each column.

1	2	2	2	2	2	2	2	2	2	2
2	2	3	3	3	3	3	3	3	3	3
3	2	5	5	10	10	10	10	10	10	10
4	2	5	10	15	18	18	20	21	21	21
5	2	10	15	29	33	33	35	38	47	50
6	2	10	17	31	35	39	42	45	54	57
7	2	10	17	31	35	39	42	45	54	57
8	2	10	23	37	41	46	49	52	61	64
9	2	11	24	38	42	47	50	53	62	65
10	2	11	24	38	42	47	50	53	62	65

f) Accumulate the above frequencies down each column.

0	0	0	0	0	0	0	0	0	0
0	1	1	1	1	1	1	1	1	1
0	1	1	5	5	5	5	5	5	5
0	5	5	9	9	12	12	13	13	13
0	5	5	9	9	12	12	17	18	18
0	5	5	17	17	20	20	25	26	28
0	5	5	17	20	23	23	28	29	31
0	5	5	17	20	23	24	29	30	32
1	11	11	23	26	29	30	35	36	38
1	11	11	23	26	29	30	35	36	38

g) Normalize the elements in the above matrix.

1	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031
2	0.031	0.046	0.046	0.046	0.046	0.046	0.046	0.046	0.046	0.046
3	0.031	0.077	0.077	0.154	0.154	0.154	0.154	0.154	0.154	0.154
4	0.031	0.077	0.154	0.231	0.277	0.277	0.308	0.323	0.323	0.323
5	0.031	0.154	0.231	0.446	0.508	0.508	0.538	0.585	0.723	0.769
6	0.031	0.154	0.262	0.477	0.538	0.600	0.646	0.692	0.831	0.877
7	0.031	0.154	0.262	0.477	0.538	0.600	0.646	0.692	0.831	0.877
8	0.031	0.154	0.354	0.569	0.631	0.708	0.754	0.800	0.938	0.985
9	0.031	0.169	0.369	0.585	0.646	0.723	0.769	0.815	0.954	1.000
10	0.031	0.169	0.369	0.585	0.646	0.723	0.769	0.815	0.954	1.000

h) Normalize the elements in the above matrix.

0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026
0.000	0.026	0.026	0.132	0.132	0.132	0.132	0.132	0.132	0.132
0.000	0.132	0.132	0.237	0.237	0.316	0.316	0.342	0.342	0.342
0.000	0.132	0.132	0.237	0.237	0.316	0.316	0.447	0.474	0.474
0.000	0.132	0.132	0.447	0.447	0.526	0.526	0.658	0.684	0.737
0.000	0.132	0.132	0.447	0.526	0.605	0.605	0.737	0.763	0.816
0.000	0.132	0.132	0.447	0.526	0.605	0.632	0.763	0.789	0.842
0.026	0.289	0.289	0.605	0.684	0.763	0.789	0.921	0.947	1.000
0.026	0.289	0.289	0.605	0.684	0.763	0.789	0.921	0.947	1.000

i) Calculate the squares of the differences in corresponding elements of the above two matrices.

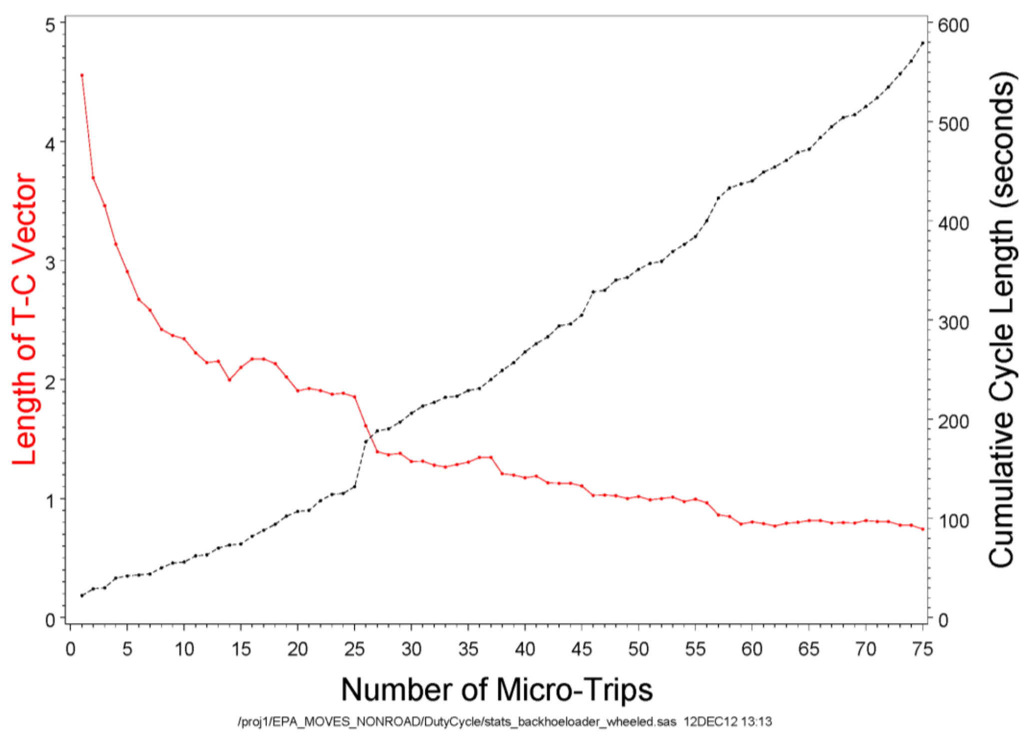
	A	B	C	D	E	F	G	H	I	J
1	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
2	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
3	0.001	0.003	0.003	0.000	0.000	0.000	0.000	0.000	0.000	0.000
4	0.001	0.003	0.000	0.000	0.002	0.002	0.000	0.000	0.000	0.000
5	0.001	0.000	0.010	0.044	0.073	0.037	0.050	0.019	0.062	0.087
6	0.001	0.000	0.017	0.001	0.008	0.005	0.014	0.001	0.021	0.020
7	0.001	0.000	0.017	0.001	0.000	0.000	0.002	0.002	0.005	0.004
8	0.001	0.000	0.049	0.015	0.011	0.010	0.015	0.001	0.022	0.020
9	0.000	0.014	0.006	0.000	0.001	0.002	0.000	0.011	0.000	0.000
10	0.000	0.014	0.006	0.000	0.001	0.002	0.000	0.011	0.000	0.000

j) Sum the squares of the differences.

0.754

An example of the discovery process as microtrips are built up is shown in Figure A3-2. The figure shows a plot of the length of the **T**-**C** vector as microtrips were added to a cycle for wheeled backhoe loaders. The figure shows that as microtrips were added, the length of the vector first dropped to a local minimum after 12 microtrips were added. The next minimum vector length was encountered after 14 microtrips were added. Subsequent lower minima were achieved when 20, 23, 28, 30, … microtrips were added. Major decreases in the length of the **T**-**C** vector occurred after 14, 28, and 59 microtrips were added. This alternate drop/plateau/increase/drop behavior is commonly seen when using this method of cycle building. At this point in cycle development, the duration of the cycle becomes important. Depending on the acceptability of the duration of the cycle being built up, a cycle with any of the specific 14, 28, or 59 microtrips could be used. These three candidate cycles would have durations of 73, 124, and 437 seconds, respectively.

Figure A3-2. Square of the Length of T-C as MicroTrips are Added: Example for Wheeled Backhoe Loaders

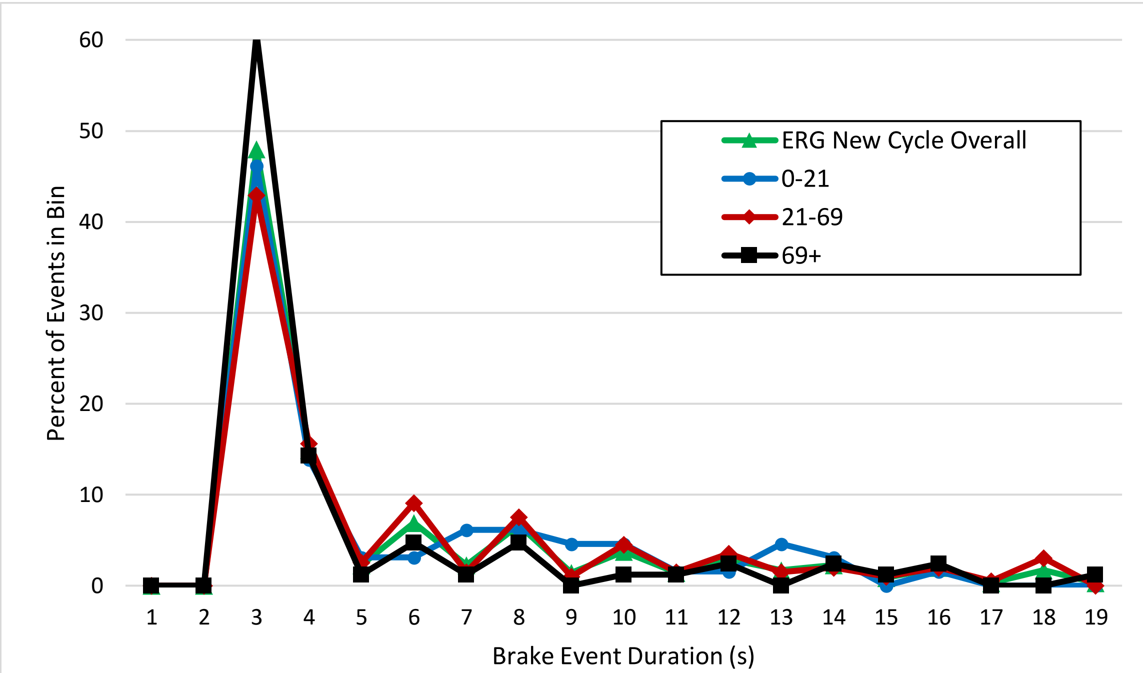


Appendix E

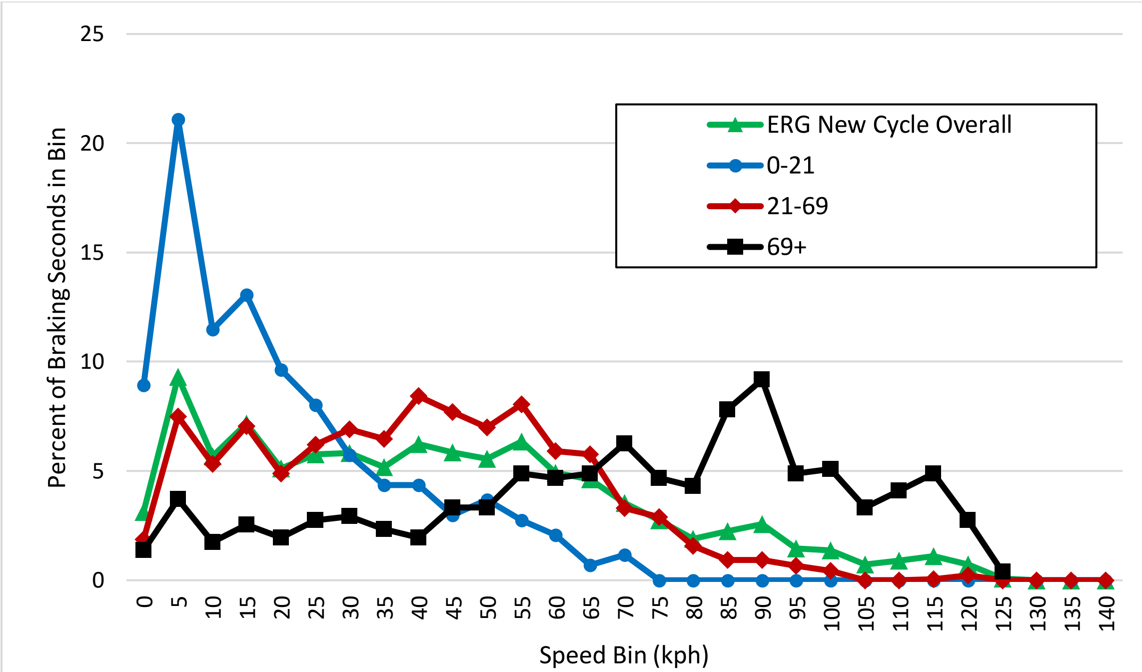
Distributions of Parameters of Interest for the Vector Method’s (New CBDC) 3 Speed Segments

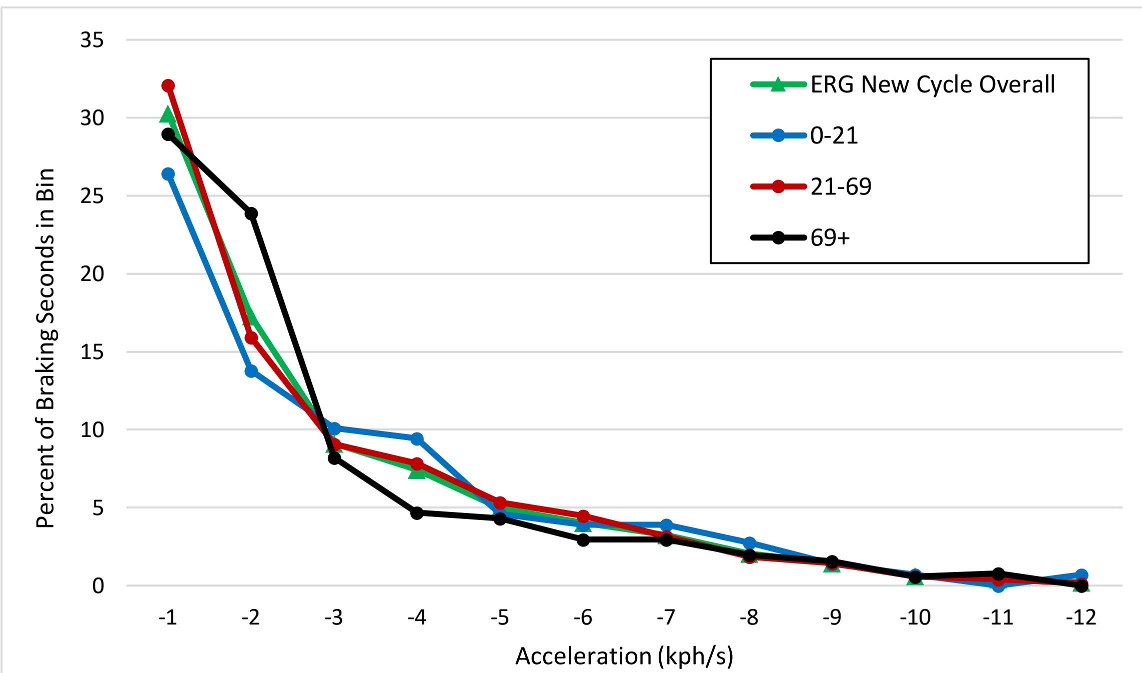
Further distributions of the four parameters of interest, broken down by the three speed segments created by the vector method, are presented in this Appendix. The distribution for the overall vector cycle (previously shown in the distributions in the *Results* section) is presented for comparison. Note again that the distributions are for the periods during brake events only; acceleration and cooling/cruise periods are not included.

The distributions of brake event durations are presented in the following figure. As described previously, the ERG cycle intentionally does not have any brake events shorter than 3 seconds.

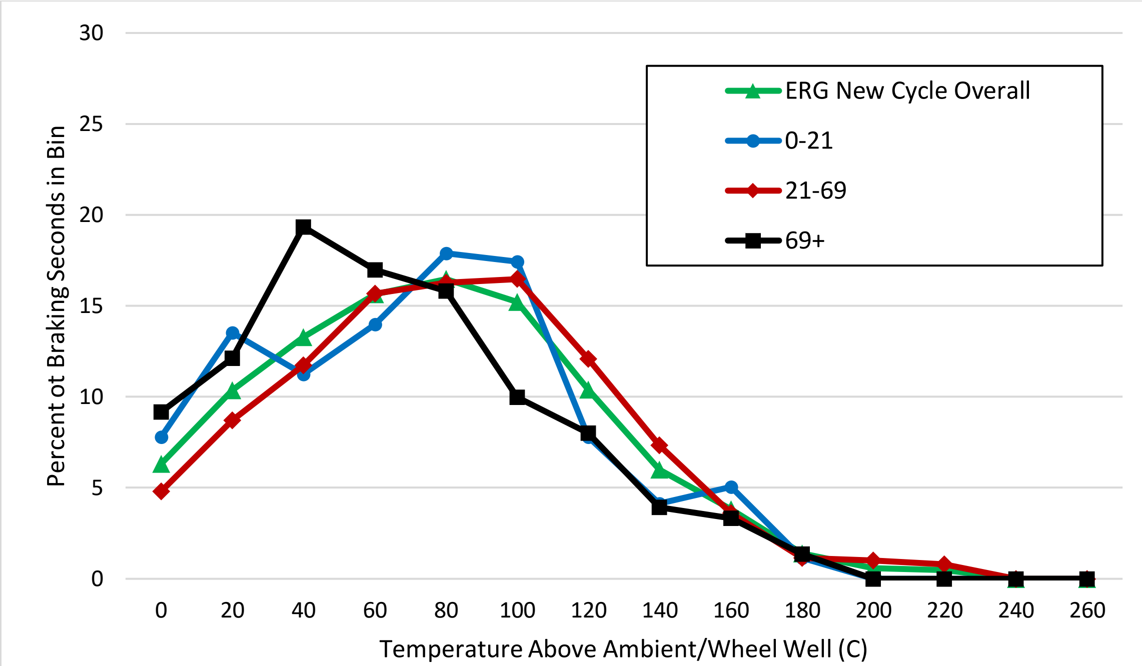


The distributions of speeds encountered during braking events are presented in the following figure. It can clearly be seen that the slow speed segment has more time in the slow speed bins, and the high speed segment has more time in the high speed bins. The distribution of (negative) acceleration rates during braking is presented in the subsequent figure.





The distributions of modeled brake temperatures for each speed segment are presented in the following figure. It can be generally seen that the temperatures for the high speed segment tend to be somewhat lower (where there would be more cooling taking place) than the temperatures for the other two speed segments.


ERG New Cycle Overall
0-21
21-69
69+
Percent ot Braking Seconds in Bin
Temperature Above Ambient/Wheel Well (C)
0
5
10
15
20
25
30
0
20
40
60
80
100
120
140
160
180
200
220
240
260

Appendix F

Test Matrix and Test Dates

The complete test matrix is presented in this Appendix. Note under Teflon Filter analysis, all planned tests in which CARB was planned for analysis of the Teflon filters are indicated. Tests in which this column is left blank may be either analyzed by EPA or not subject to any further speciation analyses depending on EPA preferences. There are four tests in the matrix that were conducted over the WLTP-Brake cycle. These are labeled in the Replicates column as WLTP-Brake A or B; there were 2 replicates of each planned WLTP-Brake test. The BMC LeafMark is listed if known and listed as Indeterminate (Ind.) if it was not known until ordered components are delivered. The 17RD016 proposal included provision for 90 days of available dynamometer time. LINK estimated that the cooling air flow setting experimentation for all assemblies would require a minimum of 5 days of dynamometer time. So, in the matrix the first 5 test days were reserved for cooling air flow rate setting, 85 tests were prescribed (including the 2 tunnel blanks), adding to a total of 90. This matrix presents the planned tests and order at the onset of the program. During the program, minor changes to the order were made for the following reasons:

- Aftermarket components were not received in time for their planned tests after ordering
- Tests were voided due to equipment malfunctions or other issues that invalidated a test that had been initiated. In this case, this test was postponed if new components needed to be ordered and the matrix was continued
- One test that was scheduled to run over the WLTP-Brake cycle was inadvertently run over the CBDC; this test was kept and the planned WLTP-Brake test was swapped into the place of an equivalent upcoming CBDC test.

As mentioned in the report, there were various reasons why the originally planned testing order was not maintained throughout the program. Delays in sourcing brake components, voided and repeat tests and other minor reasons resulted in the actual test order being changed; however LINK kept to the original plan where possible The table in this appendix also includes the actual date of all valid tests.

Test Matrix Including Planned Test Order and Actual Test Dates

Test Day #	Test Vehicle	Front/Rear	Pad Material	BMC Leaf Mark	Wheel load	# Replicates	Ref. repeat #	Teflon Filter Analysis	Test Date
1-5	Air/Sample flow setting days for each assembly								
6	F-150	Front	OES-NAO	N	ETW	N/A	1	ARB	9/30/2019
7	F-150	Front	OES-NAO	N	HLW	A		EPA	10/13/2019
8	Camry	Front	OES-NAO	A	ETW	A		ARB	10/2/2019
9	Civic	Rear (Drum)	OES-NAO	N	ETW	A		EPA	10/3/2019
10	Camry	Rear	OES-NAO	A	ETW	A		ARB	10/5/2019
11	Sienna	Front	OES-NAO	A	ETW	A		EPA	10/6/2019
12	Prius	Front	OES-NAO	A	ETW	A		EPA	10/7/2019
13	Sienna	Rear	OES-NAO	B	ETW	A		EPA	10/7/2019
14	Rogue	Front	OES-NAO	A	ETW	A			10/12/2019
15	Camry	Front	OES-NAO	A	ETW	B		EPA	10/9/2019
16	F-150	Rear	OES-NAO	A	ETW	A		EPA	10/10/2019
Testing PAUSE									10/14-20/2019
17	Tunnel Blank 1					A			10/29/2019
18	Rogue	Rear	After-NAO	Ind.	HLW	A			10/28/2019
19	Rogue	Rear	OES-NAO	A	ETW	A		ARB	10/21/2019
20	Rogue	Rear	After-NAO	Ind.	ETW	A		ARB	10/29/2019
21	Camry	Rear	OES-NAO	A	ETW	B			10/22/2019
22	Camry	Rear	After-NAO	Ind.	ETW	B			10/24/2019
23	Camry	Rear	After-LM	A?	ETW	B			10/23/2019
24	F-150	Front	OES-NAO	N	ETW	N/A	2		10/25/2019
25	Civic	Rear (Drum)	OES-NAO	N	ETW	B		ARB	10/30/2019
26	Civic	Rear (Drum)	After-NAO	Ind.	ETW	B			12/13/2019
27	Prius	Rear	OES-NAO	A	ETW	A		EPA	10/27/2019
28	Prius	Rear	After-NAO	Ind.	ETW	A		ARB	10/27/2019
29	F-150	Rear	After-NAO	N	ETW	A		ARB	11/1/2019

Test Day #	Test Vehicle	Front/Rear	Pad Material	BMC Leaf Mark	Wheel load	# Replicates	Ref. repeat #	Teflon Filter Analysis	Test Date
30	F-150	Rear	After-LM	A	ETW	A		ARB	11/2/2019
31	F-150	Rear	OES-NAO	A	HLW	A		ARB	11/2/2019
32	F-150	Rear	After-LM	A	HLW	A		ARB	11/3/2019
33	Sienna	Front	OES-NAO	A	ETW	B		ARB	11/4/2019
34	Sienna	Front	OES-NAO	A	HLW	B			11/19/2019
35	Sienna	Front	After-NAO	N	ETW	B			12/26/2019
36	Sienna	Front	After-NAO	N	HLW	B			1/26/2020
37	Rogue	Front	OES-NAO	A	HLW	A		ARB	1/26/2020
38	Rogue	Front	After-NAO	Ind.	ETW	A		ARB	11/20/2019
39	F-150	Front	OES-NAO	N	HLW	B			11/9/2019
40	F-150	Front	After-LM	A	ETW	B			11/10/2019
41	F-150	Front	After-LM	A	HLW	B			11/21/2019
42	F-150	Front	After-NAO	N	ETW	B			11/10/2019
43	F-150	Front	OES-NAO	N	ETW	N/A	3	ARB	11/11/2019
44	F-150	Front	OES	N	ETW	WLTP A			11/12/2019
45	Camry	Front	After-NAO	Ind.	ETW	A		ARB	11/22/2019
46	Camry	Front	After-LM	A?	ETW	A		ARB	11/23/2019
47	Camry	Front	OES	A	ETW	WLTP A			1/18/2020
48	Prius	Front	OES-NAO	A	ETW	B		ARB	11/26/2019
49	Prius	Front	After-NAO	Ind.	ETW	A		ARB	11/26/2019
50	Prius	Front	After-NAO	Ind.	ETW	B			1/27/2020
51	Civic	Front	OES-NAO	A	ETW	A		ARB	12/6/2019
52	Civic	Front	After-NAO	Ind.	ETW	A		ARB	12/7/2019
53	Sienna	Rear	OES-NAO	B	ETW	B		ARB	12/8/2019
54	Sienna	Rear	OES-NAO	B	HLW	B			12/9/2019
55	Sienna	Rear	After-NAO	N	ETW	B			12/10/2019
56	Sienna	Rear	After-NAO	N	HLW	B			12/11/2019
57	Civic	Rear (Drum)	After-NAO	Ind.	ETW	A		ARB	12/12/2019

Test Day #	Test Vehicle	Front/Rear	Pad Material	BMC Leaf Mark	Wheel load	# Replicates	Ref. repeat #	Teflon Filter Analysis	Test Date
58	Camry	Rear	After-NAO	Ind.	ETW	A		ARB	12/19/2019
59	Camry	Rear	After-LM	A?	ETW	A		ARB	12/20/2019
60	Rogue	Front	OES-NAO	A	ETW	B		ARB	12/16/2019
61	Rogue	Front	OES-NAO	A	HLW	B			12/17/2019
62	Rogue	Front	After-NAO	Ind.	ETW	B			12/18/2019
63	F-150	Front	After-LM	A	ETW	A		ARB	12/20/2019
64	F-150	Front	After-LM	A	HLW	A		ARB	12/21/2019
65	F-150	Front	After-NAO	N	ETW	A		ARB	12/22/2019
66	Tunnel Blank 2					B			1/5/2020
67	F-150	Front	OES-NAO	N	ETW	N/A	4		1/16/2020
68	Sienna	Front	OES-NAO	A	HLW	A		ARB	12/23/2019
69	Sienna	Front	After-NAO	N	ETW	A		ARB	12/24/2019
70	Sienna	Front	After-NAO	N	HLW	A		ARB	12/25/2019
71	Camry	Front	After-NAO	Ind.	ETW	B			12/27/2019
72	Camry	Front	After-LM	A?	ETW	B			12/28/2019
73	Camry	Front	OES	A	ETW	WLTP B			1/21/2020
74	F-150	Rear	OES-NAO	A	ETW	B		ARB	12/29/2019
75	F-150	Rear	After-NAO	N	ETW	B			12/30/2019
76	F-150	Rear	After-LM	A	ETW	B			12/31/2019
77	F-150	Rear	OES-NAO	A	HLW	B			1/19/2020
78	F-150	Rear	After-LM	A	HLW	B			1/25/2020
79	Prius	Rear	OES-NAO	A	ETW	B		ARB	1/12/2020
80	Prius	Rear	After-NAO	Ind.	ETW	B			1/28/2020
81	Rogue	Rear	OES-NAO	A	ETW	B			1/4/2020
82	Rogue	Rear	After-NAO	Ind.	ETW	B			1/4/2020
83	Rogue	Rear	After-NAO	Ind.	HLW	B			1/5/2020
84	Civic	Front	OES-NAO	A	ETW	B			1/10/2020
85	Civic	Front	After-NAO	Ind.	ETW	B			1/11/2020

Test Day #	Test Vehicle	Front/Rear	Pad Material	BMC Leaf Mark	Wheel load	# Replicates	Ref. repeat #	Teflon Filter Analysis	Test Date
86	Sienna	Rear	OES-NAO	B	HLW	A		ARB	1/13/2020
87	Sienna	Rear	After-NAO	N	ETW	A		ARB	1/29/2020
88	Sienna	Rear	After-NAO	N	HLW	A		ARB	1/14/2020
89	F-150	Front	OES	N	ETW	WLTP B			1/17/2020
90	F-150	Front	OES-NAO	N	ETW	N/A	5	ARB	1/17/2020

Appendix G

CVS Flow Setting Results

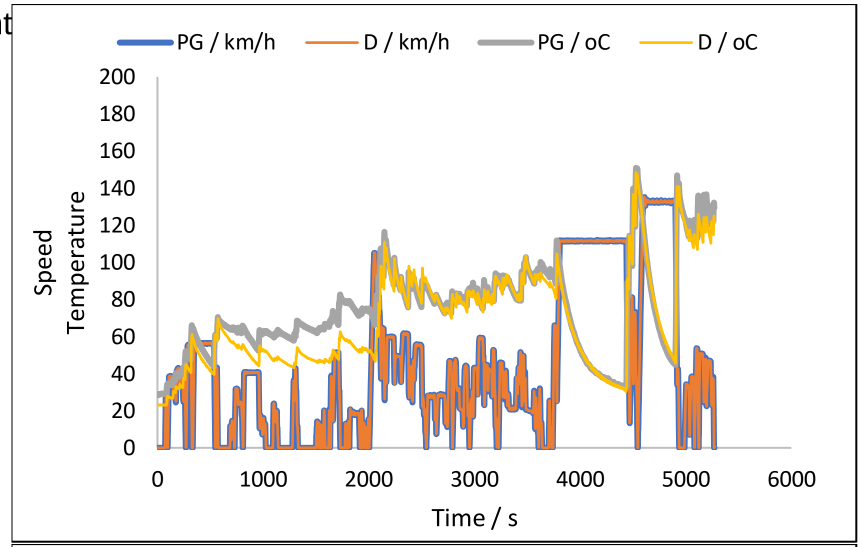
This appendix presents the temperatures measured to validate the CVS air flowrate setting. Brake rotor temperatures as measured on the proving ground track over the WLTP-Brake Trip 10 are presented as the target for matching. The measured brake rotor temperatures from the same speed trace run on the dynamometer are presented for comparison. Results are shown for the final selected flowrate for each brake assembly (that shown in **Error! Reference source not found.** of the main report). Note that the selection method biased the temperature match to be best around the peak temperature for each assembly; ERG's literature search indicated that high temperatures represent the driving mode in which brake emissions could be expected to be highest[4], and matching at elevated temperatures also allowed a similar temperature range to be covered during each test as the track given that tests begin at room temperature. Temperature traces are presented for the front and rear assemblies of each vehicle.

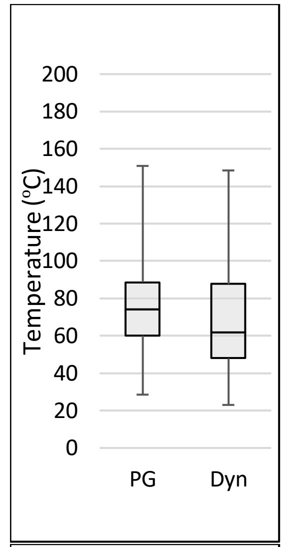
Temperature and speed traces for each assembly are presented; traces labeled as "PG" represent the proving ground track testing, and those labeled "D" represent the dynamometer test. At the right of each trace are corresponding box plots indicating various statistics on the proving ground and dynamometer temperature traces. The central line of each box is the median temperature, and the top and bottom of each box are the 75th and 25th percentile values, respectively. The ends of each bar display the maximum and minimum values for each trace.

[4] B.D. Garg, S.H. Cadle, P.A. Mulawa, P.J. Groblicki, C. Laroo, G.A. Parr, "Brake Wear Particulate Matter Emissions," Environmental Science and Technology, 2000, Volume 34, Number 21, pages 4463-4469, DOI: 10.1021/es001108h.

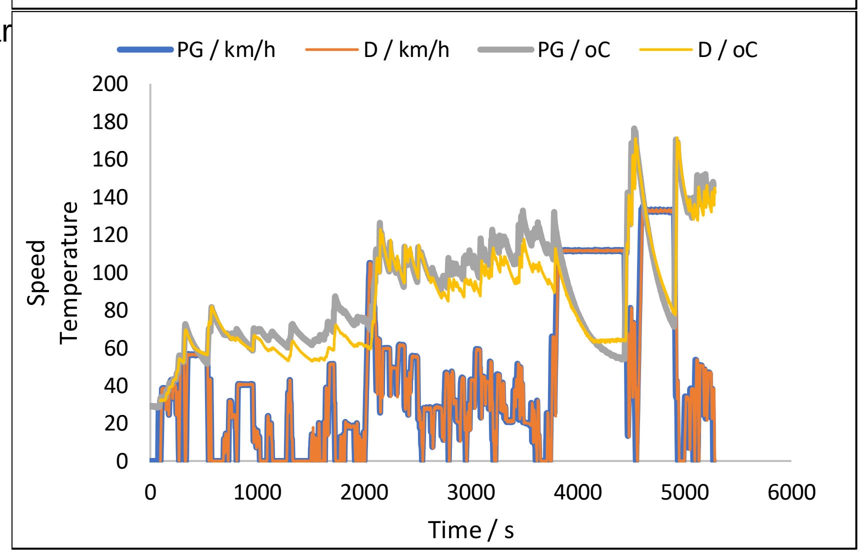
Camry Temperature Traces for CVS Flow Rate Setting

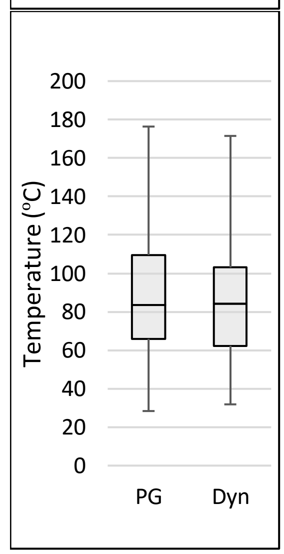
Front





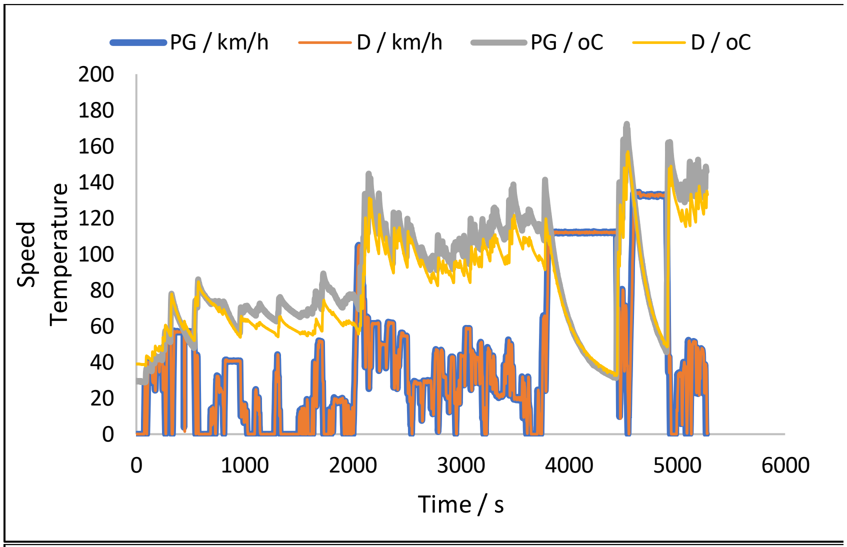
Rear

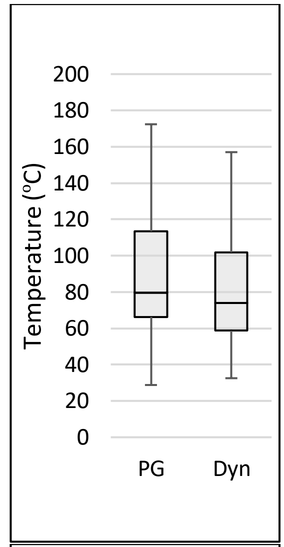




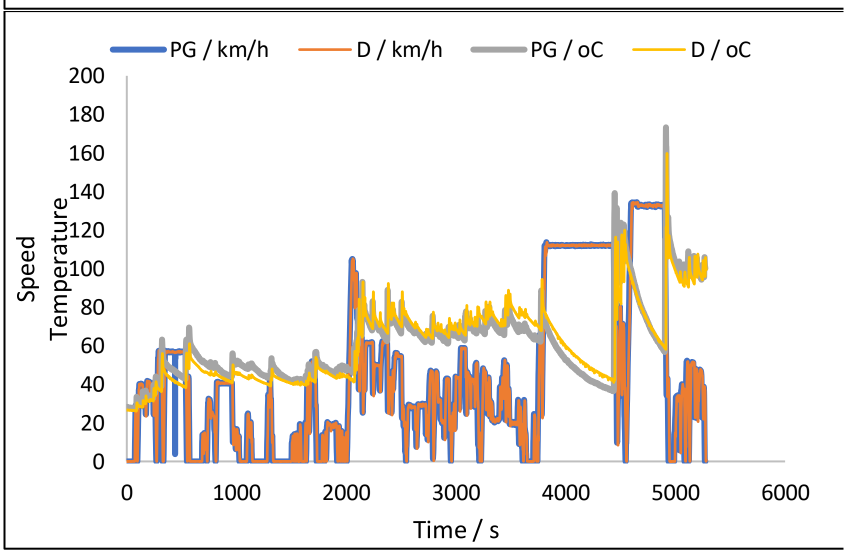
Civic Temperature Traces for CVS Flow Rate Setting

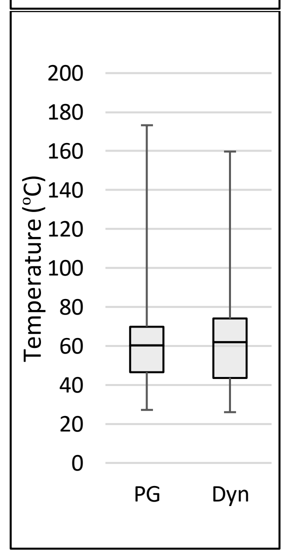
Front





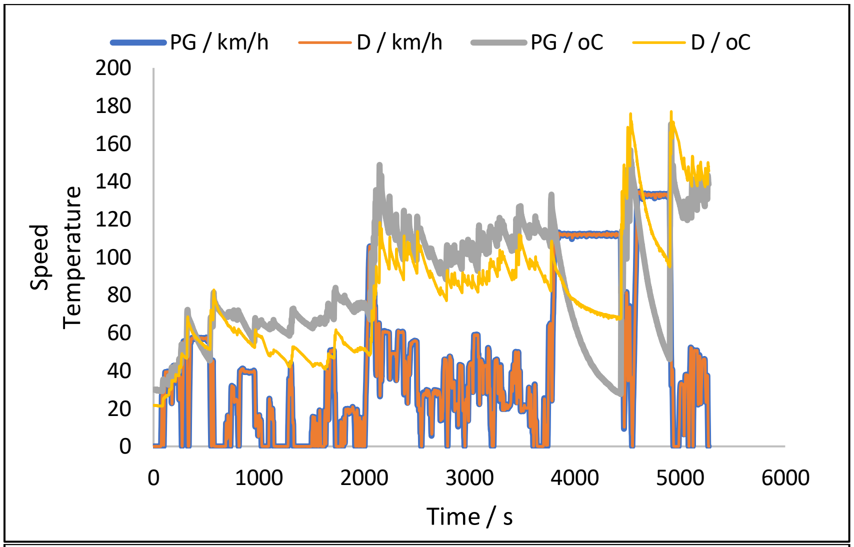
Rear

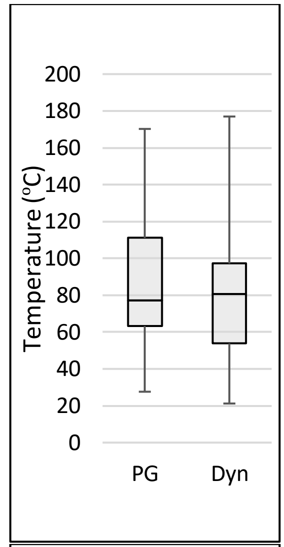




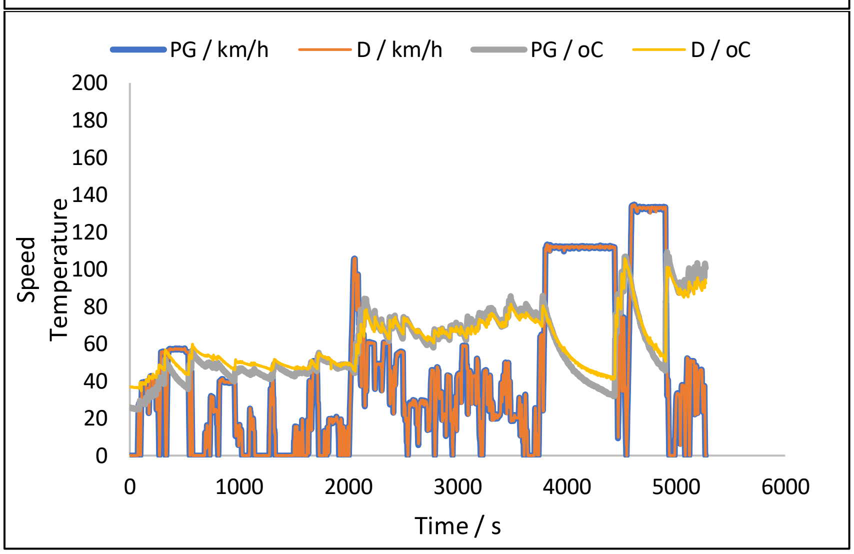
F-150 Temperature Traces for CVS Flow Rate Setting

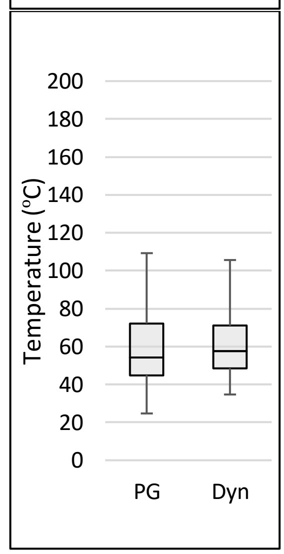
Front





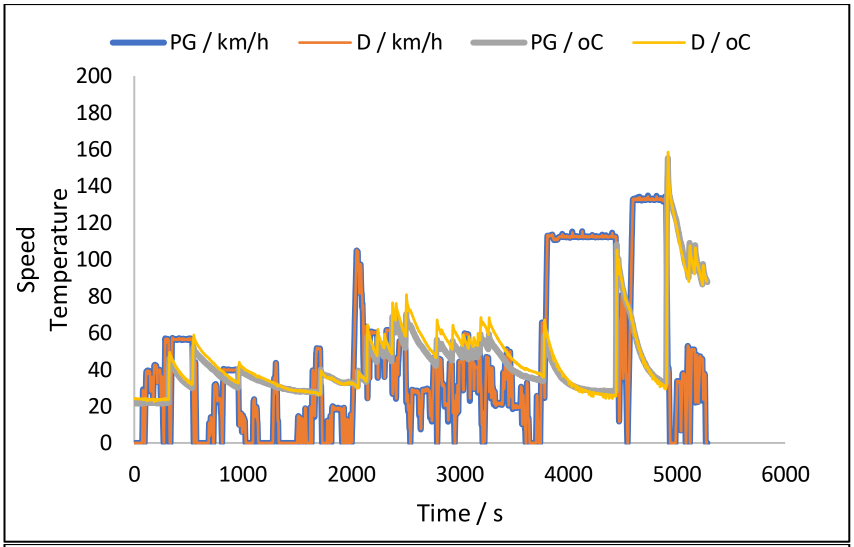
Rear

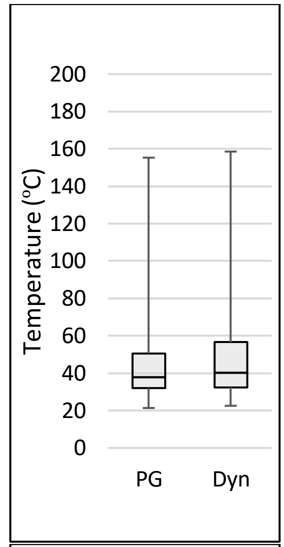




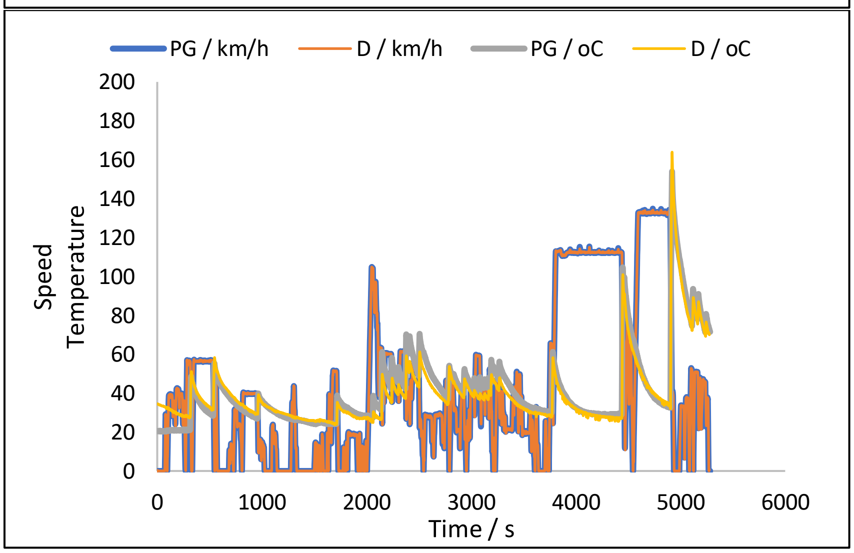
Prius Temperature Traces for CVS Flow Rate Setting

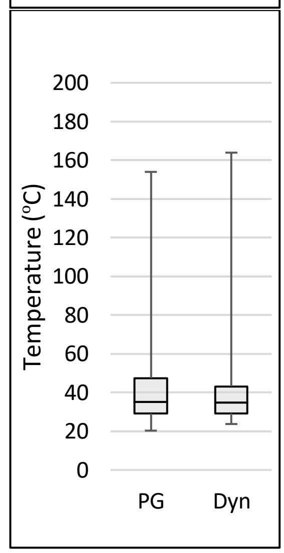
Front





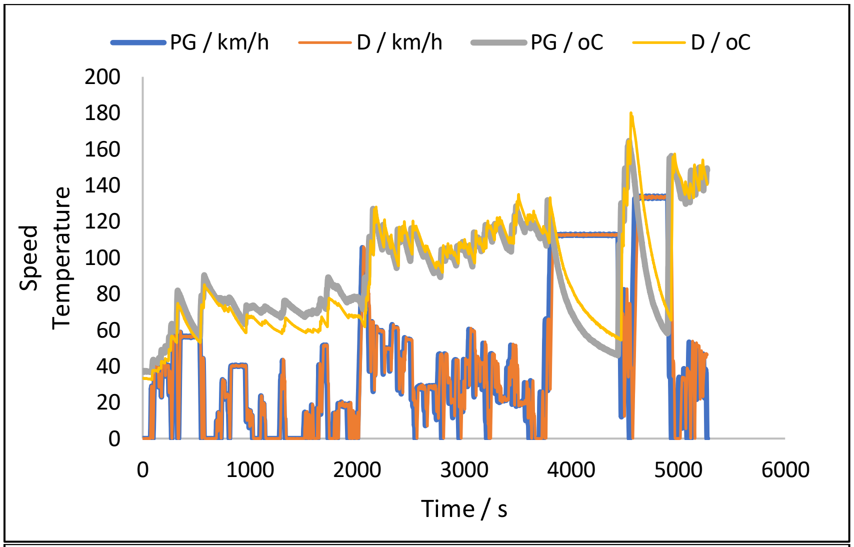
Rear

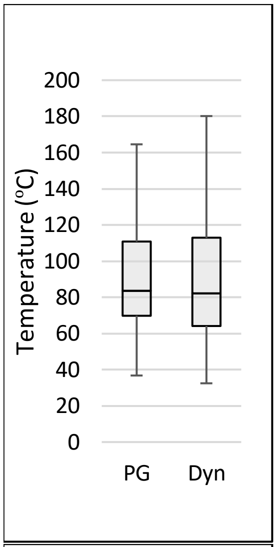




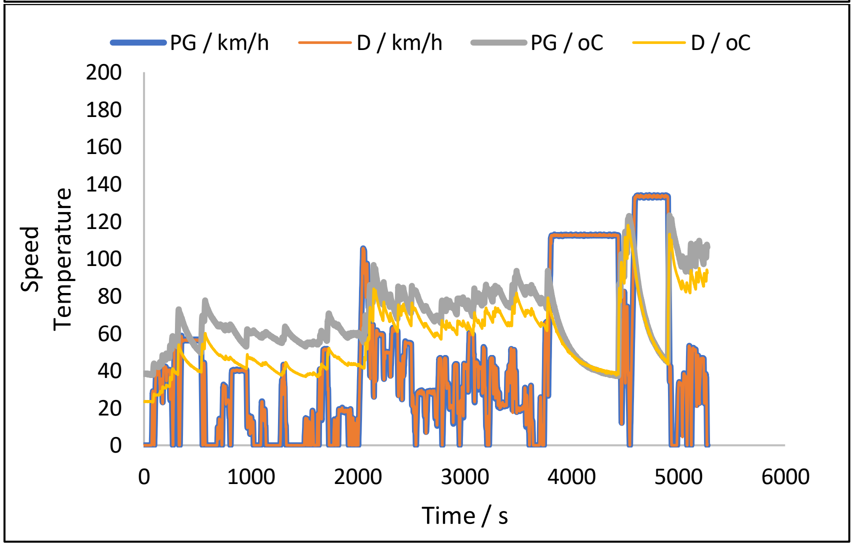
Rogue Temperature Traces for CVS Flow Rate Setting

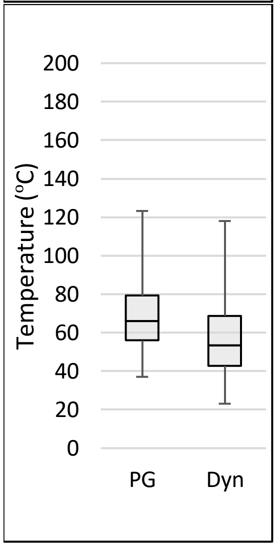
Front





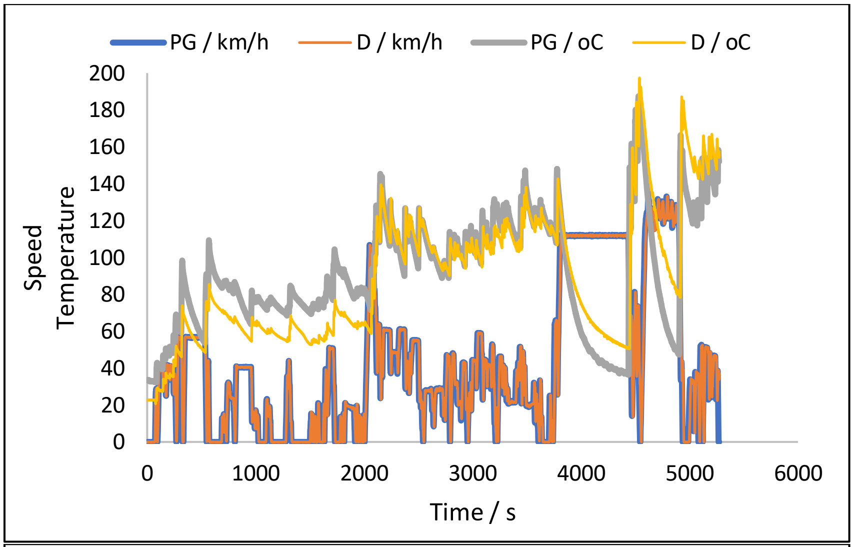
Rear

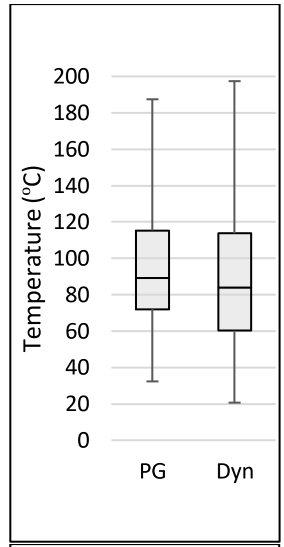




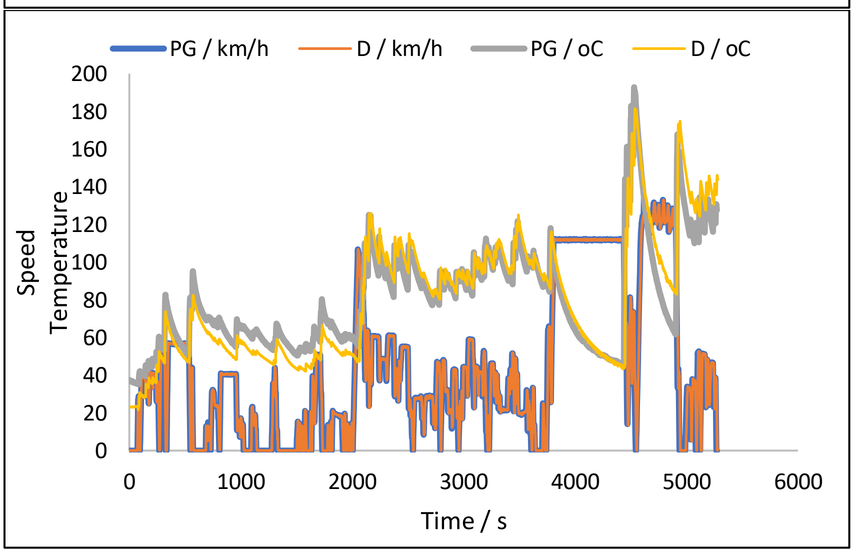
Sienna Temperature Traces for CVS Flow Rate Setting

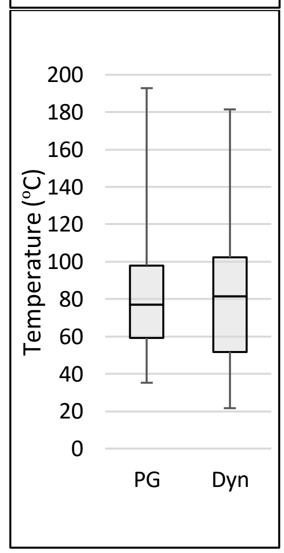
Front





Rear





Appendix H

Tabulated Test Result Summary

Test results and measured operational parameters are presented in this appendix. “Test day” refers to the test day number given in the Task 2 test matrix, not necessarily the actual order in which tests were conducted. “Avg. Torque” refers to the torque applied to the dynamometer drive shaft by the hydraulic brakes during the test, and “Avg. Press” refers to the average brake-circuit hydraulic pressure during the test. “PN” refers to particle number count as measured by the condensation particle counter (CPC), which measures between the range of 23 nm to 2.1 µm. The three size cutpoints are given for the gravimetric mass measurement of the 100S4, and the PM10, as measured by the 47mm Teflon PMS, is given in the rightmost column.

Test Day #	Test Vehicle	Front / Rear	Pad Material	Wheel Load	Avg. Torque N·m	Avg. Press kPa	Avg. Rotor Temp ºC	Peak Rotor Temp ºC	PN 23 nm-2.1 µm CPC #/cc	Avg. CPC PN 23 nm - 2.1 µm #	Total Pad and Rotor Wear (g)[a]	100S4 Sg3 (PM2.5-10) Emission mg/mi	100S4 Sg4 (PM1-2.5) Emission mg/mi	100S4 Aft Filter (PM < 1) Emission mg/mi	Brake PM_{10} per PMS (mg/mi)
6	**F-150**	**Front**	**OES-NAO**	**ETW**	259	594	103.2	234.9	29.0	1.072E+11	3.7	0.7512	0.4933	0.3315	1.3432
7	F-150	Front	OES-NAO	HLW	316	674	119.2	251.2	33.9	1.252E+11	3.3	1.1711	0.6792	0.5587	1.5741
8	Camry	Front	OES-NAO	ETW	146	570	110.4	246.3	83.6	4.532E+10	6.2	1.2773	0.4987	0.1436	1.6942
9	Civic	Rear	OES-NAO	ETW	34	832	125.2	231.7	91.9	4.977E+10	1.5	0.1156	0.1472	0.1120	0.3493
10	Camry	Rear	OES-NAO	ETW	51	497	114.3	181.9	118.7	6.430E+10	2.7	0.6329	0.4848	0.1752	1.0943
11	Sienna	Front	OES-NAO	ETW	183	493	117.6	243.4	255.3	1.341E+11	9.9	2.4060	1.0530	0.3115	3.2632
12	Prius	Front	OES-NAO	ETW	58	302	73.1	186.0	41.1	8.311E+10	2.9	0.5794	0.4008	0.1483	1.3922
13	Sienna	Rear	OES-NAO	ETW	88	792	134.1	237.5	149.6	8.110E+10	3.7	0.9403	0.5772	0.0831	1.3773
14	Rogue	Front	OES-NAO	ETW	152	646	118.1	236.5	577.1	3.130E+11	6.2	1.6787	1.0086	0.3467	2.7309
15	Camry	Front	OES-NAO	ETW	133	526	110.4	245.3	138.0	7.522E+10	6.2	1.5849	0.5995	0.1228	2.0689
16	F-150	Rear	OES-NAO	ETW	95	430	73.5	119.1	184.4	1.000E+11	6.5	0.7476	0.5345	0.1941	1.3135
17	**Tunnel Blank 1**								0.2						0.0291
18	Rogue	Rear	After-NAO	HLW	58	599	76.8	162.7	80.4	4.405E+10	3.3	0.4307	0.3169	0.1102	0.7834
19	Rogue	Rear	OES-NAO	ETW	56	661	70.2	142.3	151.8	8.223E+10	2.6	0.7191	0.4743	0.1219	1.2108
20	Rogue	Rear	After-NAO	ETW	50	564	75.3	154.2	132.0	7.227E+10	3.3	0.4856	0.3565	0.1291	0.9789
21	Camry	Rear	OES-NAO	ETW	51	552	116.2	186.2	107.4	5.819E+10	2.8	0.6533	0.4907	0.1183	1.1458
22	Camry	Rear	After-NAO	ETW	45	413	127.7	206.6	128.1	7.014E+10	4	0.7179	0.5572	0.1571	1.2446
23	Camry	Rear	After-LM	ETW	51	552	111.1	185.6	186.6	1.022E+11	3.1	1.7370	0.6974	0.2095	2.2983
24	**F-150**	**Front**	**OES-NAO**	**ETW**	249	549	103.5	237.1	16.4	6.123E+10	5.8	0.6689	0.3496	0.3622	1.0859
25	Civic	Rear	OES-NAO	ETW	32	788	96.9	153.9	58.1	3.179E+10	5.2	0.0731	0.0804	0.0713	0.3296

Test Day #	Test Vehicle	Front / Rear	Pad Material	Wheel Load	Avg. Torque N·m	Avg. Press kPa	Avg. Rotor Temp °C	Peak Rotor Temp °C	PN 23 nm-2.1 µm CPC #/cc	Avg. CPC PN 23 nm - 2.1 µm #	Total Pad and Rotor Wear (g)[a]	100S4 Sg3 (PM2.5-10) Emission mg/mi	100S4 Sg4 (PM1-2.5) Emission mg/mi	100S4 Aft Filter (PM < 1) Emission mg/mi	Brake PM_{10} per PMS (mg/mi)
26	Civic	Rear	After-NAO	ETW	33	739	92.8	175.6	104.2	5.707E+10	3.2	0.7868	0.3270	0.1264	1.3536
27	Prius	Rear	OES-NAO	ETW	20	246	62.3	156.1	17.7	3.630E+10	1.1	0.2391	0.2019	0.0944	0.5442
28	Prius	Rear	After-NAO	ETW	21	274	63.7	160.9	25.6	5.229E+10	1.3	0.1784	0.1582	0.1449	0.3637
29	F-150	Rear	After-NAO	ETW	84	329	70.9	117.8	269.0	1.475E+11	3.4	1.4611	0.9500	0.2989	2.5550
30	F-150	Rear	After-LM	ETW	88	579	67.4	117.6	144.5	7.918E+10	3	1.4611	0.9500	0.2989	2.6306
31	F-150	Rear	OES-NAO	HLW	105	453	86.5	146.2	164.0	9.176E+10	5.7	0.8994	0.4939	0.1011	1.1918
32	F-150	Rear	After-LM	HLW	111	631	72.8	125.4	139.0	7.619E+10	3.2	1.2050	0.5050	0.0903	1.5381
33	Sienna	Front	OES-NAO	ETW	172	504	113.8	248.3	240.0	1.316E+11	7.3	1.6431	0.8754	0.1959	2.6295
34	Sienna	Front	OES-NAO	HLW	197	523	121.8	268.3	266.6	1.462E+11	7.1	2.3284	1.1091	0.2546	3.3531
35	Sienna	Front	After-NAO	ETW	170	520	120.9	250.8	663.3	3.641E+11	6.4	1.8041	1.2351	0.3557	3.4047
36	Sienna	Front	After-NAO	HLW	189	530	129.3	260.6	424.5	2.331E+11	1.7	3.0364	1.7150	0.5246	5.3524
37	Rogue	Front	OES-NAO	HLW	159	622	139.4	264.6	438.4	2.403E+11	0.5	3.3931	1.6843	0.5282	5.5660
38	Rogue	Front	After-NAO	ETW	146	530	122.4	255.4	312.3	1.712E+11	6.8	2.1538	1.1387	0.3025	2.5123
39	F-150	Front	OES-NAO	HLW	257	559	104.1	253.6	36.8	1.372E+11	4.5	0.7348	0.4031	0.3193	1.0776
40	F-150	Front	After-LM	ETW	226	557	91.6	213.1	62.2	2.322E+11	16.6	3.9896	1.9996	0.4236	5.5549
41	F-150	Front	After-LM	HLW	276	635	99.9	244.0	88.4	3.301E+11	18.3	7.5629	2.6190	0.2579	9.6947
42	F-150	Front	After-NAO	ETW	226	651	98.5	214.4	31.8	1.188E+11	5.3	0.7222	0.4763	0.0614	1.3003
43	**F-150**	**Front**	**OES-NAO**	**ETW**	241	456	106.4	218.9	20.4	7.612E+10	3.8	0.8705	0.5081	0.0860	1.2329
44	F-150	Front	OES-NAO	ETW	228	487	96.9	211.4	16.3	6.070E+10	3.9	0.6250	0.3792	0.0061	1.0556
45	Camry	Front	After-NAO	ETW	135	505	103.1	234.5	188.9	1.035E+11	4.5	1.7274	0.7565	0.2221	2.5411
46	Camry	Front	After-LM	ETW	144	523	107.0	243.2	383.0	2.084E+11	7.9	3.2827	0.8459	0.2772	4.1068
47	Camry	Front	OES-NAO	ETW	149	613	76.9	165.6	17.0	1.664E+10	6.4	0.3780	0.1267	0.0383	0.5591
48	Prius	Front	OES-NAO	ETW	56	300	64.0	173.2	20.1	4.113E+10	2.6	0.4632	0.2710	0.0539	0.8795
49	Prius	Front	After-NAO	ETW	56	304	67.8	190.3	66.8	1.368E+11	2.6	0.4466	0.3859	0.1820	0.9305
50	Prius	Front	After-NAO	ETW	54	257	77.0	183.5	334.9	6.860E+11	0.8	0.6171	0.5630	0.3135	1.7420
51	Civic	Front	OES-NAO	ETW	106	542	104.7	235.4	263.3	1.446E+11	5.4	1.0051	0.4334	0.0668	1.4537

Test Day #	Test Vehicle	Front / Rear	Pad Material	Wheel Load	Avg. Torque N·m	Avg. Press kPa	Avg. Rotor Temp °C	Peak Rotor Temp °C	PN 23 nm-2.1 µm CPC #/cc	Avg. CPC PN 23 nm - 2.1 µm #	Total Pad and Rotor Wear (g)[a]	100S4 Sg3 (PM2.5-10) Emission mg/mi	100S4 Sg4 (PM1-2.5) Emission mg/mi	100S4 Aft Filter (PM < 1) Emission mg/mi	Brake PM_{10} per PMS (mg/mi)
52	Civic	Front	After-NAO	ETW	99	531	107.1	239.9	364.0	1.999E+11	3	1.1477	0.6194	0.1725	1.7565
53	Sienna	Rear	OES-NAO	ETW	74	657	130.5	239.1	144.3	7.919E+10	3.4	0.6065	0.6103	0.0849	1.6315
54	Sienna	Rear	OES-NAO	HLW	84	765	149.1	274.5	184.3	1.012E+11	3.6	1.5234	0.8009	0.1372	2.3943
55	Sienna	Rear	After-NAO	ETW	79	715	138.9	250.7	79.2	4.349E+10	4.7	0.6038	0.3699	0.0488	1.0051
56	Sienna	Rear	After-NAO	HLW	92	822	156.2	274.0	71.6	3.930E+10	4.2	0.8197	0.4015	0.0542	0.8939
57	Civic	Rear	After-NAO	ETW	36	755	113.9	218.0	65.9	3.609E+10	2.6	0.6065	0.2886	0.0135	0.9999
58	Camry	Rear	After-NAO	ETW	46	387	145.6	214.9	143.5	7.865E+10	3.5	0.6286	0.5292	0.1481	1.2192
59	Camry	Rear	After-LM	ETW	48	511	122.1	192.1	342.0	1.874E+11	2.1	2.2237	1.0269	0.2528	3.2695
60	Rogue	Front	OES-NAO	ETW	127	548	122.6	231.7	412.5	2.269E+11	9.5	3.0699	1.5073	0.5092	4.9036
61	Rogue	Front	OES-NAO	HLW	148	608	136.7	253.5	314.4	1.723E+11	13.8	3.7672	1.5381	0.5390	5.7154
62	Rogue	Front	After-NAO	ETW	133	472	131.5	247.3	268.9	1.474E+11	5.9	1.7445	1.0346	0.2664	2.7544
63	F-150	Front	After-LM	ETW	261	637	88.4	210.8	105.1	3.925E+11	14.5	6.5346	2.7330	0.7429	8.3941
64	F-150	Front	After-LM	HLW	291	626	110.2	264.1	115.7	4.277E+11	18.9	10.8371	3.8848	0.7797	13.199
65	F-150	Front	After-NAO	ETW	242	610	102.1	227.3	53.6	2.004E+11	2.9	1.8582	0.9182	0.3070	2.6385
66	**Tunnel Blank 2**								0.4						0.0962
67	**F-150**	**Front**	**OES-NAO**	**ETW**	261	630	69.1	159.3	14.5	8.013E+10	4.2	0.5668	0.2393	0.2140	1.3995
68	Sienna	Front	OES-NAO	HLW	198	577	124.5	259.6	275.8	1.514E+11	10.1	2.6269	1.2261	0.2320	3.9597
69	Sienna	Front	After-NAO	ETW	156	482	115.1	248.2	803.5	4.448E+11	3.8	2.6351	1.3625	0.5110	4.0958
70	Sienna	Front	After-NAO	HLW	184	573	126.7	274.6	484.0	2.656E+11	8.4	4.0160	1.7572	0.6438	6.2149
71	Camry	Front	After-NAO	ETW	141	514	104.8	254.2	189.0	1.037E+11	7.2	1.9406	0.8306	0.2826	3.1981
72	Camry	Front	After-LM	ETW	143	505	101.1	223.5	146.0	8.011E+10	4.8	2.6269	0.6129	0.1381	3.1771
73	Camry	Front	OES-NAO	ETW	143	591	79.3	178.4	24.7	2.273E+10	5.2	0.5023	0.1566	0.0475	0.6961
74	F-150	Rear	OES-NAO	ETW	92	414	73.9	144.6	203.4	1.117E+11	5.9	0.9210	0.5715	0.1228	1.6133
75	F-150	Rear	After-NAO	ETW	79	323	72.2	119.7	224.8	1.234E+11	6	2.0653	1.0736	0.3268	3.4768
76	F-150	Rear	After-LM	ETW	79	431	68.6	120.2	306.3	1.681E+11	4.4	1.4341	0.7892	0.2266	2.4870
77	F-150	Rear	OES-NAO	HLW	99	349	91.4	150.5	229.9	1.263E+11	4.8	2.0013	0.9708	0.2411	3.2885

Test Day #	Test Vehicle	Front / Rear	Pad Material	Wheel Load	Avg. Torque N·m	Avg. Press kPa	Avg. Rotor Temp °C	Peak Rotor Temp °C	PN 23 nm-2.1 µm CPC #/cc	Avg. CPC PN 23 nm - 2.1 µm #	Total Pad and Rotor Wear (g)[a]	100S4 Sg3 (PM2.5-10) Emission mg/mi	100S4 Sg4 (PM1-2.5) Emission mg/mi	100S4 Aft Filter (PM < 1) Emission mg/mi	Brake PM_{10} per PMS (mg/mi)
78	F-150	Rear	After-LM	HLW	97	422	83.6	131.7	383.3	2.106E+11	2.4	2.2069	1.0535	0.3422	3.6268
79	Prius	Rear	OES-NAO	ETW	20	261	60.0	151.3	20.3	4.170E+10	0.9	0.2083	0.1915	0.0472	0.4232
80	Prius	Rear	After-NAO	ETW	21	242	66.6	168.4	20.0	4.092E+10	0.7	0.1649	0.1818	0.1551	0.3686
81	Rogue	Rear	OES-NAO	ETW	51	631	68.2	145.3	163.8	8.976E+10	2.8	0.7546	0.4059	0.1156	1.3110
82	Rogue	Rear	After-NAO	ETW	46	477	72.2	141.3	104.9	5.747E+10	2.3	0.5387	0.3816	0.0831	0.4514
83	Rogue	Rear	After-NAO	HLW	51	510	79.7	168.3	127.4	6.987E+10	3.6	0.6408	0.4449	0.0822	1.1996
84	Civic	Front	OES-NAO	ETW	112	560	107.4	233.0	157.5	8.669E+10	3.3	0.9255	0.4161	0.0930	1.1391
85	Civic	Front	After-NAO	ETW	103	532	105.9	245.6	409.3	2.254E+11	4.2	1.4231	0.7178	0.1923	2.2485
86	Sienna	Rear	OES-NAO	HLW	92	811	155.6	273.5	193.9	1.068E+11	4.2	1.5052	0.7826	0.1535	2.4259
87	Sienna	Rear	After-NAO	ETW	84	738	143.6	248.5	84.2	4.623E+10	1.2	0.6640	0.3804	0.0650	1.1487
88	Sienna	Rear	After-NAO	HLW	96	836	167.3	298.7	93.1	5.105E+10	8.5	0.7798	0.4349	0.1129	1.1979
89	F-150	Front	OES-NAO	ETW	251	613	72.9	159.5	14.2	7.996E+10	3.5	0.5392	0.2495	0.2728	0.7214
90	**F-150**	**Front**	**OES-NAO**	**ETW**	259	557	100.2	221.6	14.9	5.553E+10	2.2	0.7425	0.3616	0.2149	1.1561

[a] – Note that the total pad and rotor wear is measured as the difference between the components' weight before installation into the dynamometer and the weight after removal from the dynaomomter. As such, it includes mass lost during both the burnish cycle and the test cycle.

Appendix I

Teflon Filter Masses and Weight Gains

The Appendix 3 table includes the Teflon filter weights for each test. The table presents the test information such as matrix test day, vehicle and friction material, then initial and final filter masses along with the filter weight gain. Measured masses were corrected by LINK according to 40 CFR 1065.690.

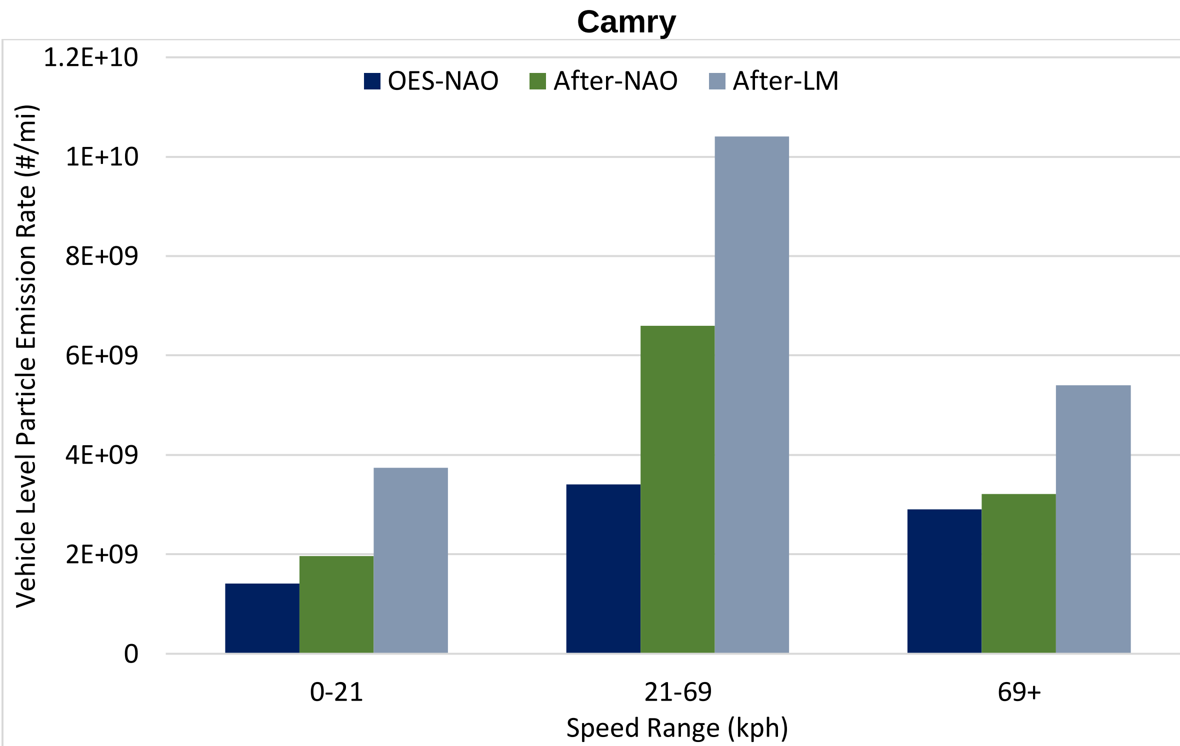
Test Day	Vehicle	Axle	FM	Initial Mass, mg	Final mass, mg	Gain, mg
6	2015 Ford F-150	Front	OES-NAO	397.300	397.420	0.120
7	2015 Ford F-150	Front	OES-NAO	398.036	398.186	0.150
8	2011 Toyota Camry	Front	OES-NAO	140.149	141.174	1.026
9	2013 Honda Civic	Rear	OES-NAO	393.764	393.971	0.206
10	2011 Toyota Camry	Rear	OES-NAO	137.179	137.878	0.699
11	2013 Toyota Sienna	Front	OES-NAO	393.233	395.281	2.048
12	2016 Toyota Prius	Front	OES-NAO	397.415	397.649	0.234
13	2013 Toyota Sienna	Rear	OES-NAO	392.106	392.965	0.859
14	2016 Nissan Rogue	Front	OES-NAO	136.503	138.207	1.704
15	2011 Toyota Camry	Front	OES-NAO	393.155	394.453	1.298
16	2015 Ford F-150	Rear	OES-NAO	390.599	391.409	0.810
17	Tunnel Blank 1	Holder 1	N/A	391.932	391.952	0.020
17	Tunnel Blank 1	Holder 2	N/A	392.407	392.424	0.017
18	2016 Nissan Rogue	Rear	AM1-NAO	393.805	394.271	0.466
19	2016 Nissan Rogue	Rear	OES-NAO	134.383	135.112	0.729
20	2016 Nissan Rogue	Rear	AM1-NAO	139.931	140.506	0.575
21	2011 Toyota Camry	Rear	OES-NAO	393.603	394.331	0.728
22	2011 Toyota Camry	Rear	AM1-NAO	392.703	393.475	0.772
23	2011 Toyota Camry	Rear	AM2-LM	393.149	394.566	1.417
24	2015 Ford F-150	Front	OES-NAO	389.913	390.016	0.103
25	2013 Honda Civic	Rear	OES-NAO	139.579	139.781	0.202
26	2013 Honda Civic	Rear	AM1-NAO	394.218	395.017	0.800
27	2016 Toyota Prius	Rear	OES-NAO	393.438	393.525	0.087
28	2016 Toyota Prius	Rear	AM1-NAO	140.551	140.608	0.057
29	2015 Ford F-150	Rear	AM1-NAO	138.622	140.263	1.641
30	2015 Ford F-150	Rear	AM2-LM	138.622	140.263	1.641
31	2015 Ford F-150	Rear	OES-NAO	136.124	136.880	0.757
32	2015 Ford F-150	Rear	AM2-LM	140.479	141.382	0.903
33	2013 Toyota Sienna	Front	OES-NAO	140.272	141.922	1.650
34	2013 Toyota Sienna	Front	OES-NAO	395.212	397.267	2.055
35	2013 Toyota Sienna	Front	AM1-NAO	385.961	388.048	2.087
36	2013 Toyota Sienna	Front	AM1-NAO	390.25509	393.5353	3.280213
37	2016 Nissan Rogue	Front	OES-NAO	137.16998	140.54	3.369999
38	2016 Nissan Rogue	Front	AM1-NAO	139.26646	140.8154	1.548947
39	2015 Ford F-150	Front	OES-NAO	398.76226	398.8559	0.093603
40	2015 Ford F-150	Front	AM2-LM	386.14182	386.6455	0.503642
41	2015 Ford F-150	Front	AM2-LM	397.83607	398.7045	0.868463
42	2015 Ford F-150	Front	AM1-NAO	394.15255	394.2648	0.112251
43	2015 Ford F-150	Front	OES-NAO	140.57629	140.6887	0.112449
44	2015 Ford F-150	Front	OES-NAO	391.06811	391.1615	0.093414
45	2011 Toyota Camry	Front	AM1-NAO	138.90356	140.5453	1.641713
46	2011 Toyota Camry	Front	AM2-LM	136.4385	138.9856	2.547125
47	2011 Toyota Camry	Front	OES-NAO	397.24408	397.7454	0.501278

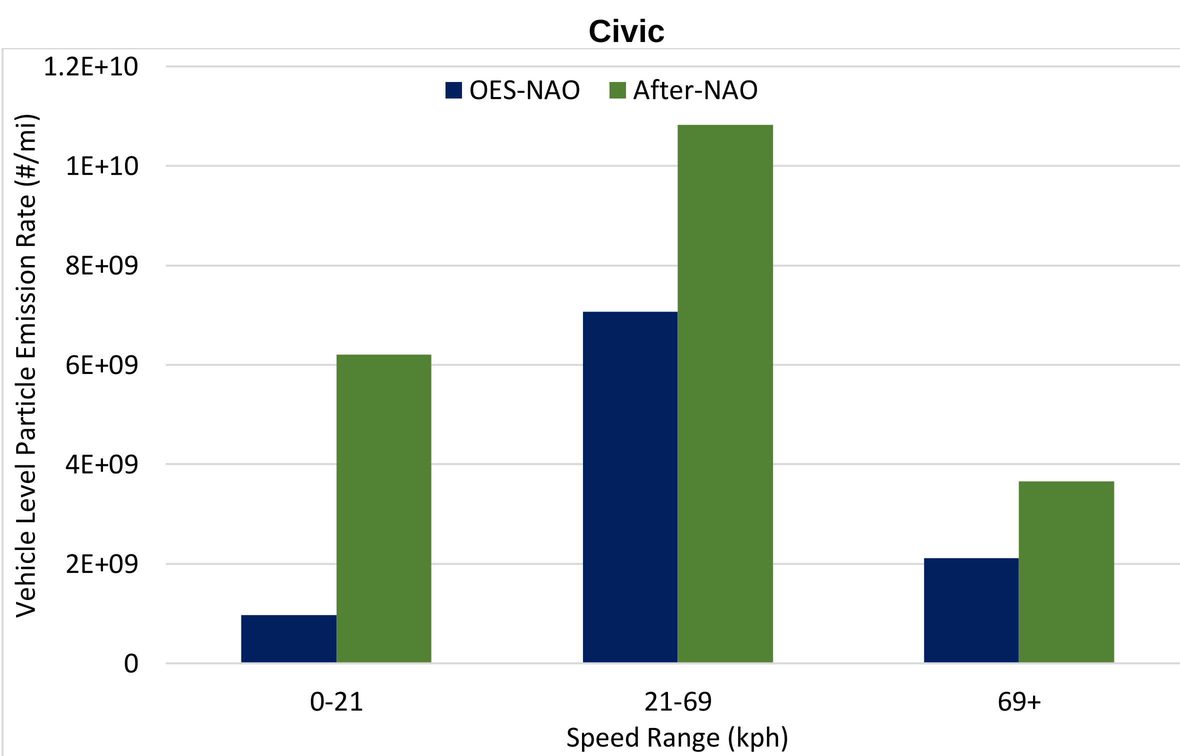
Test Day	Vehicle	Axle	FM	Initial Mass, mg	Final mass, mg	Gain, mg
48	2016 Toyota Prius	Front	OES-NAO	138.26622	138.4028	0.136554
49	2016 Toyota Prius	Front	AM1-NAO	139.52668	139.6785	0.151833
50	2016 Toyota Prius	Front	AM1-NAO	394.66786	394.9486	0.28079
51	2013 Honda Civic	Front	OES-NAO	138.64294	139.4748	0.831865
52	2013 Honda Civic	Front	AM1-NAO	138.72689	139.8098	1.082931
53	2013 Toyota Sienna	Rear	OES-NAO	139.70822	140.7141	1.005873
54	2013 Toyota Sienna	Rear	OES-NAO	397.6197	399.0959	1.476172
55	2013 Toyota Sienna	Rear	AM1-NAO	398.91986	399.5321	0.612234
56	2013 Toyota Sienna	Rear	AM1-NAO	393.55956	394.1107	0.551122
57	2013 Honda Civic	Rear	AM1-NAO	138.67537	139.2955	0.620158
58	2011 Toyota Camry	Rear	AM1-NAO	139.12557	139.8727	0.747152
59	2011 Toyota Camry	Rear	AM2-LM	140.84926	142.8771	2.027863
60	2016 Nissan Rogue	Front	OES-NAO	137.08673	140.11	3.023235
61	2016 Nissan Rogue	Front	OES-NAO	397.17737	400.5745	3.397165
62	2016 Nissan Rogue	Front	AM1-NAO	398.49649	400.1743	1.677852
63	2015 Ford F-150	Front	AM2-LM	137.55389	138.3013	0.747395
64	2015 Ford F-150	Front	AM2-LM	138.04894	139.2027	1.153721
65	2015 Ford F-150	Front	AM1-NAO	134.84165	135.078	0.236363
66	Tunnel Blank 2	Holder 1	N/A	137.5176	137.5451	0.027471
66	Tunnel Blank 2	Holder 2	N/A	399.15441	399.2404	0.085962
67	2015 Ford F-150	Rear	OES-NAO	395.69223	395.8723	0.180073
68	2013 Toyota Sienna	Front	OES-NAO	140.67803	143.1193	2.441265
69	2013 Toyota Sienna	Front	AM1-NAO	140.3819	142.9374	2.555467
70	2013 Toyota Sienna	Front	AM1-NAO	138.91632	142.7021	3.785822
71	2011 Toyota Camry	Front	AM1-NAO	391.42171	393.358	1.936318
72	2011 Toyota Camry	Front	AM2-LM	402.79979	404.6765	1.876715
73	2011 Toyota Camry	Front	OES-NAO	391.02543	391.6269	0.601518
74	2015 Ford F-150	Rear	OES-NAO	133.68903	134.6658	0.976815
75	2015 Ford F-150	Rear	AM1-NAO	401.15934	403.3029	2.143558
76	2015 Ford F-150	Rear	AM2-LM	400.94102	402.4835	1.542485
77	2015 Ford F-150	Rear	OES-NAO	394.76378	396.767	2.003203
78	2015 Ford F-150	Rear	AM2-LM	393.19452	395.4306	2.236035
79	2016 Toyota Prius	Rear	OES-NAO	137.48165	137.5553	0.073652
80	2016 Toyota Prius	REAR	AM1-NAO	138.53058	138.5905	0.059953
81	2016 Nissan Rogue	Rear	OES-NAO	395.58496	396.3594	0.774408
82	2016 Nissan Rogue	Rear	AM1-NAO	401.93869	402.2087	0.269963
83	2016 Nissan Rogue	Rear	AM1-NAO	394.0117	394.738	0.726318
84	2013 Honda Civic	Front	OES-NAO	393.52493	394.2314	0.70647
85	2013 Honda Civic	Front	AM1-NAO	393.7694	395.1889	1.41946
86	2013 Toyota Sienna	Rear	OES-NAO	138.36691	139.8178	1.450881
87	2013 Toyota Sienna	REAR	AM1-NAO	140.40394	141.1037	0.699745
88	2013 Toyota Sienna	Rear	AM1-NAO	136.94338	137.6687	0.725299
89	2015 Ford F-150	Front	OES-NAO	398.31912	398.4171	0.097973
90	2015 Ford F-150	Front	OES-NAO	139.29281	139.3964	0.103568

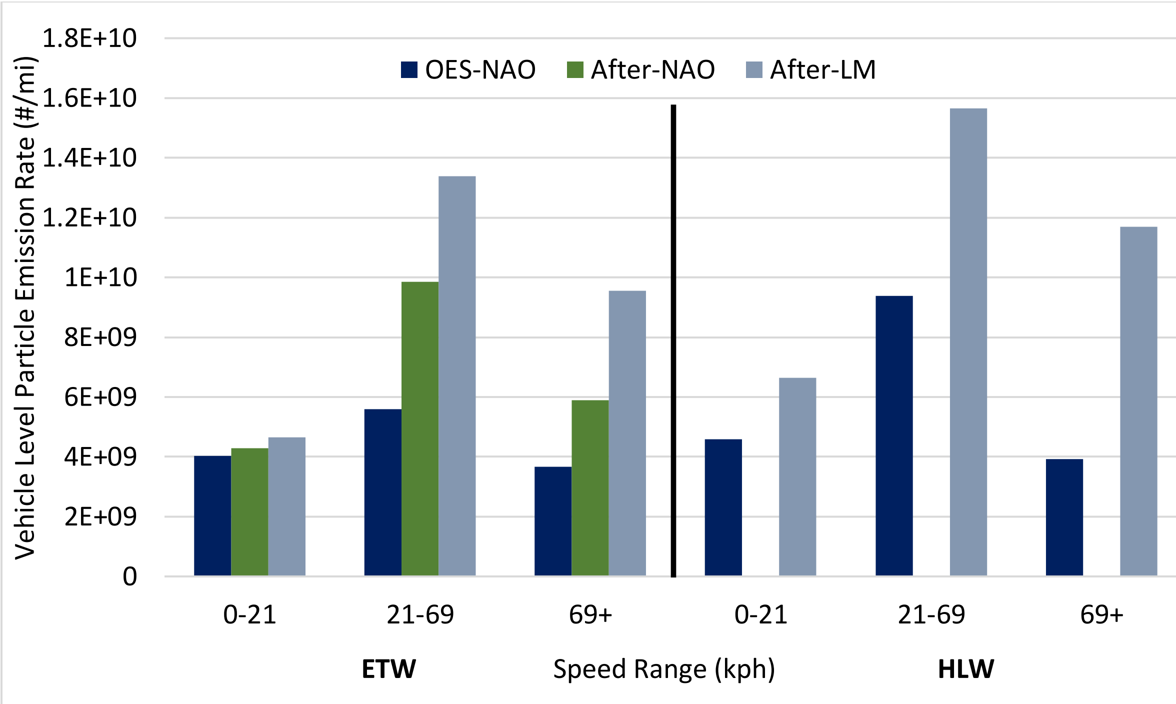
Appendix J

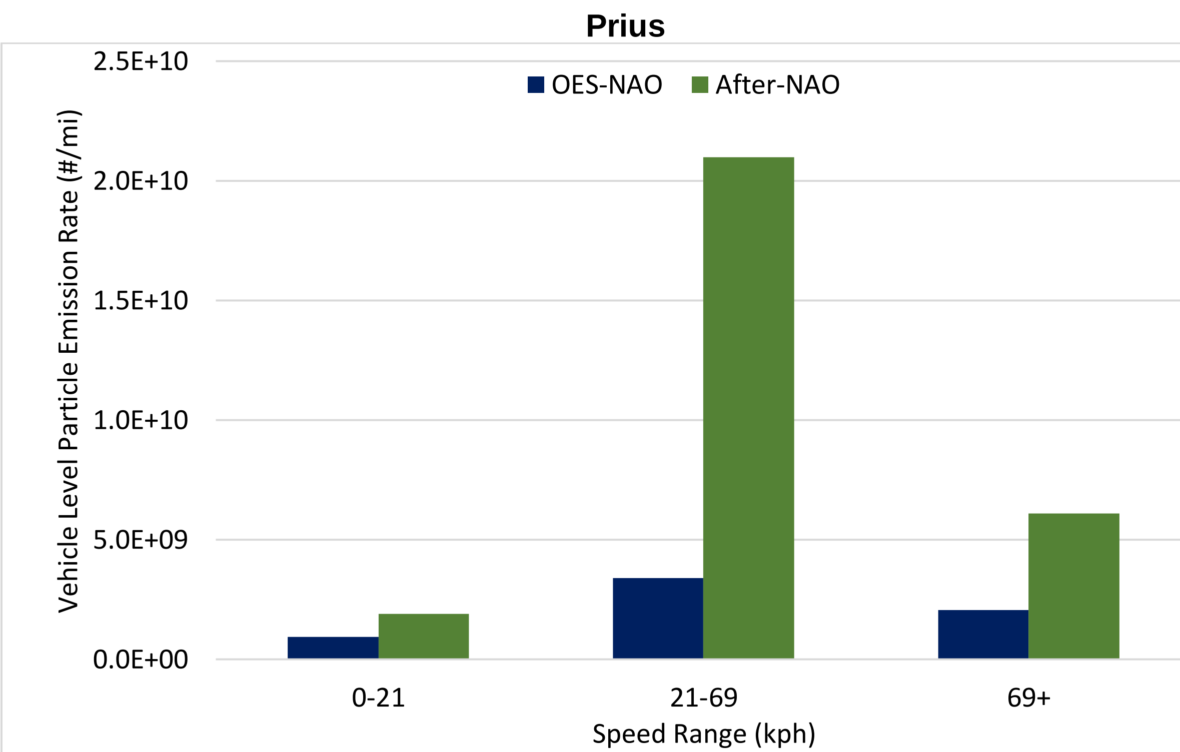
Vehicle-Level Particle Number Emission Rates by Speed Segment

This Appendix presents the CPC-measured vehicle-level particle number emission rates for each vehicle model. Bar charts are given for each model, categorized by pad material and grouped by average speed range. The values presented indicate the vehicle-level particle count emission rate on a per-distance basis.

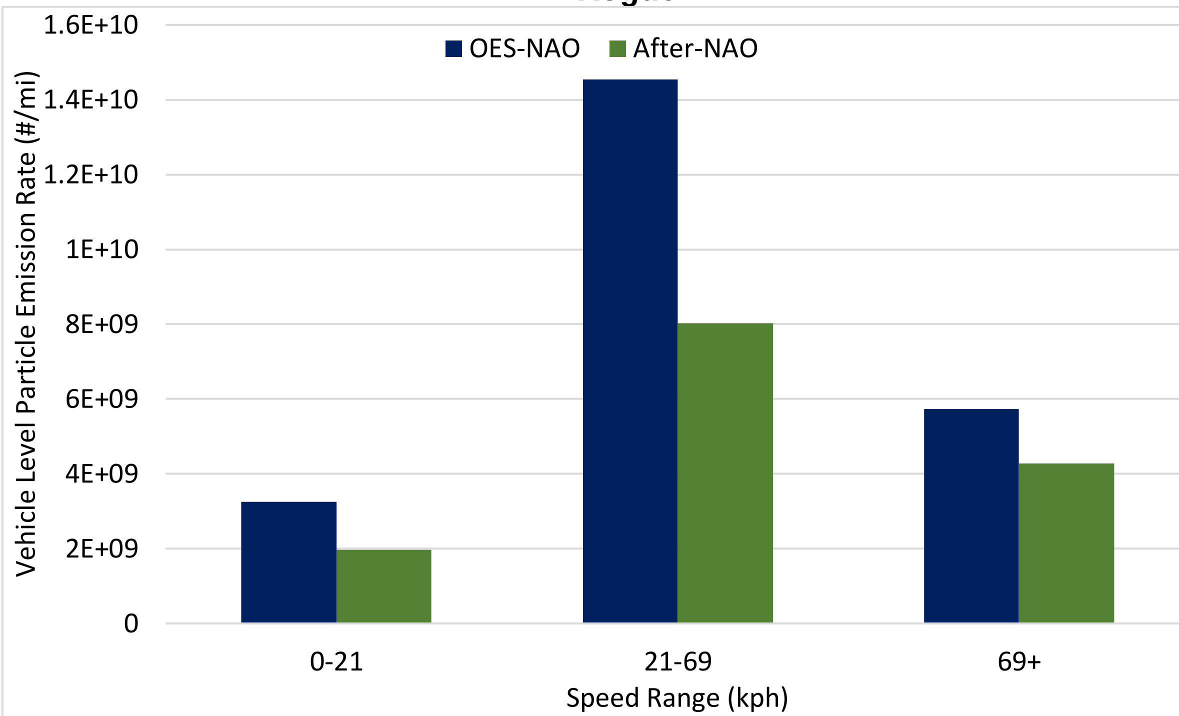




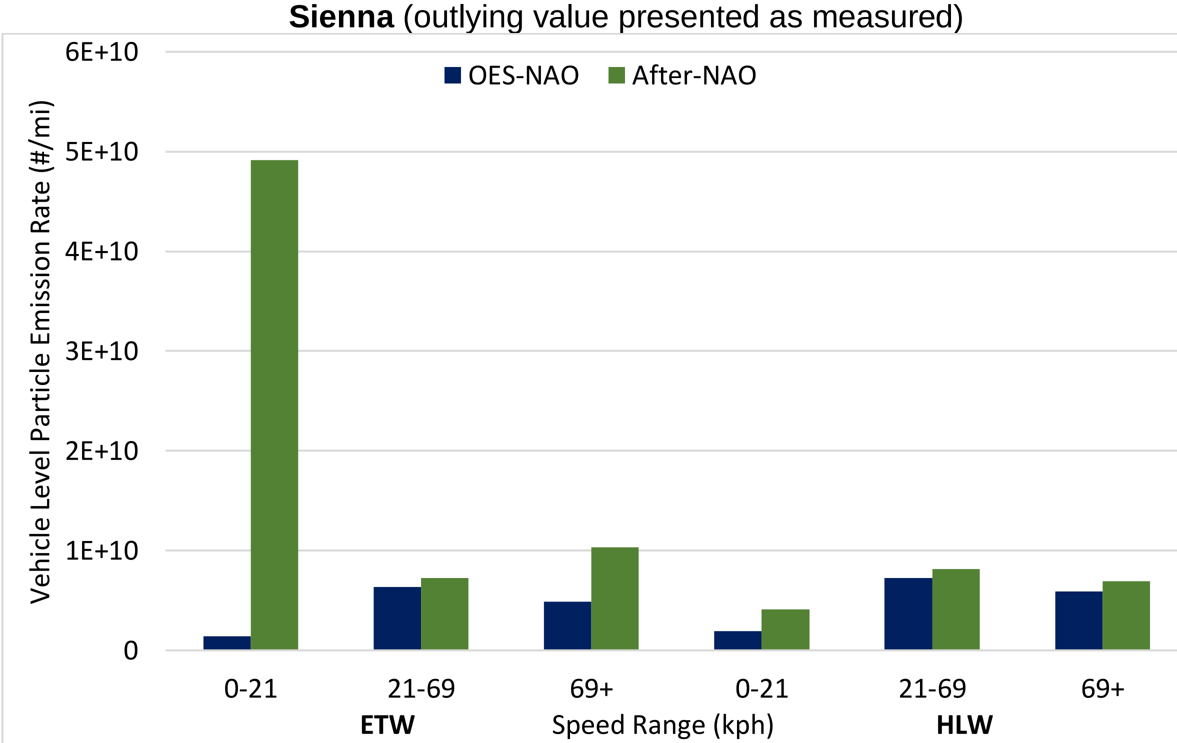

Vehicle Level Particle Emission Rate (#/mi)
OES-NAO
After-NAO
After-LM
1.8E+10
1.6E+10
1.4E+10
1.2E+10
1E+10
8E+09
6E+09
4E+09
2E+09
0
0-21
21-69
69+
0-21
21-69
69+
ETW
Speed Range (kph)
HLW


Prius
Vehicle Level Particle Emission Rate (#/mi)
OES-NAO
After-NAO
2.5E+10
2.0E+10
1.5E+10
1.0E+10
5.0E+09
0.0E+00
0-21
21-69
69+
Speed Range (kph)

Rogue



Sienna (outlying value presented as measured)



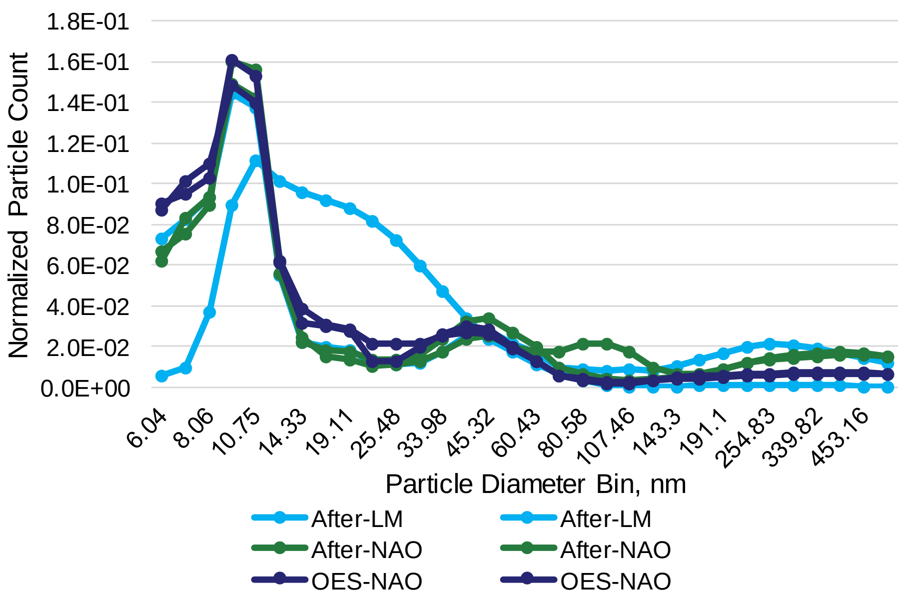
Appendix K

EEPS Particle Size Distributions

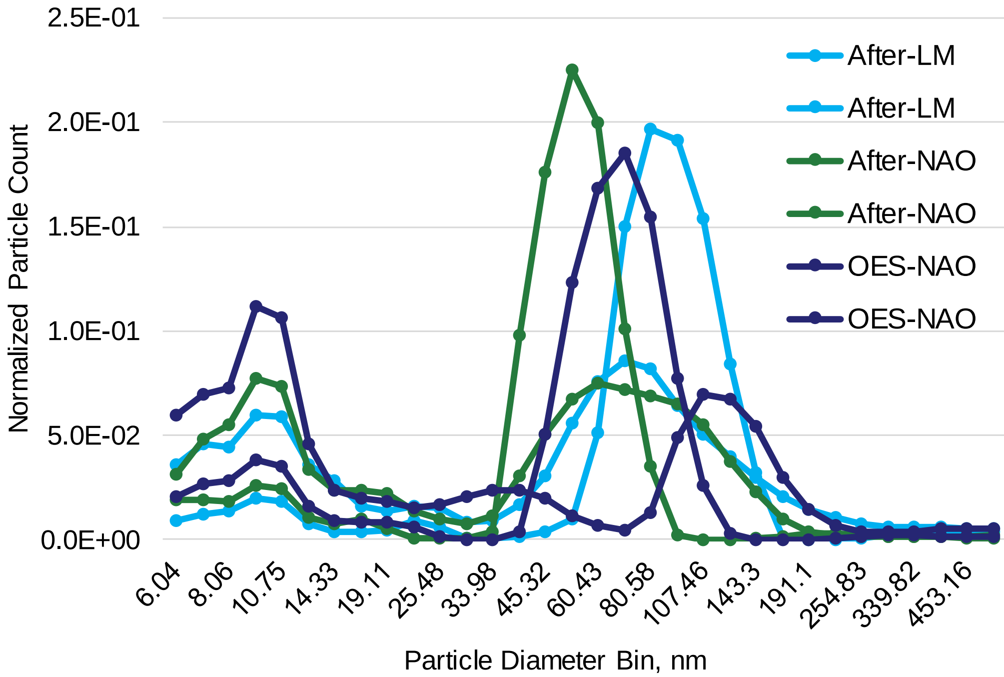
This appendix includes the particle size distributions measured by the EEPS ((5.6 – 560 nm)) during each test. Results are presented for the front and rear assemblies of each vehicle, and are color coded by the friction material and, where applicable, the test weight.

Camry Particle Size Distributions Measured by EEPS

Front

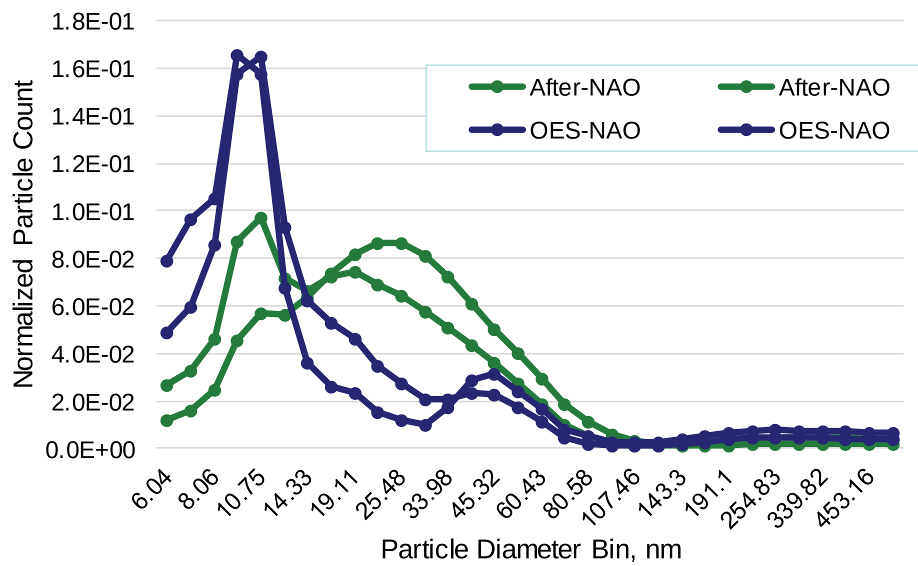


Rear

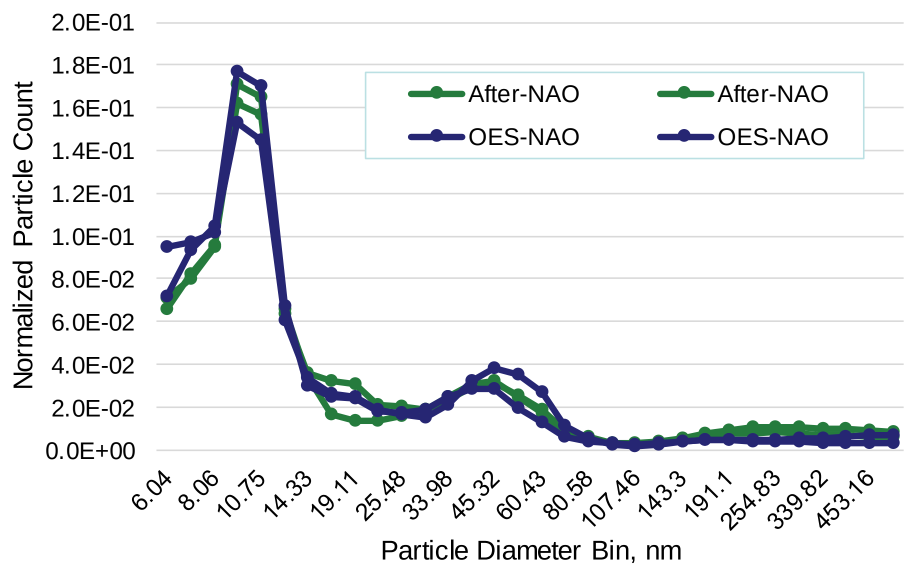


Civic Particle Size Distributions Measured by EEPS

Front

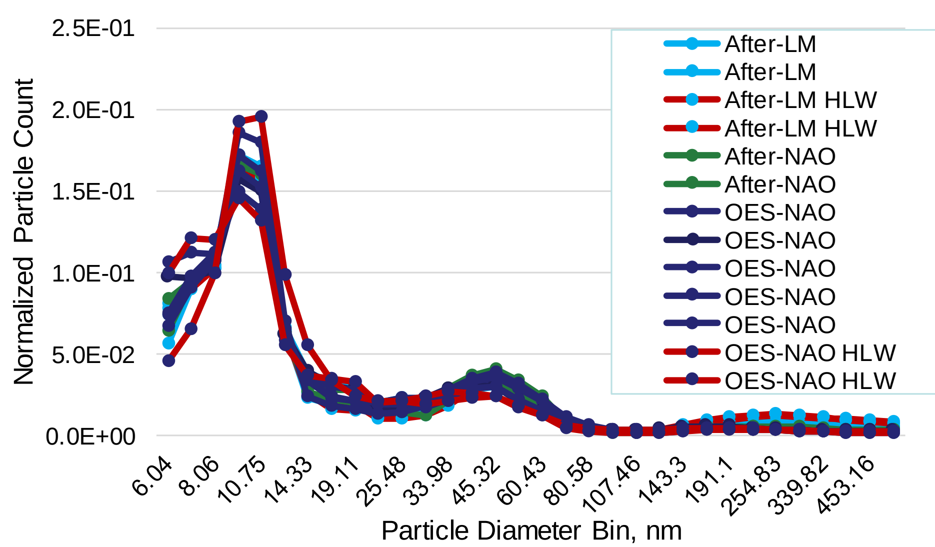


Rear

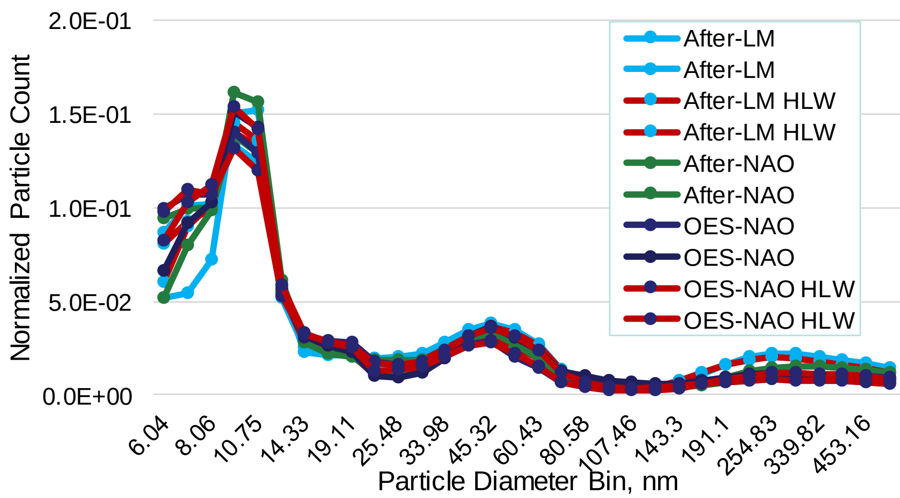


F-150 Particle Size Distributions Measured by EEPS

Front

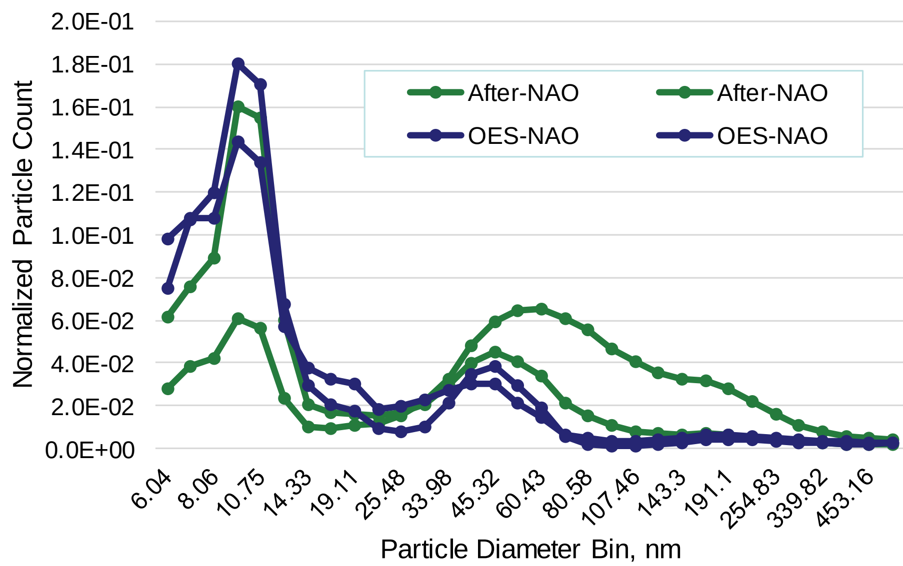


Rear

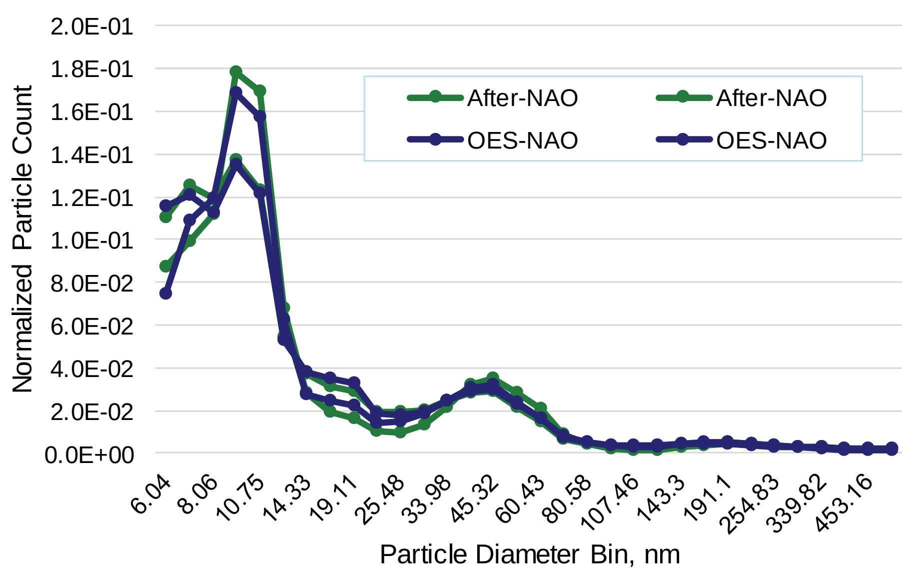


Prius Particle Size Distributions Measured by EEPS

Front

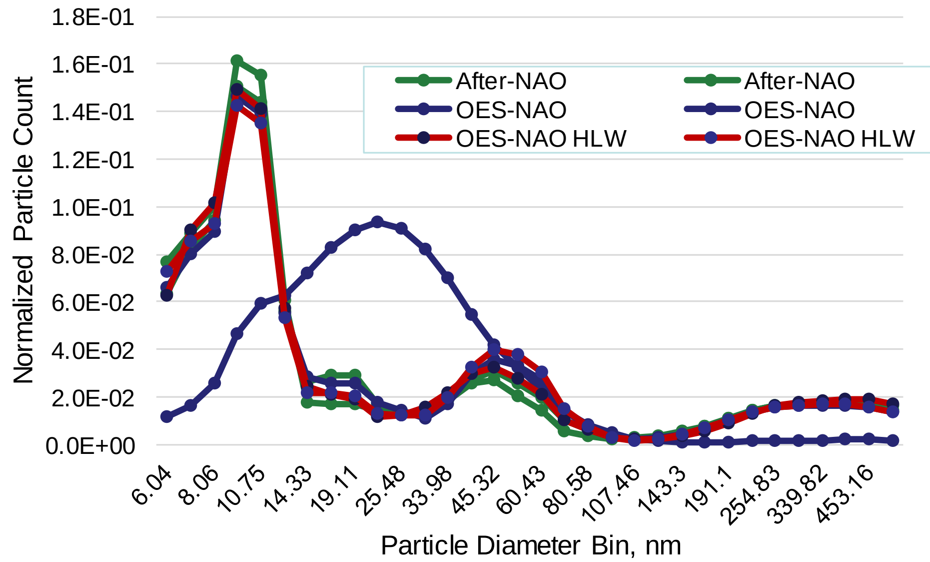


Rear

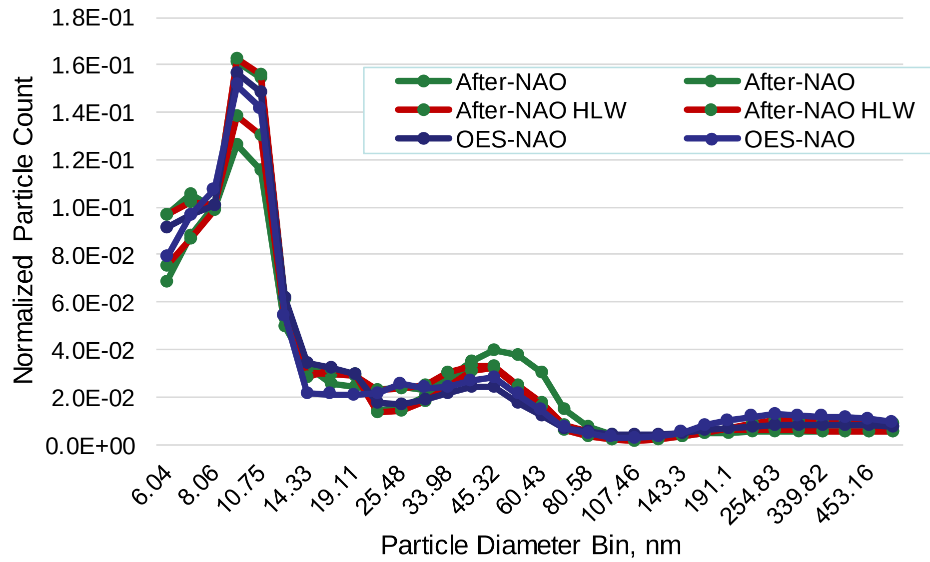


Rogue Particle Size Distributions Measured by EEPS

Front

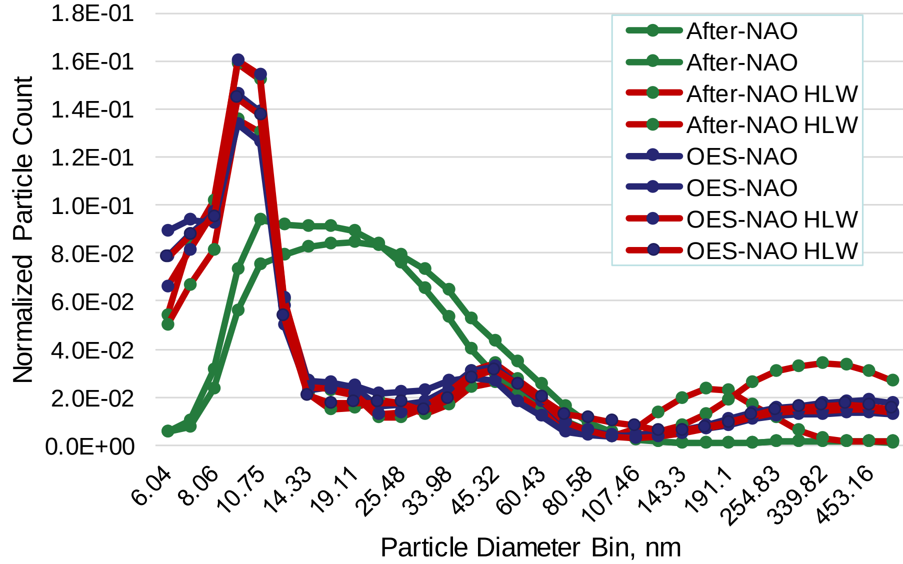


Rear

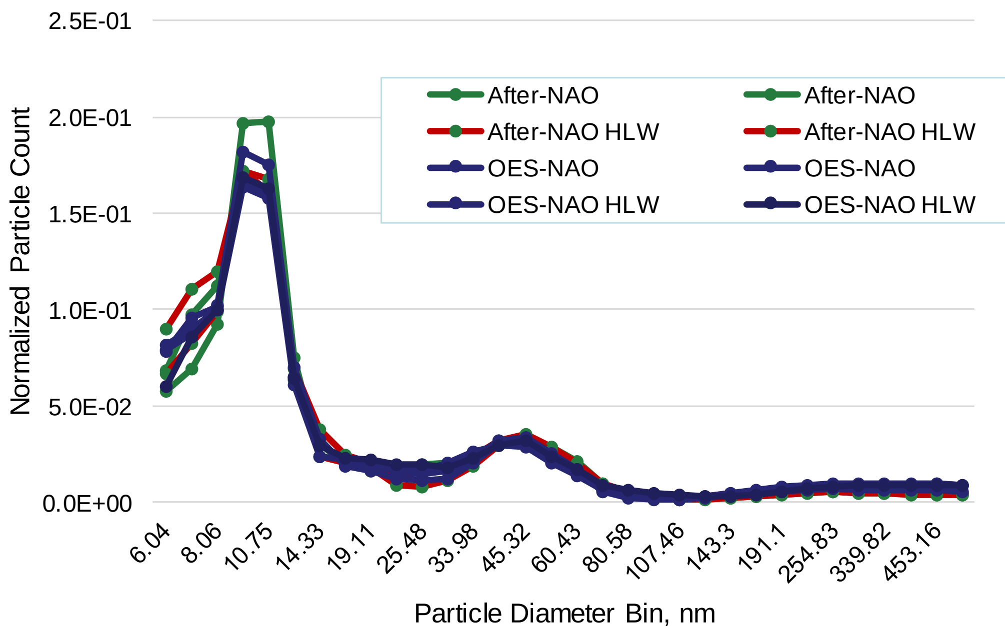


Sienna Particle Size Distributions Measured by EEPS

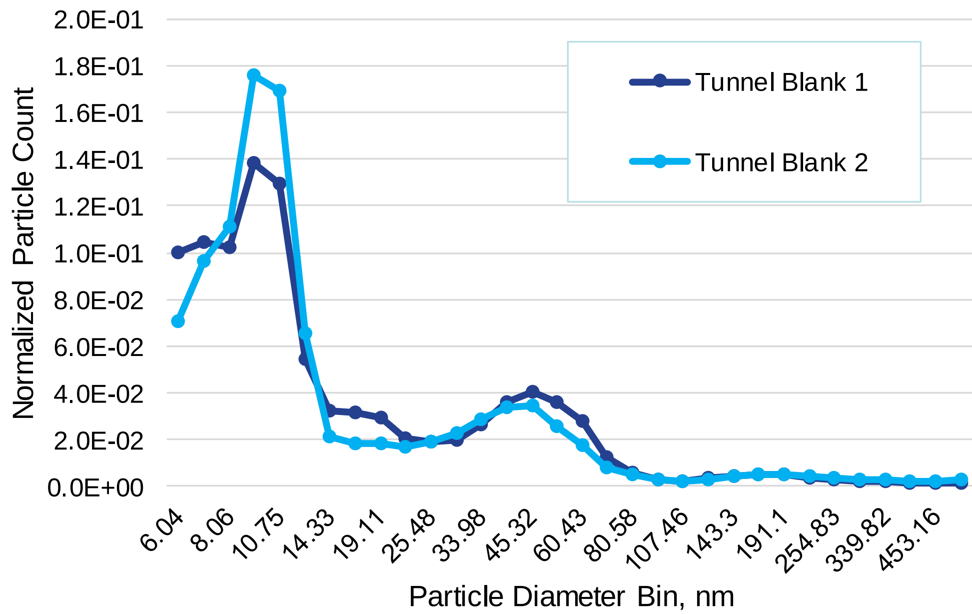
Front



Rear



Tunnel Blank Particle Size Distributions Measured by EEPS



Appendix L

Zero Blank Results

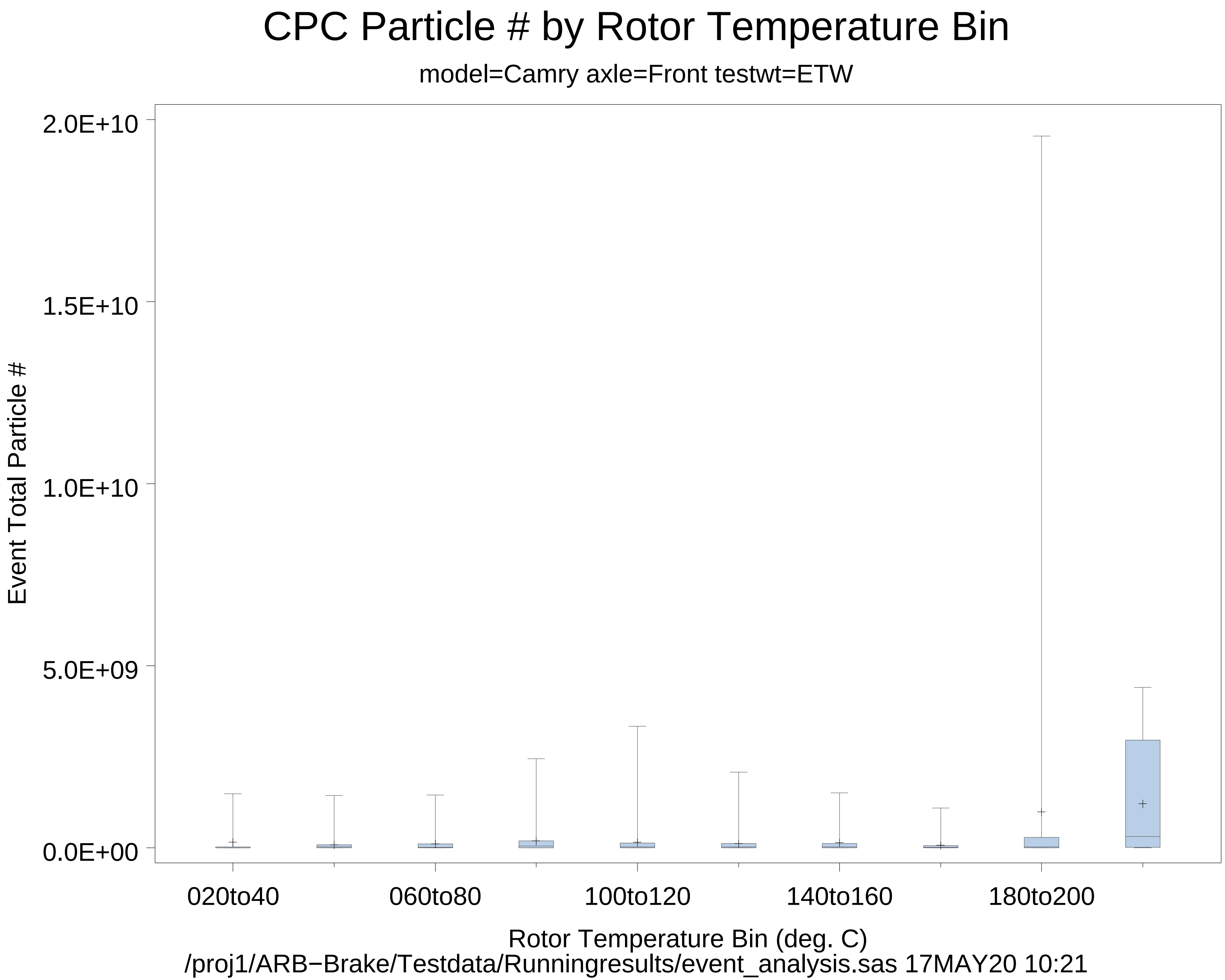
The table in this Appendix presents the PTFE filter and 100S4 impactor weights and weight gains during the zero blank experiments.

Experiment	Measurement Location	Initial (mg)	Final (mg)	Weight Gain (mg)
Zero Blank 1	100S4 Stg1	78.648	78.638	-0.010
	100S4 Stg2	78.224	78.222	-0.002
	100S4 Stg3	78.251	78.253	0.002
	100S4 Stg4	78.303	78.304	0.001
	100S4 AF	120.988	120.979	-0.009
	PMS PM10	391.103	391.114	0.011
Zero Blank 2	100S4 Stg1	78.152	78.149	-0.003
	100S4 Stg2	78.149	78.146	-0.003
	100S4 Stg3	78.142	78.140	-0.002
	100S4 Stg4	78.361	78.360	-0.001
	100S4 AF	123.260	123.240	-0.020
	PMS PM10	136.924	136.943	0.019
Zero Blank 3	100S4 Stg1	77.825	77.827	0.002
	100S4 Stg2	77.863	77.862	-0.001
	100S4 Stg3	78.048	78.048	0.000
	100S4 Stg4	77.840	77.838	-0.002
	100S4 AF	122.583	122.581	-0.002
	PMS PM10	398.319	398.320	0.001
Zero Blank 4	100S4 Stg1	76.757	76.758	0.001
	100S4 Stg2	77.828	77.823	-0.004
	100S4 Stg3	78.090	78.088	-0.002
	100S4 Stg4	77.822	77.819	-0.002
	100S4 AF	121.674	121.667	-0.007
	PMS PM10	140.422	140.489	0.067
Zero Blank 5	100S4 Stg1	77.837	77.836	0.000
	100S4 Stg2	77.354	77.354	0.000
	100S4 Stg3	78.256	78.255	-0.001
	100S4 Stg4	77.661	77.660	-0.001
	100S4 AF	121.697	121.693	-0.004
	PMS PM10	383.604	383.621	0.017
Zero Blank 6	100S4 Stg1	76.758	76.761	0.003
	100S4 Stg2	77.823	77.830	0.007
	100S4 Stg3	78.088	78.089	0.001
	100S4 Stg4	77.819	77.823	0.004
	100S4 AF	121.667	121.673	0.006
	PMS PM10	140.489	140.404	-0.085

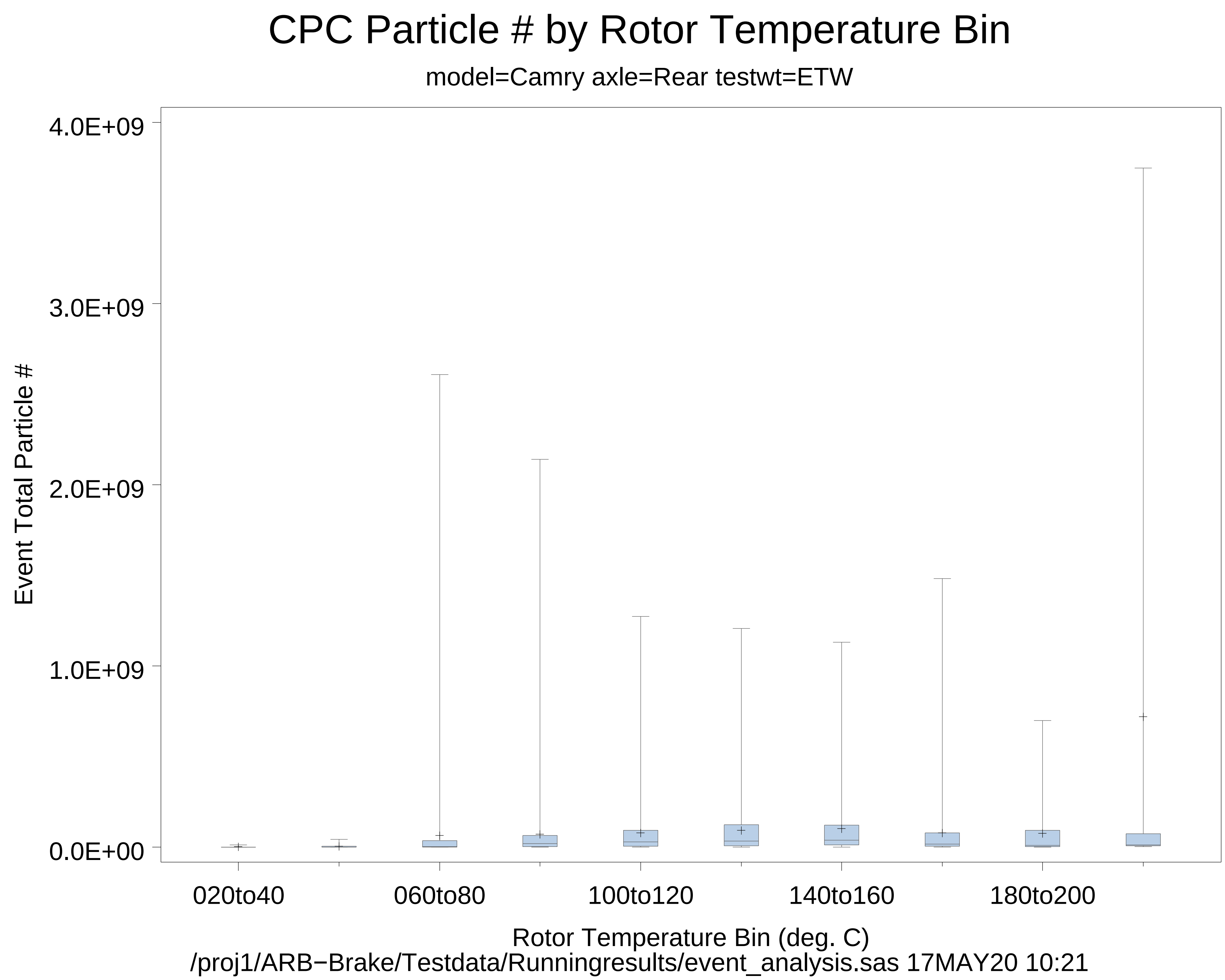
Appendix M

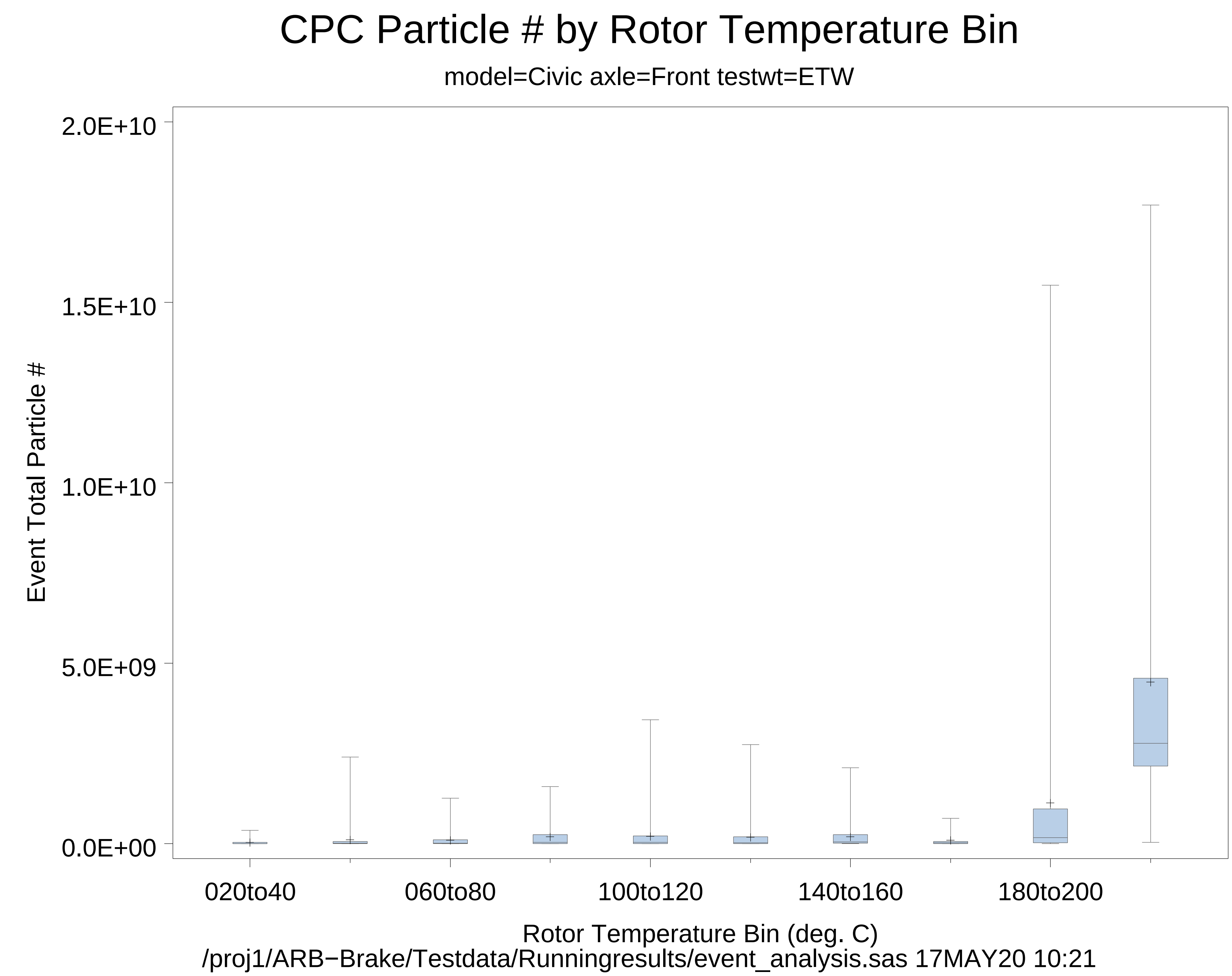
Box Plots of CPC and QCM By-Event Results by Temperature Bin

This Appendix presents box and whisker plots of brake event total CPC and QCM emissions binned by rotor temperature. Plots are presented by model, axle, and test weight. Boxes for temperature bins are only presented if the bin contains 6 or more observations.

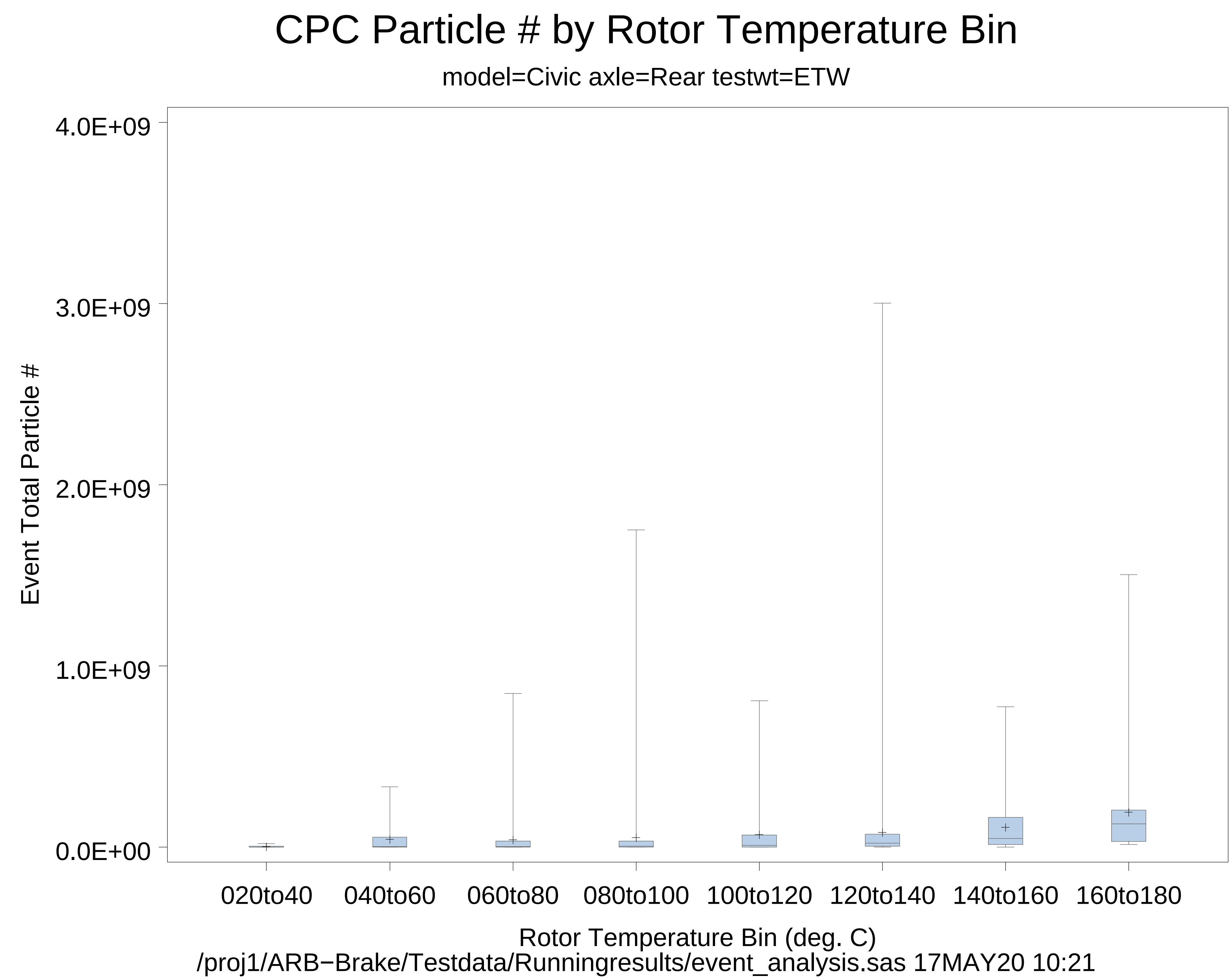


CPC Particle # by Rotor Temperature Bin
model=Camry axle=Front testwt=ETW
Event Total Particle #
2.0E+10
1.5E+10
1.0E+10
5.0E+09
0.0E+00
020to40
060to80
100to120
140to160
180to200
Rotor Temperature Bin (deg. C)
/proj1/ARB−Brake/Testdata/Runningresults/event_analysis.sas 17MAY20 10:21

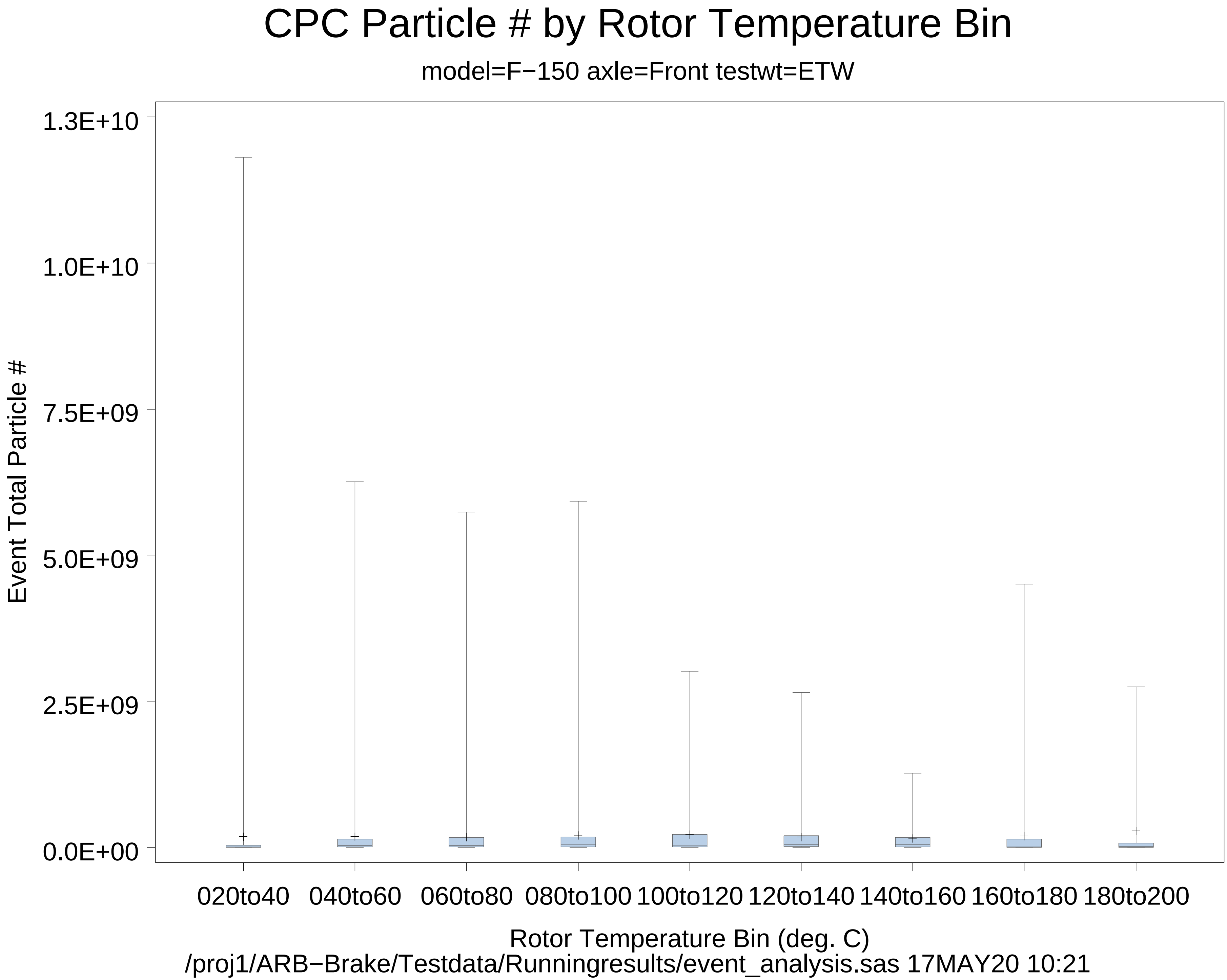

CPC Particle # by Rotor Temperature Bin
model=Camry axle=Rear testwt=ETW
Event Total Particle #
4.0E+09
3.0E+09
2.0E+09
1.0E+09
0.0E+00
020to40
060to80
100to120
140to160
180to200
Rotor Temperature Bin (deg. C)
/proj1/ARB−Brake/Testdata/Runningresults/event_analysis.sas 17MAY20 10:21



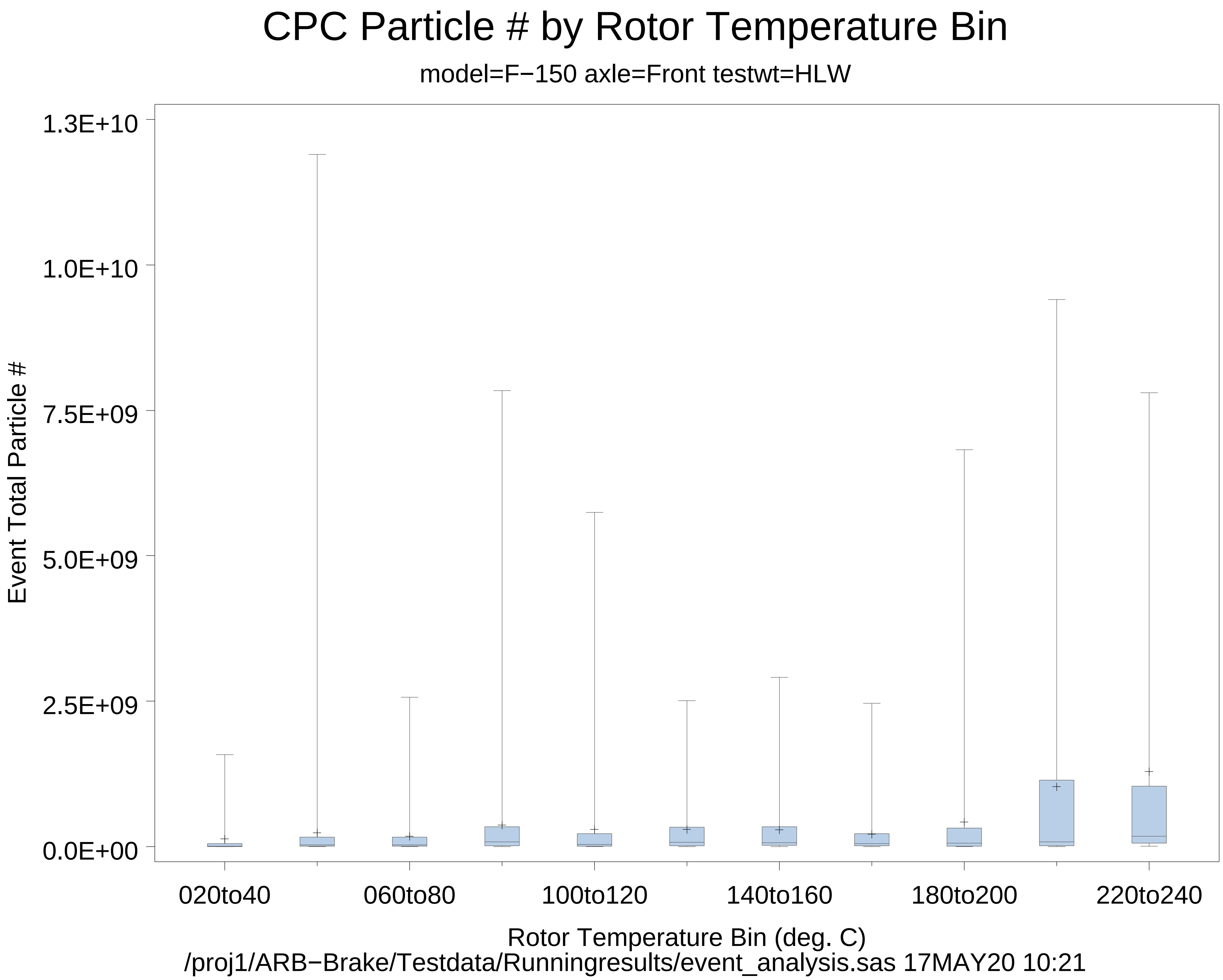
CPC Particle # by Rotor Temperature Bin
model=Civic axle=Front testwt=ETW
Event Total Particle #
2.0E+10
1.5E+10
1.0E+10
5.0E+09
0.0E+00
020to40
060to80
100to120
140to160
180to200
Rotor Temperature Bin (deg. C)
/proj1/ARB−Brake/Testdata/Runningresults/event_analysis.sas 17MAY20 10:21



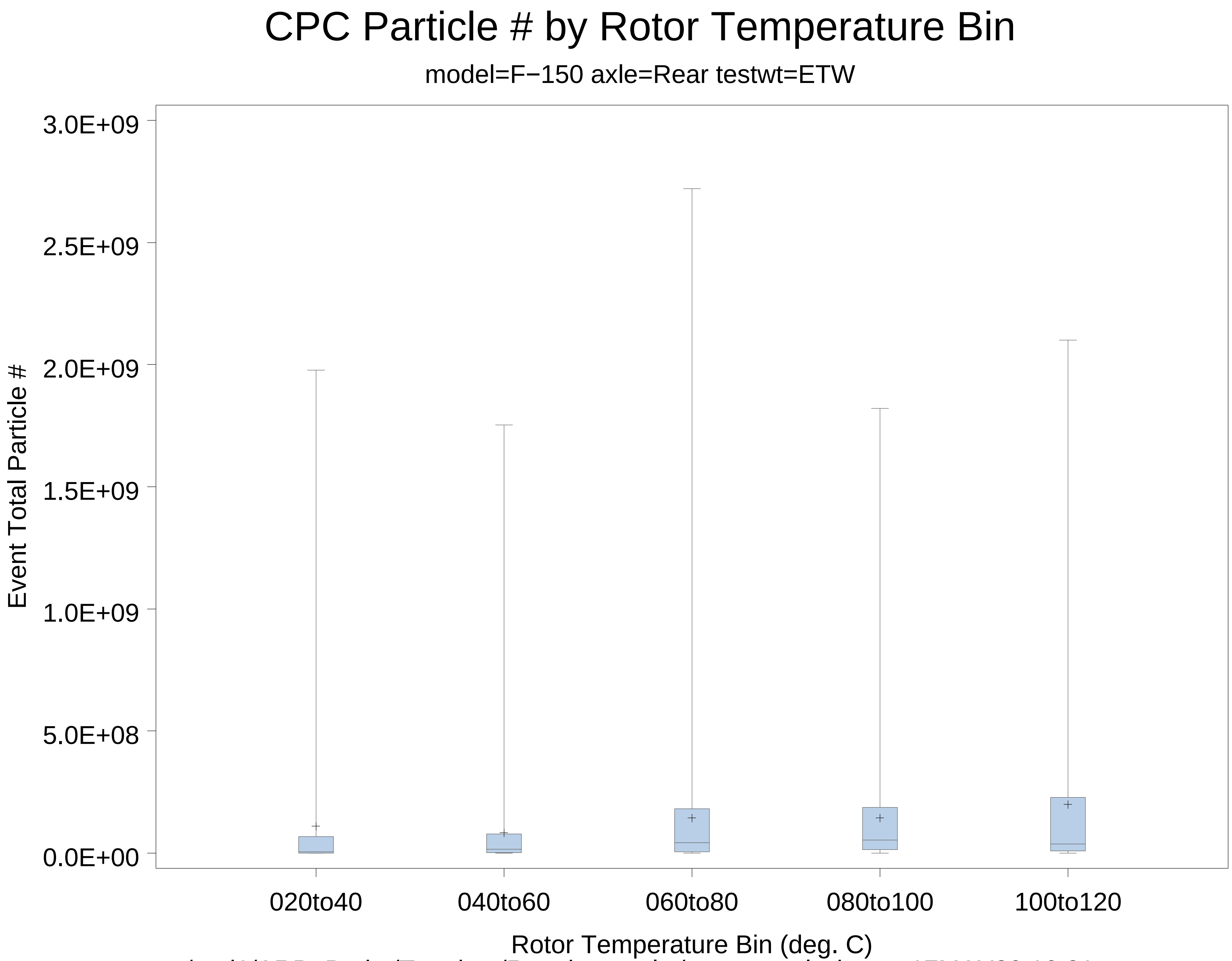
CPC Particle # by Rotor Temperature Bin
model=Civic axle=Rear testwt=ETW
Event Total Particle #
4.0E+09
3.0E+09
2.0E+09
1.0E+09
0.0E+00
020to40
040to60
060to80
080to100
100to120
120to140
140to160
160to180
Rotor Temperature Bin (deg. C)
/proj1/ARB−Brake/Testdata/Runningresults/event_analysis.sas 17MAY20 10:21



CPC Particle # by Rotor Temperature Bin
model=F−150 axle=Front testwt=ETW
Event Total Particle #
1.3E+10
1.0E+10
7.5E+09
5.0E+09
2.5E+09
0.0E+00
020to40
040to60
060to80
080to100
100to120
120to140
140to160
160to180
180to200
Rotor Temperature Bin (deg. C)
/proj1/ARB−Brake/Testdata/Runningresults/event_analysis.sas 17MAY20 10:21



CPC Particle # by Rotor Temperature Bin
model=F−150 axle=Front testwt=HLW
Event Total Particle #
1.3E+10
1.0E+10
7.5E+09
5.0E+09
2.5E+09
0.0E+00
020to40
060to80
100to120
140to160
180to200
220to240
Rotor Temperature Bin (deg. C)
/proj1/ARB−Brake/Testdata/Runningresults/event_analysis.sas 17MAY20 10:21



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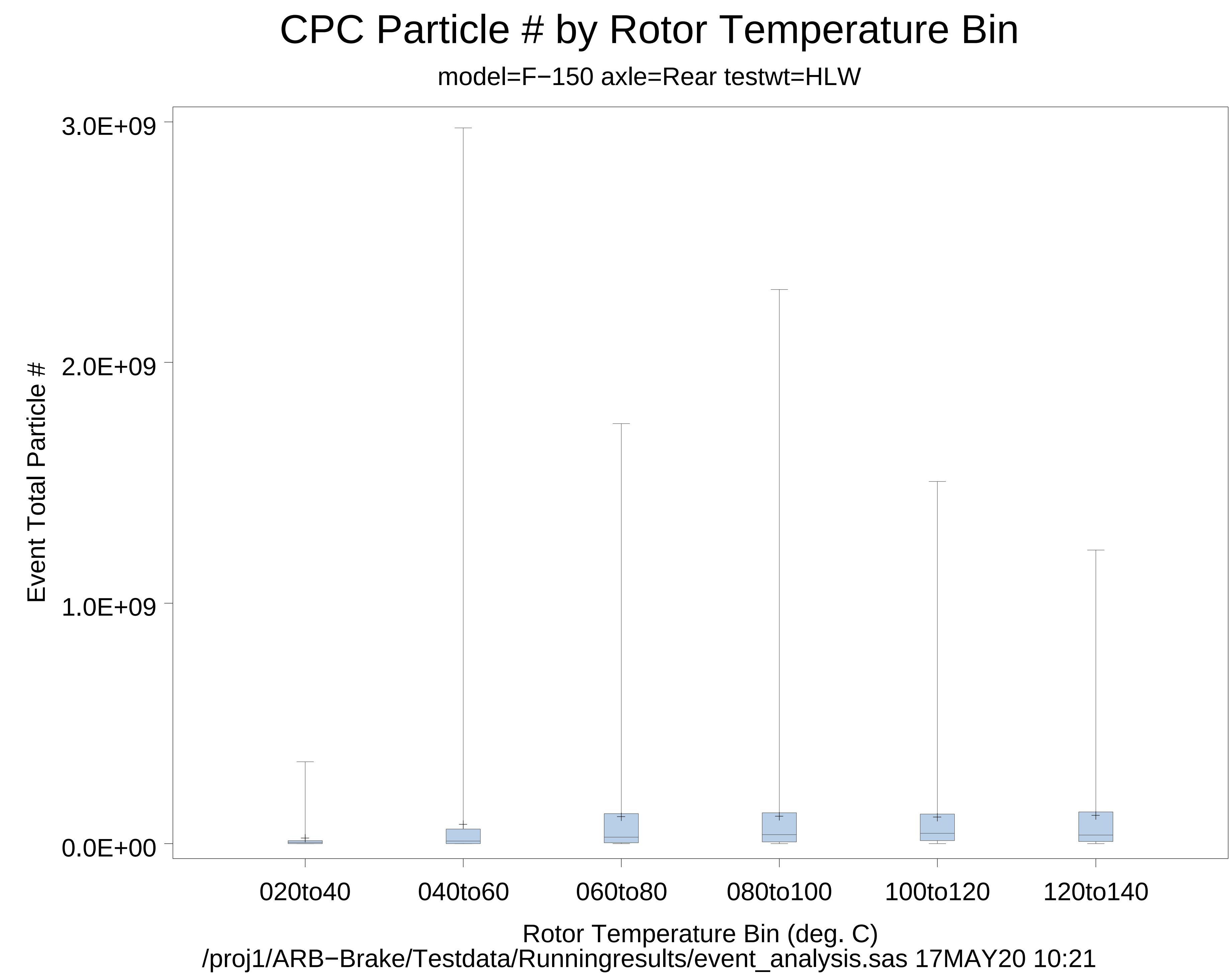
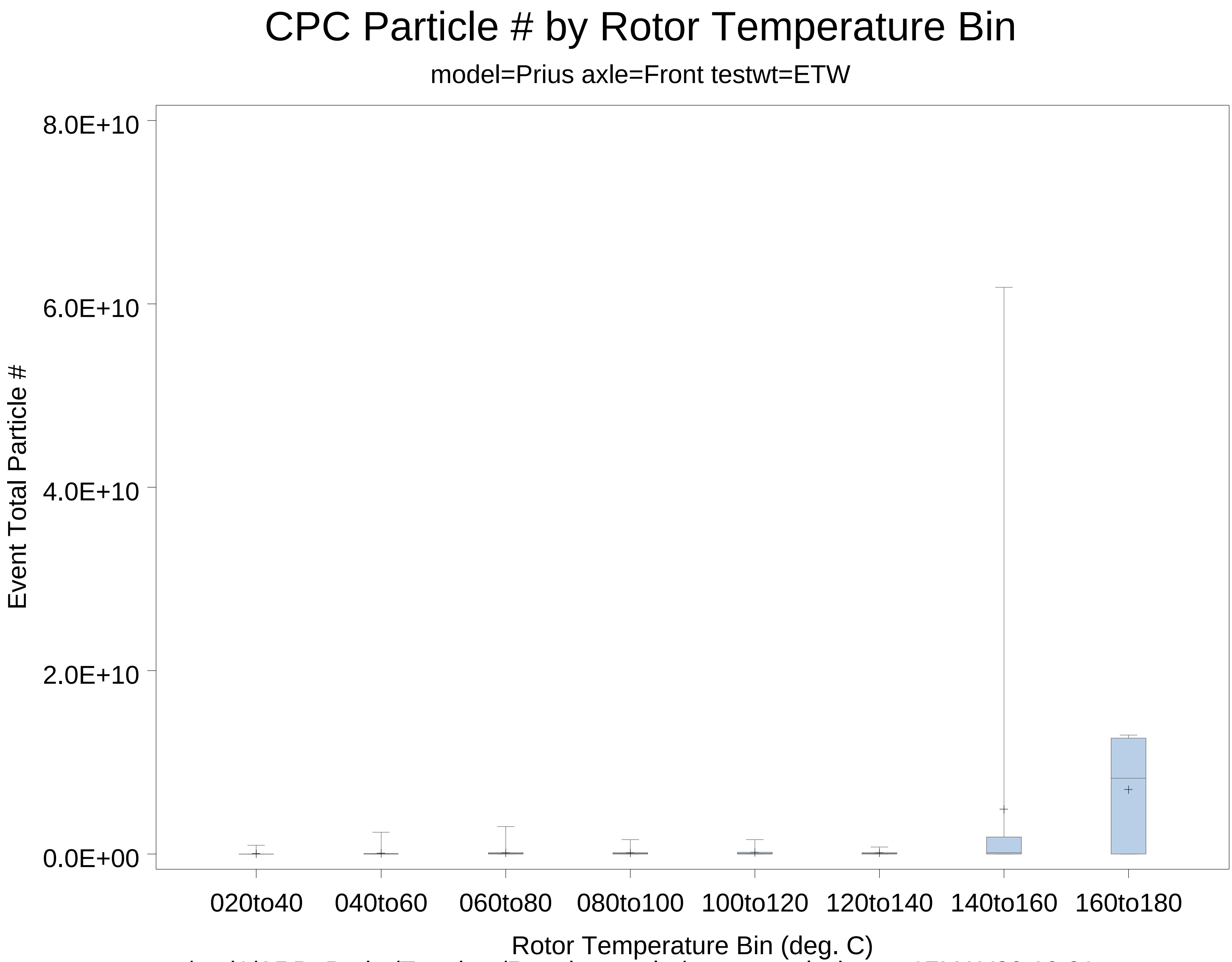
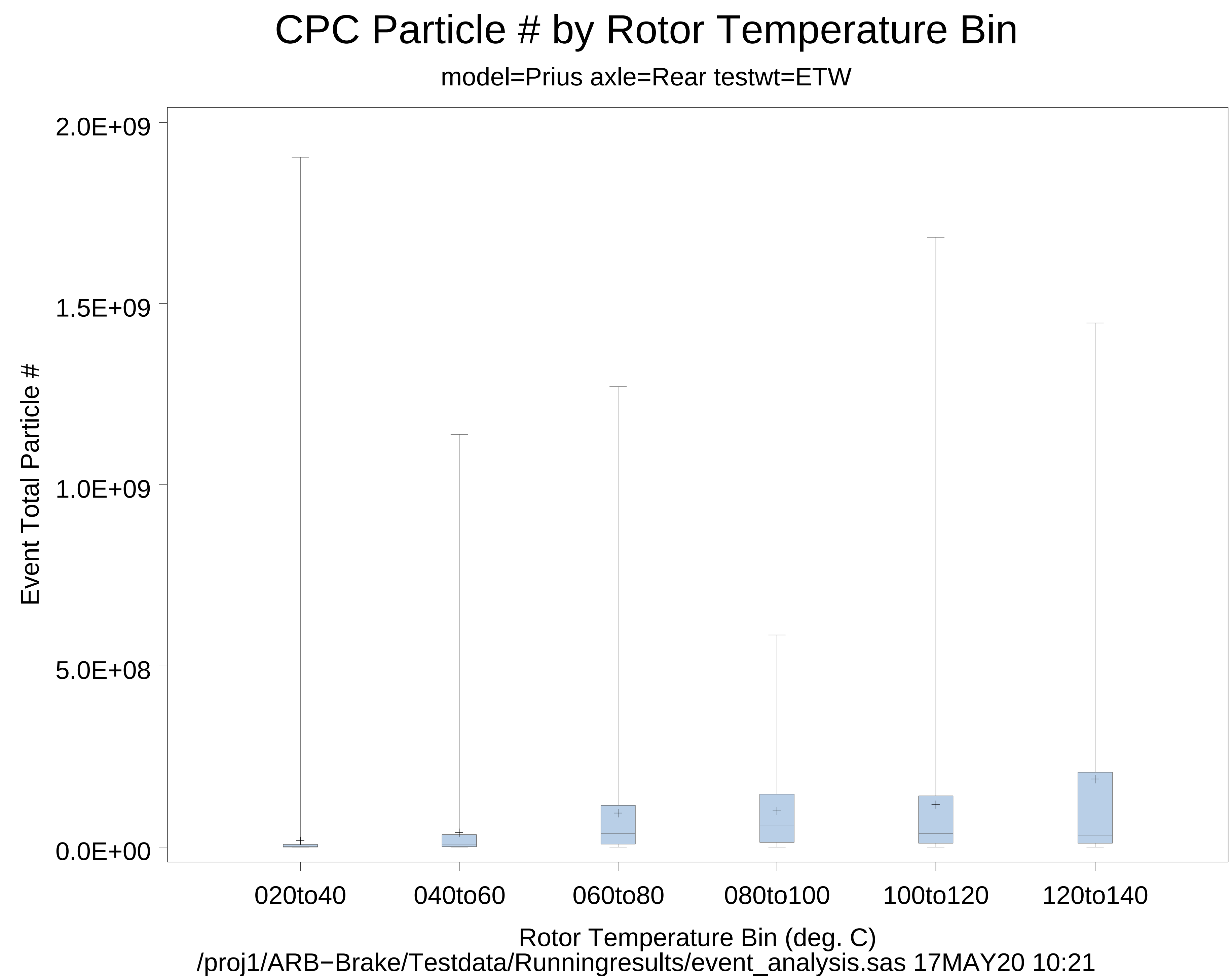
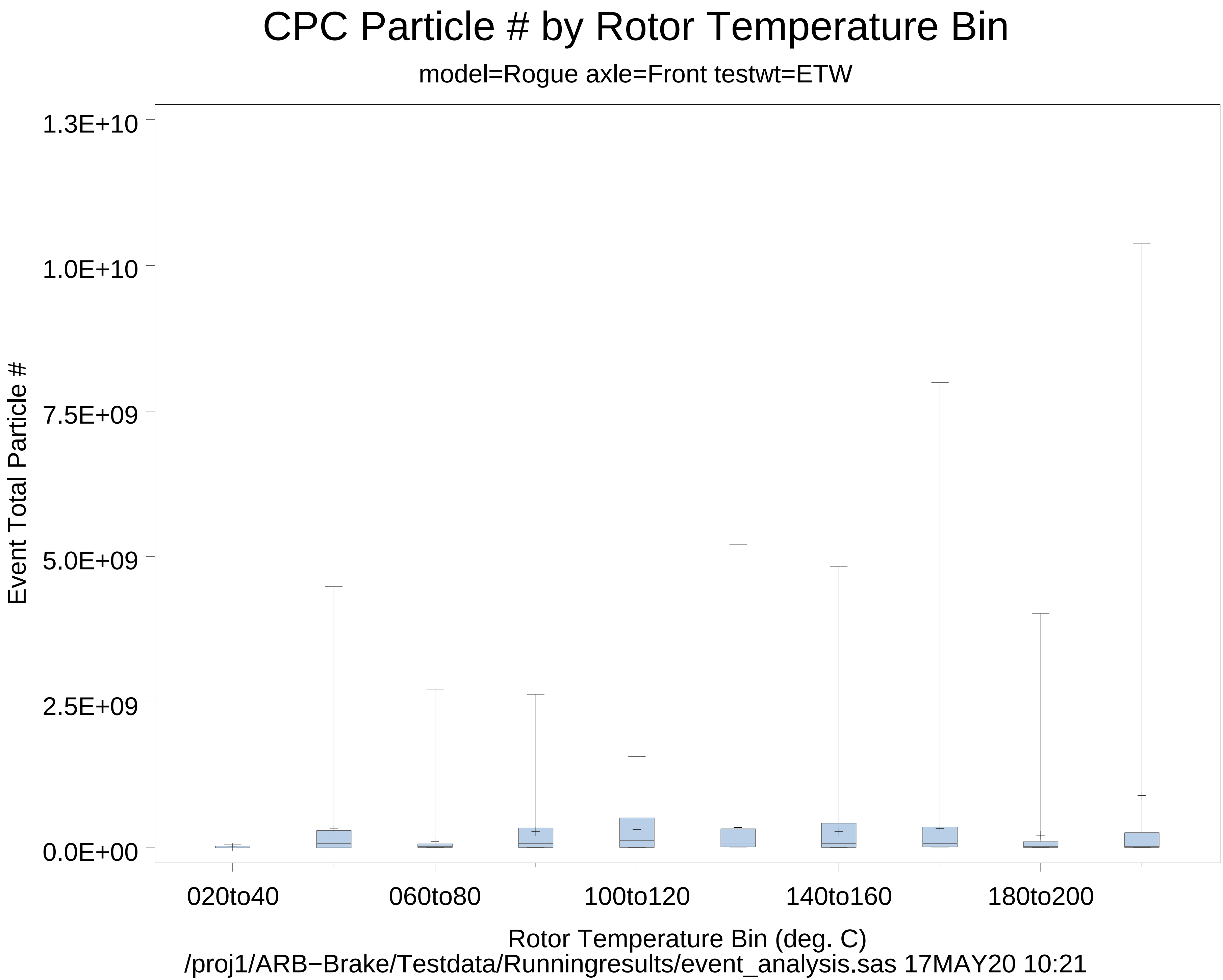
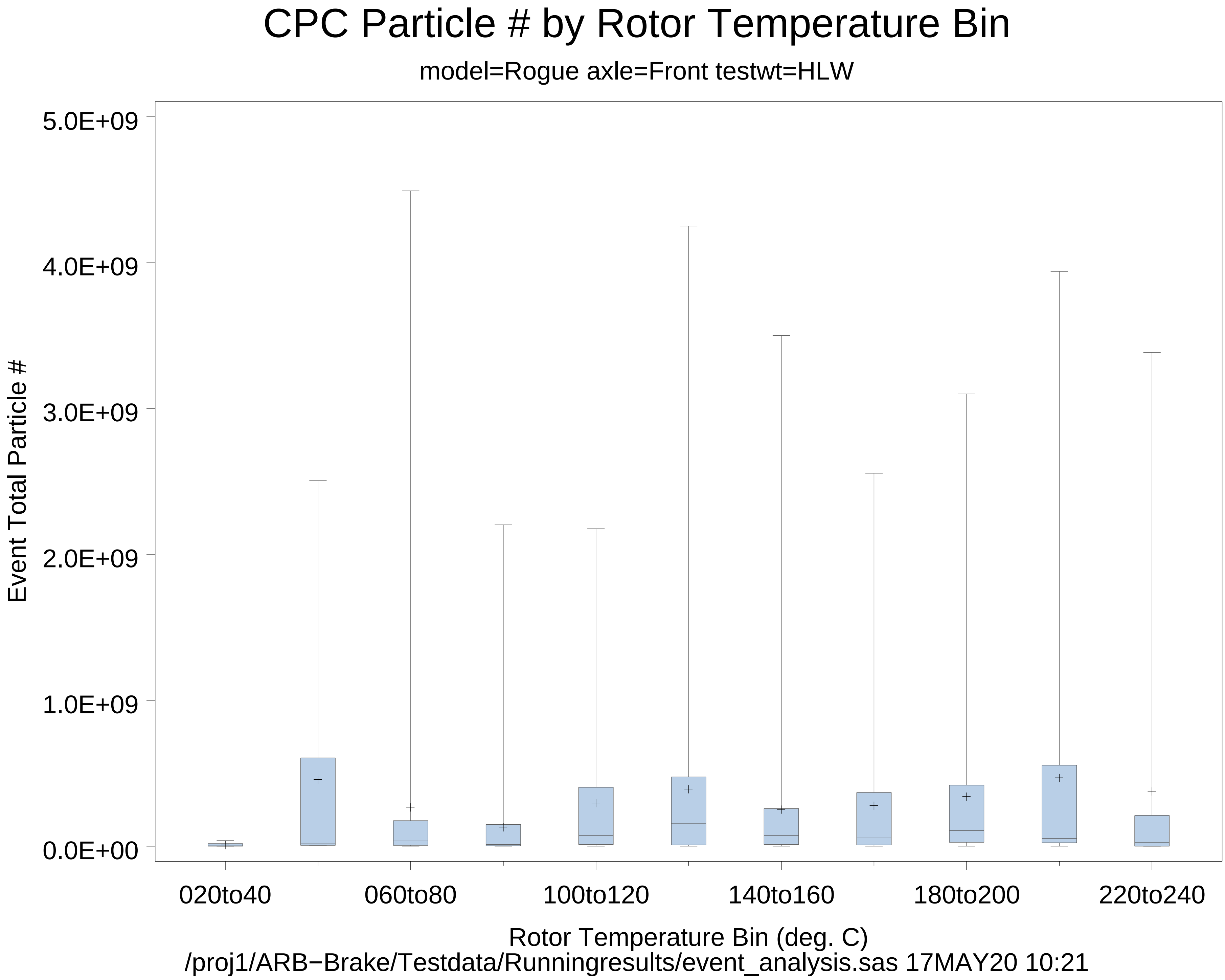

CPC Particle # by Rotor Temperature Bin
model=F−150 axle=Rear testwt=HLW
Event Total Particle #
3.0E+09
2.0E+09
1.0E+09
0.0E+00
020to40
040to60
060to80
080to100
100to120
120to140
Rotor Temperature Bin (deg. C)
/proj1/ARB−Brake/Testdata/Runningresults/event_analysis.sas 17MAY20 10:21

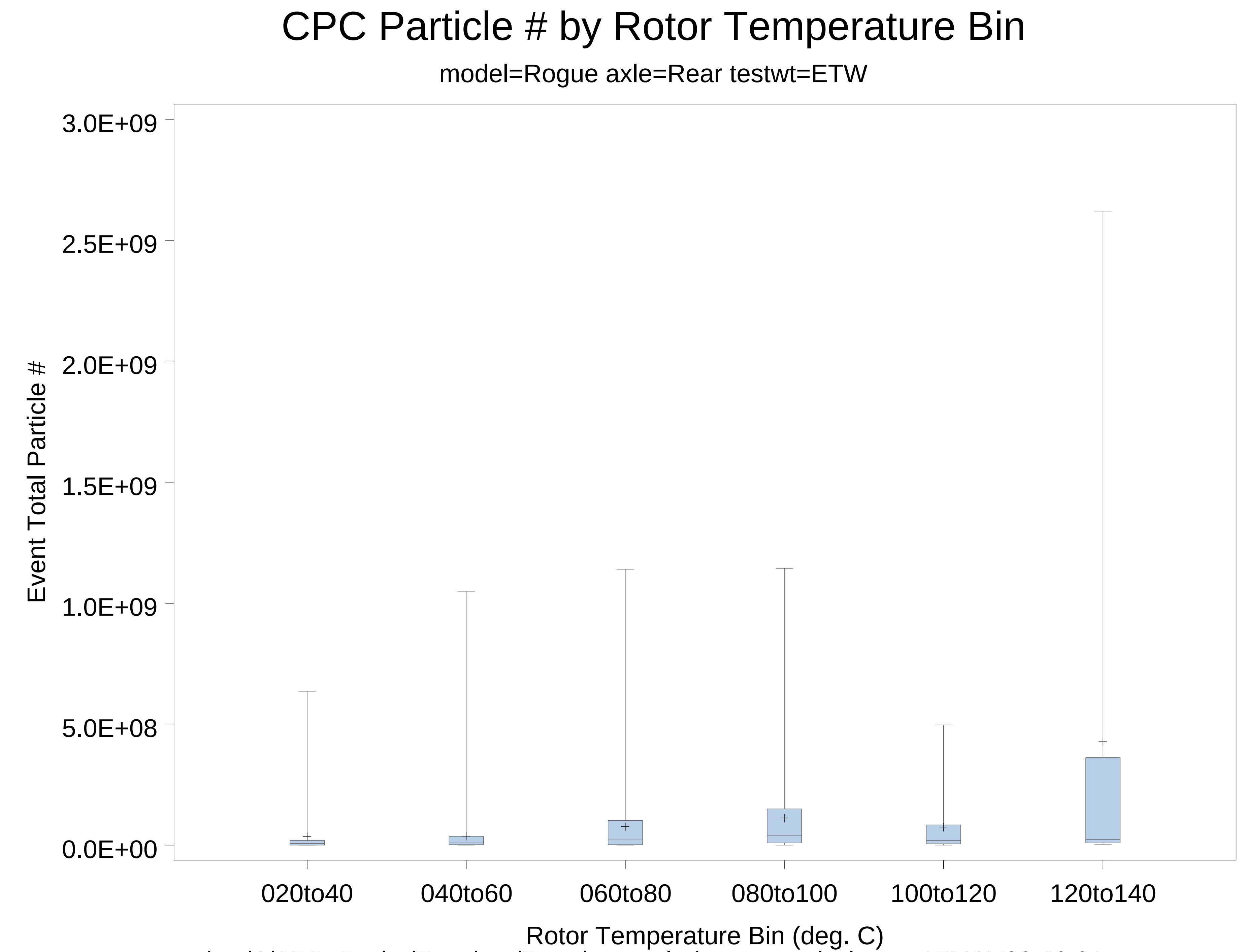


/proj1/ARB−Brake/Testdata/Runningresults/event_analysis.sas 17MAY20 10:21


CPC Particle # by Rotor Temperature Bin
model=Prius axle=Rear testwt=ETW
Event Total Particle #
2.0E+09
1.5E+09
1.0E+09
5.0E+08
0.0E+00
020to40
040to60
060to80
080to100
100to120
120to140
Rotor Temperature Bin (deg. C)
/proj1/ARB−Brake/Testdata/Runningresults/event_analysis.sas 17MAY20 10:21


CPC Particle # by Rotor Temperature Bin
model=Rogue axle=Front testwt=ETW
Event Total Particle #
1.3E+10
1.0E+10
7.5E+09
5.0E+09
2.5E+09
0.0E+00
020to40
060to80
100to120
140to160
180to200
Rotor Temperature Bin (deg. C)
/proj1/ARB−Brake/Testdata/Runningresults/event_analysis.sas 17MAY20 10:21


CPC Particle # by Rotor Temperature Bin
model=Rogue axle=Front testwt=HLW
Event Total Particle #
5.0E+09
4.0E+09
3.0E+09
2.0E+09
1.0E+09
0.0E+00
020to40
060to80
100to120
140to160
180to200
220to240
Rotor Temperature Bin (deg. C)
/proj1/ARB−Brake/Testdata/Runningresults/event_analysis.sas 17MAY20 10:21



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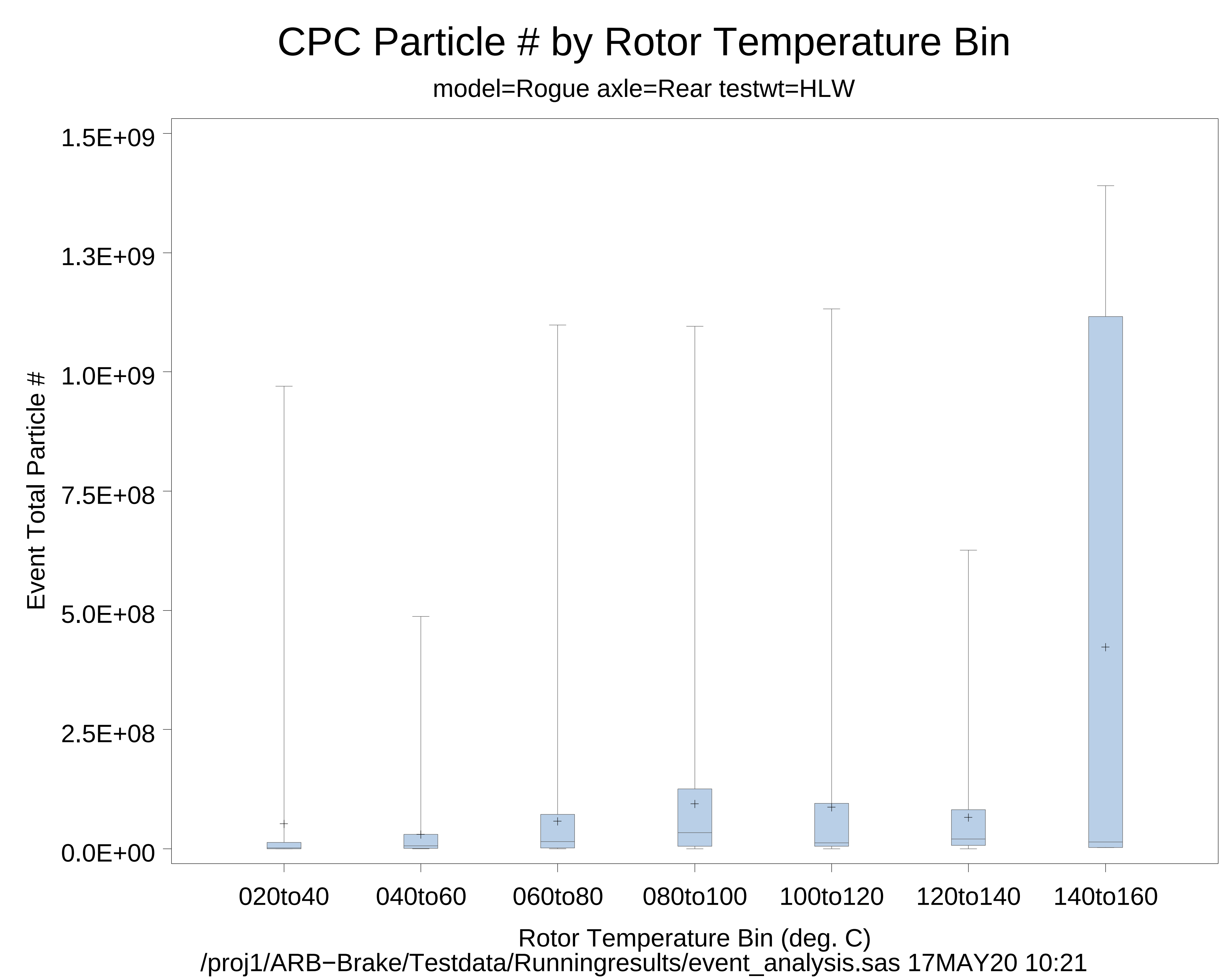
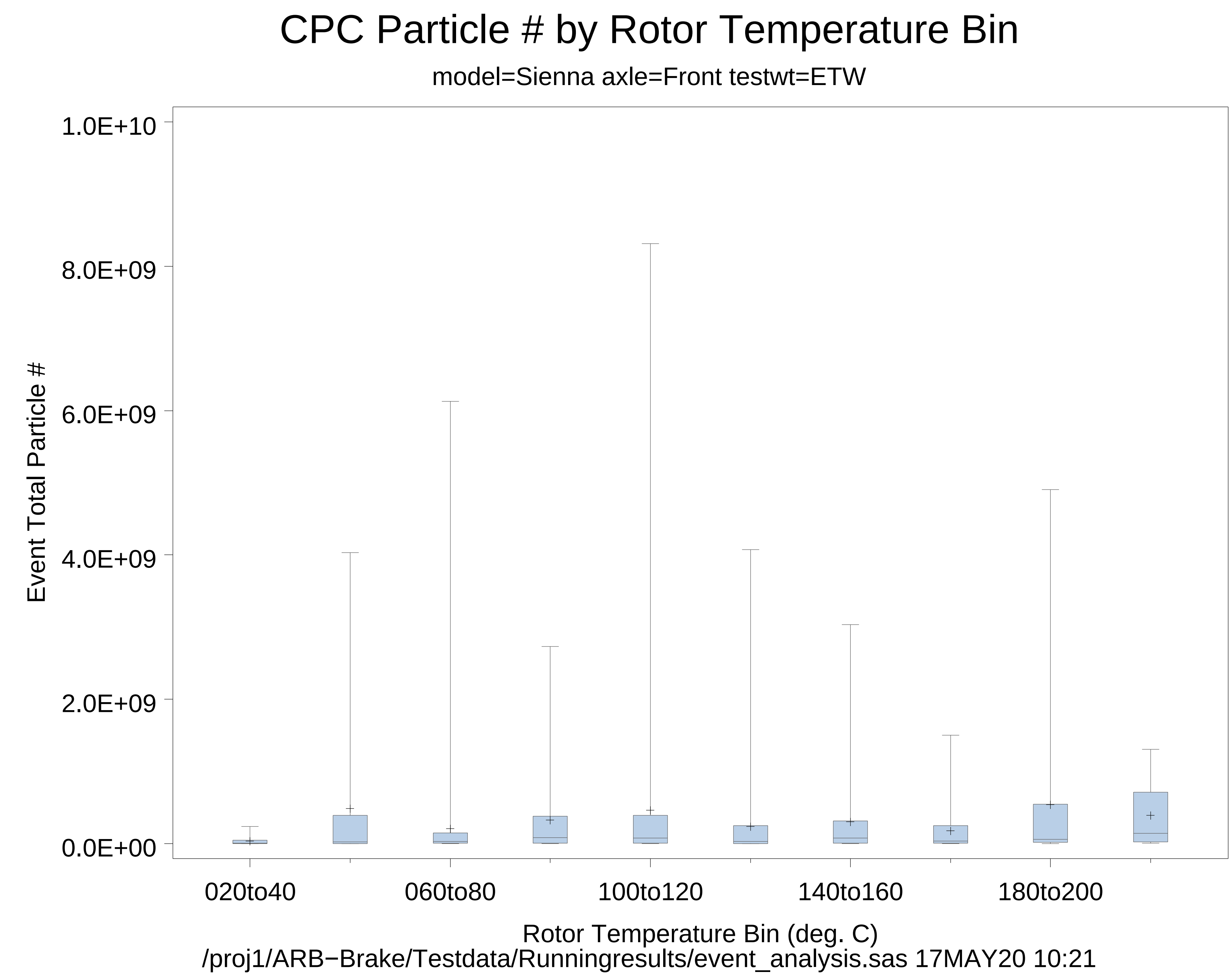
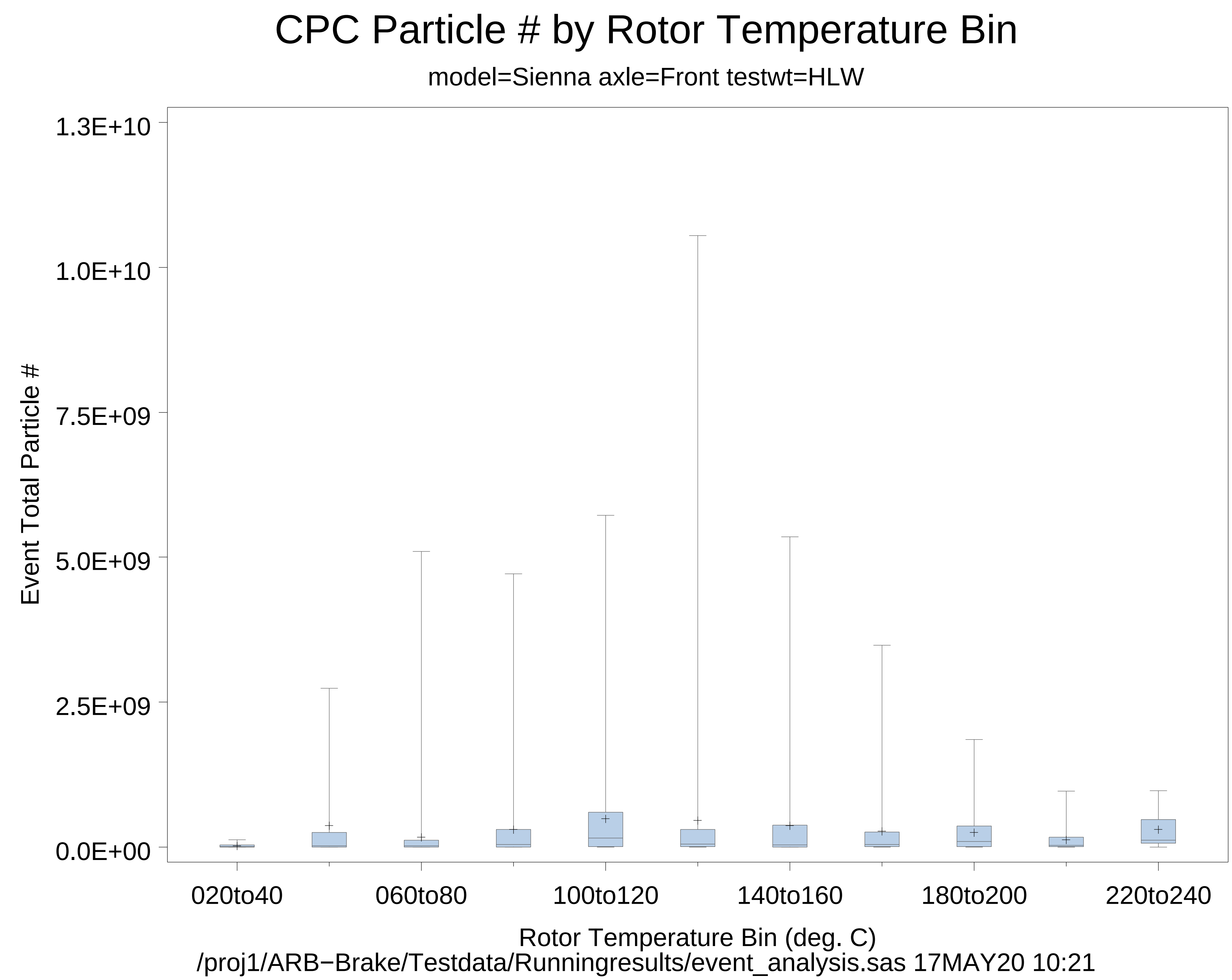
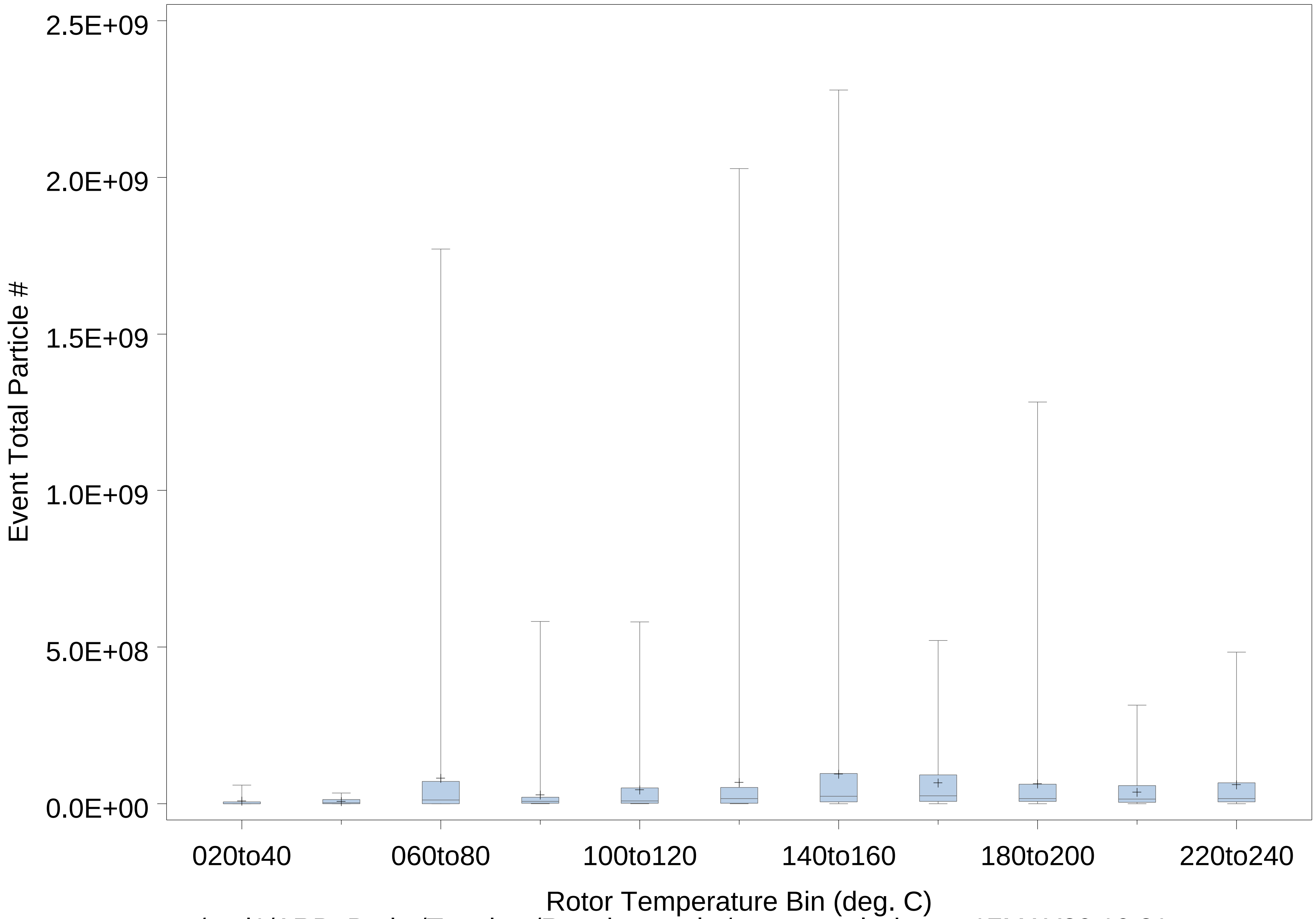

CPC Particle # by Rotor Temperature Bin
model=Rogue axle=Rear testwt=HLW
Event Total Particle #
1.5E+09
1.3E+09
1.0E+09
7.5E+08
5.0E+08
2.5E+08
0.0E+00
020to40
040to60
060to80
080to100
100to120
120to140
140to160
Rotor Temperature Bin (deg. C)
/proj1/ARB−Brake/Testdata/Runningresults/event_analysis.sas 17MAY20 10:21


CPC Particle # by Rotor Temperature Bin
model=Sienna axle=Front testwt=ETW
Event Total Particle #
1.0E+10
8.0E+09
6.0E+09
4.0E+09
2.0E+09
0.0E+00
020to40
060to80
100to120
140to160
180to200
Rotor Temperature Bin (deg. C)
/proj1/ARB−Brake/Testdata/Runningresults/event_analysis.sas 17MAY20 10:21

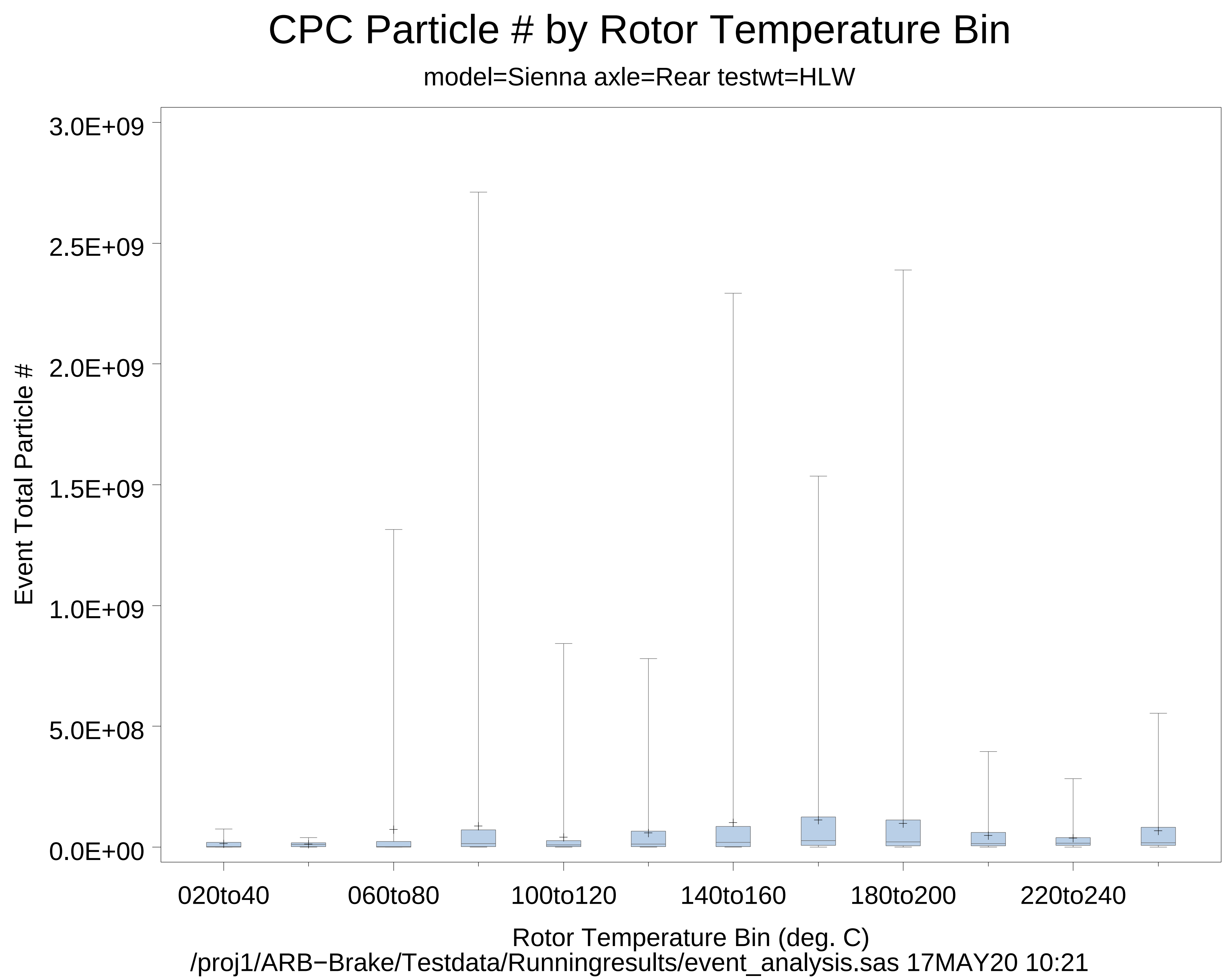

CPC Particle # by Rotor Temperature Bin
model=Sienna axle=Front testwt=HLW
Event Total Particle #
1.3E+10
1.0E+10
7.5E+09
5.0E+09
2.5E+09
0.0E+00
020to40
060to80
100to120
140to160
180to200
220to240
Rotor Temperature Bin (deg. C)
/proj1/ARB−Brake/Testdata/Runningresults/event_analysis.sas 17MAY20 10:21

CPC Particle # by Rotor Temperature Bin

model=Sienna axle=Rear testwt=ETW

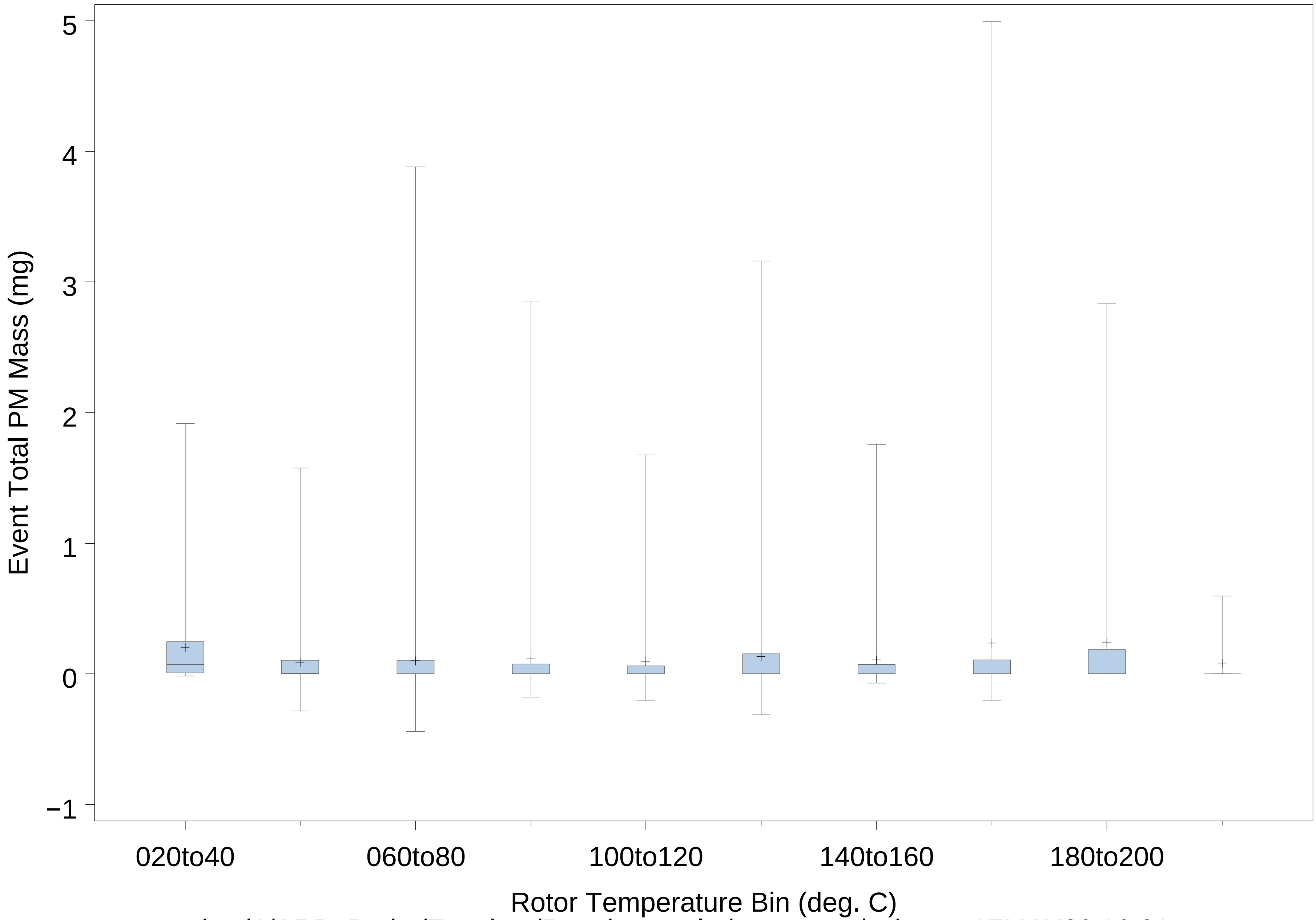


/proj1/ARB−Brake/Testdata/Runningresults/event_analysis.sas 17MAY20 10:21

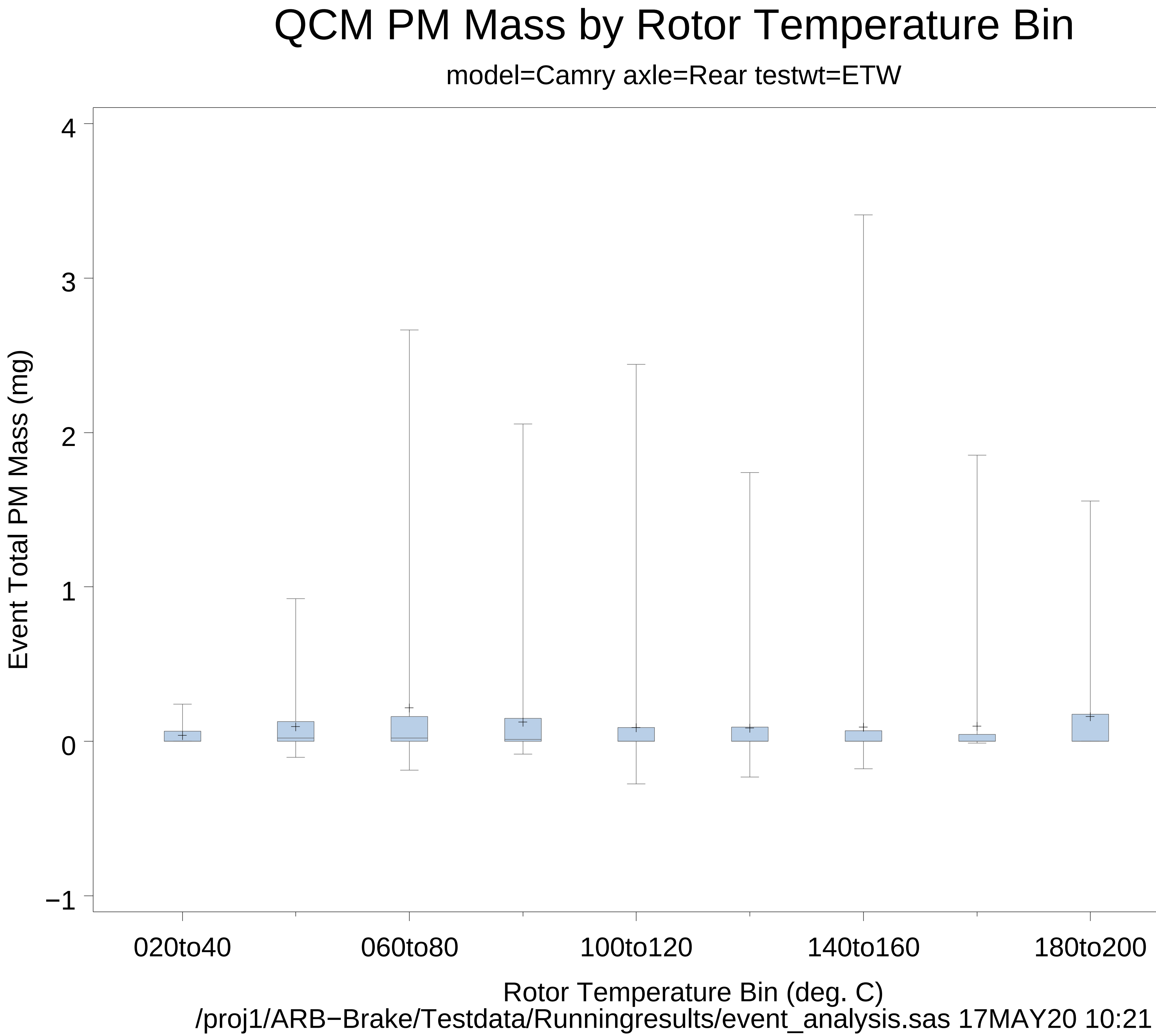

CPC Particle # by Rotor Temperature Bin
model=Sienna axle=Rear testwt=HLW
Event Total Particle #
3.0E+09
2.5E+09
2.0E+09
1.5E+09
1.0E+09
5.0E+08
0.0E+00
020to40
060to80
100to120
140to160
180to200
220to240
Rotor Temperature Bin (deg. C)
/proj1/ARB−Brake/Testdata/Runningresults/event_analysis.sas 17MAY20 10:21

QCM PM Mass by Rotor Temperature Bin

model=Camry axle=Front testwt=ETW

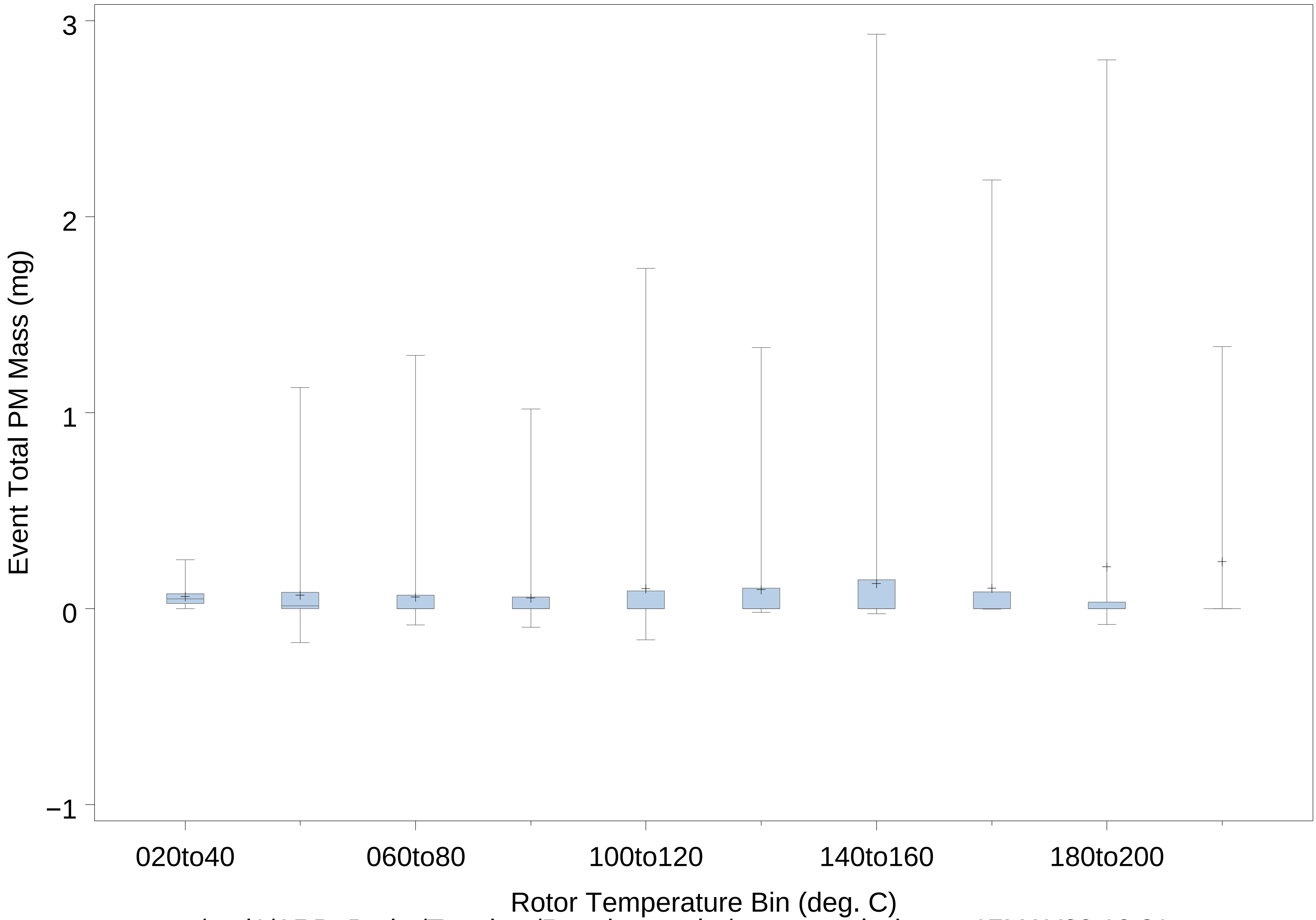


/proj1/ARB−Brake/Testdata/Runningresults/event_analysis.sas 17MAY20 10:21

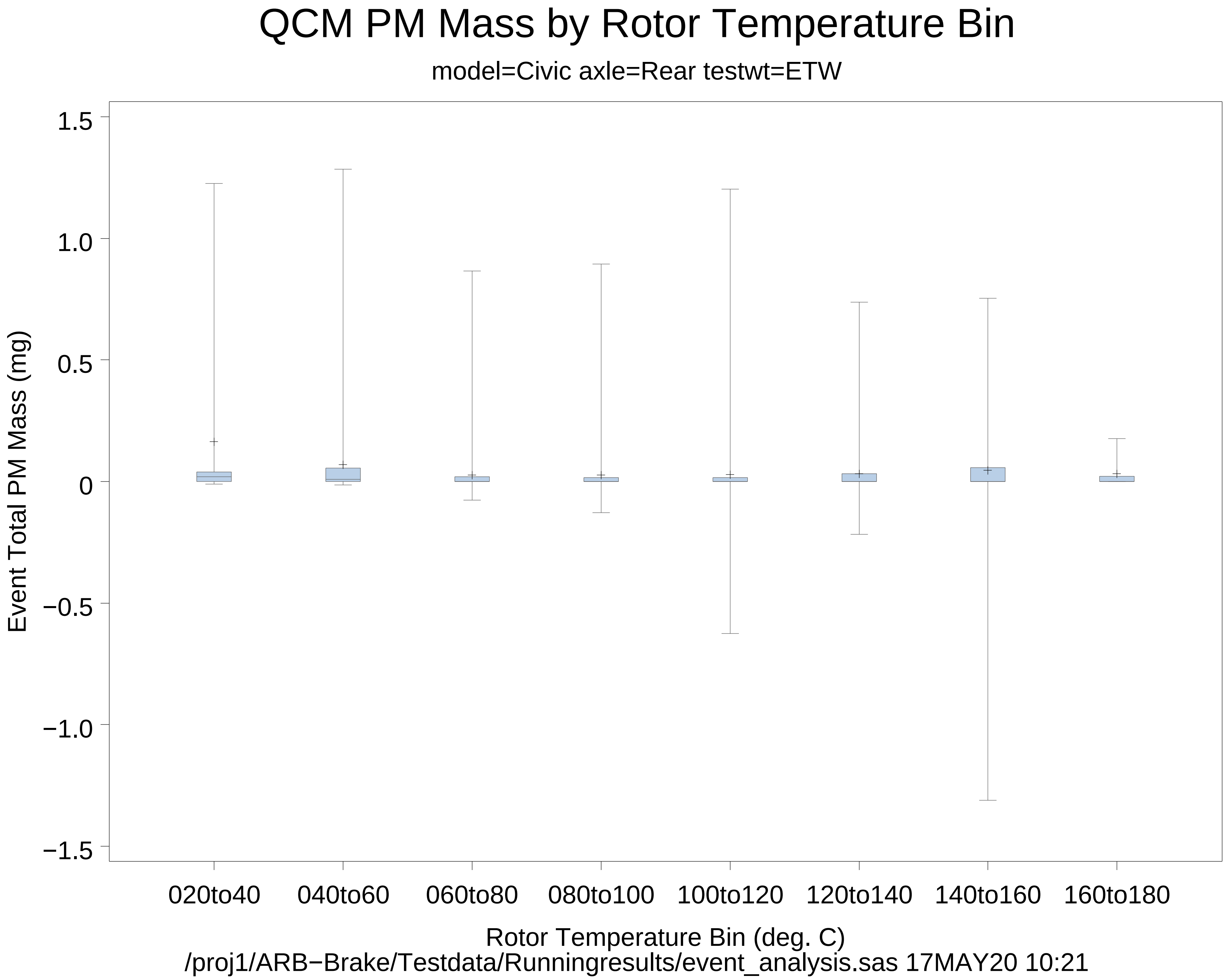

QCM PM Mass by Rotor Temperature Bin
model=Camry axle=Rear testwt=ETW
Event Total PM Mass (mg)
4
3
2
1
0
−1
020to40
060to80
100to120
140to160
180to200
Rotor Temperature Bin (deg. C)
/proj1/ARB−Brake/Testdata/Runningresults/event_analysis.sas 17MAY20 10:21

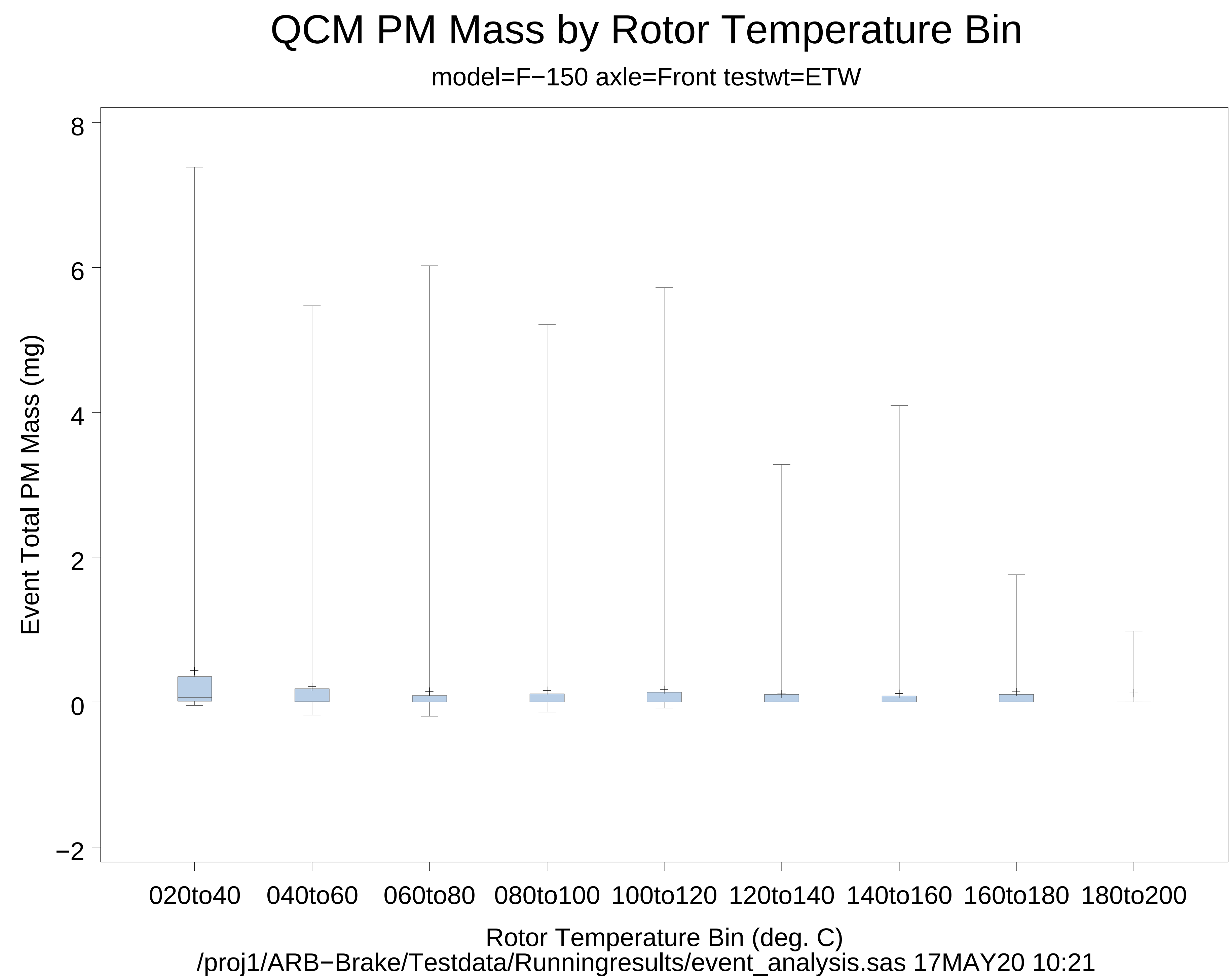
QCM PM Mass by Rotor Temperature Bin

model=Civic axle=Front testwt=ETW



/proj1/ARB−Brake/Testdata/Runningresults/event_analysis.sas 17MAY20 10:21

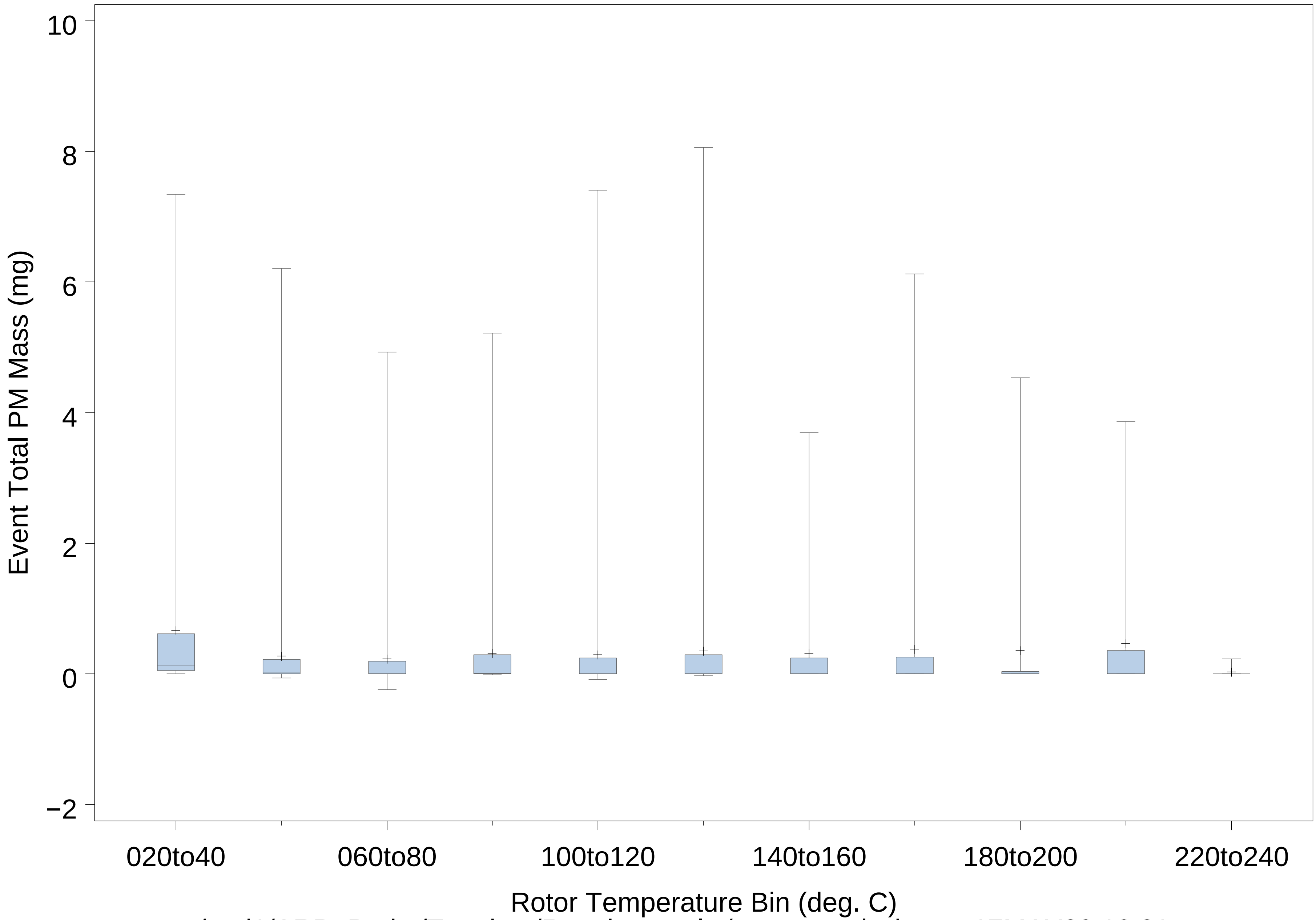

QCM PM Mass by Rotor Temperature Bin
model=Civic axle=Rear testwt=ETW
Event Total PM Mass (mg)
1.5
1.0
0.5
0
−0.5
−1.0
−1.5
020to40
040to60
060to80
080to100
100to120
120to140
140to160
160to180
Rotor Temperature Bin (deg. C)
/proj1/ARB−Brake/Testdata/Runningresults/event_analysis.sas 17MAY20 10:21



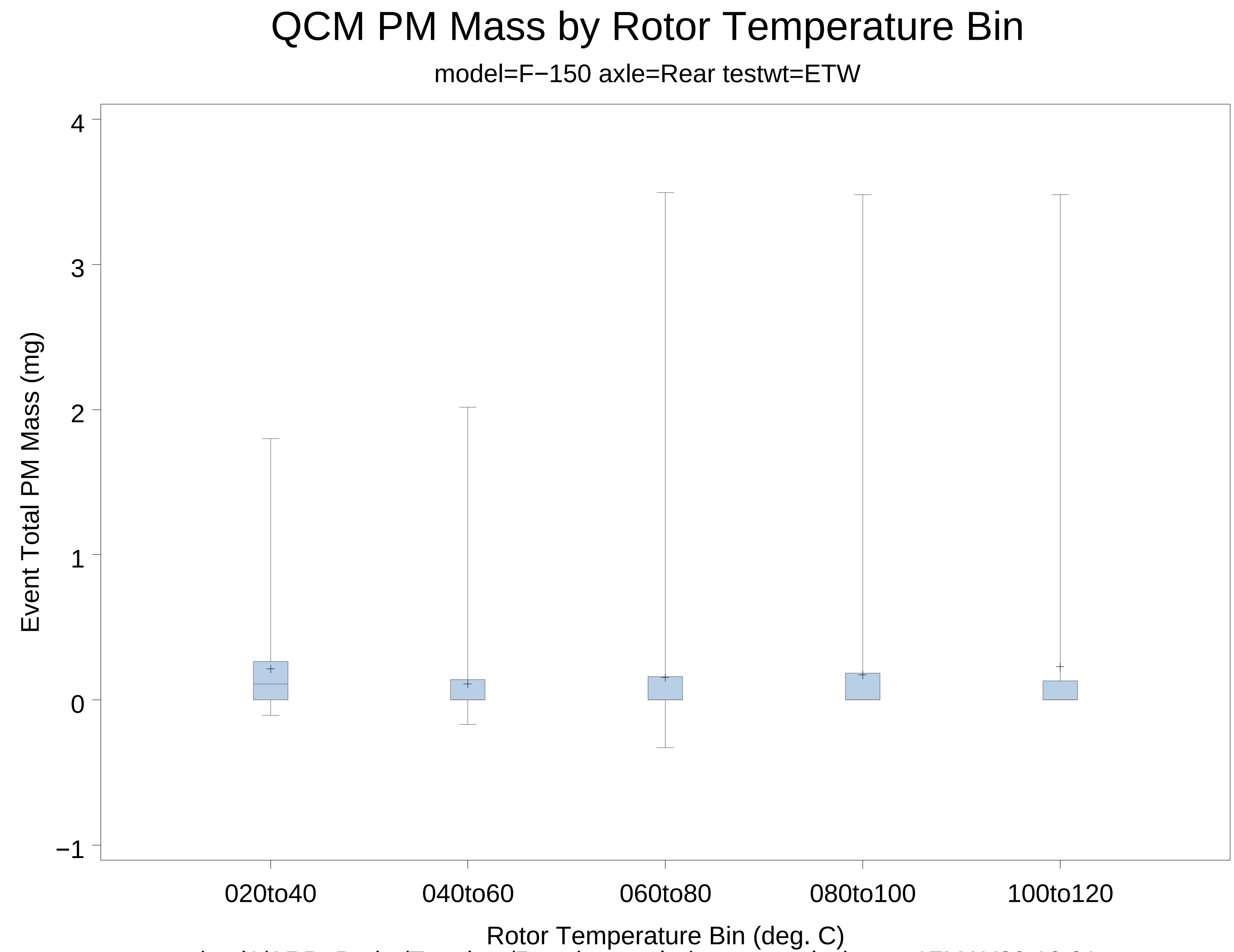
QCM PM Mass by Rotor Temperature Bin
model=F−150 axle=Front testwt=ETW
Event Total PM Mass (mg)
8
6
4
2
0
−2
020to40
040to60
060to80
080to100
100to120
120to140
140to160
160to180
180to200
Rotor Temperature Bin (deg. C)
/proj1/ARB−Brake/Testdata/Runningresults/event_analysis.sas 17MAY20 10:21

QCM PM Mass by Rotor Temperature Bin

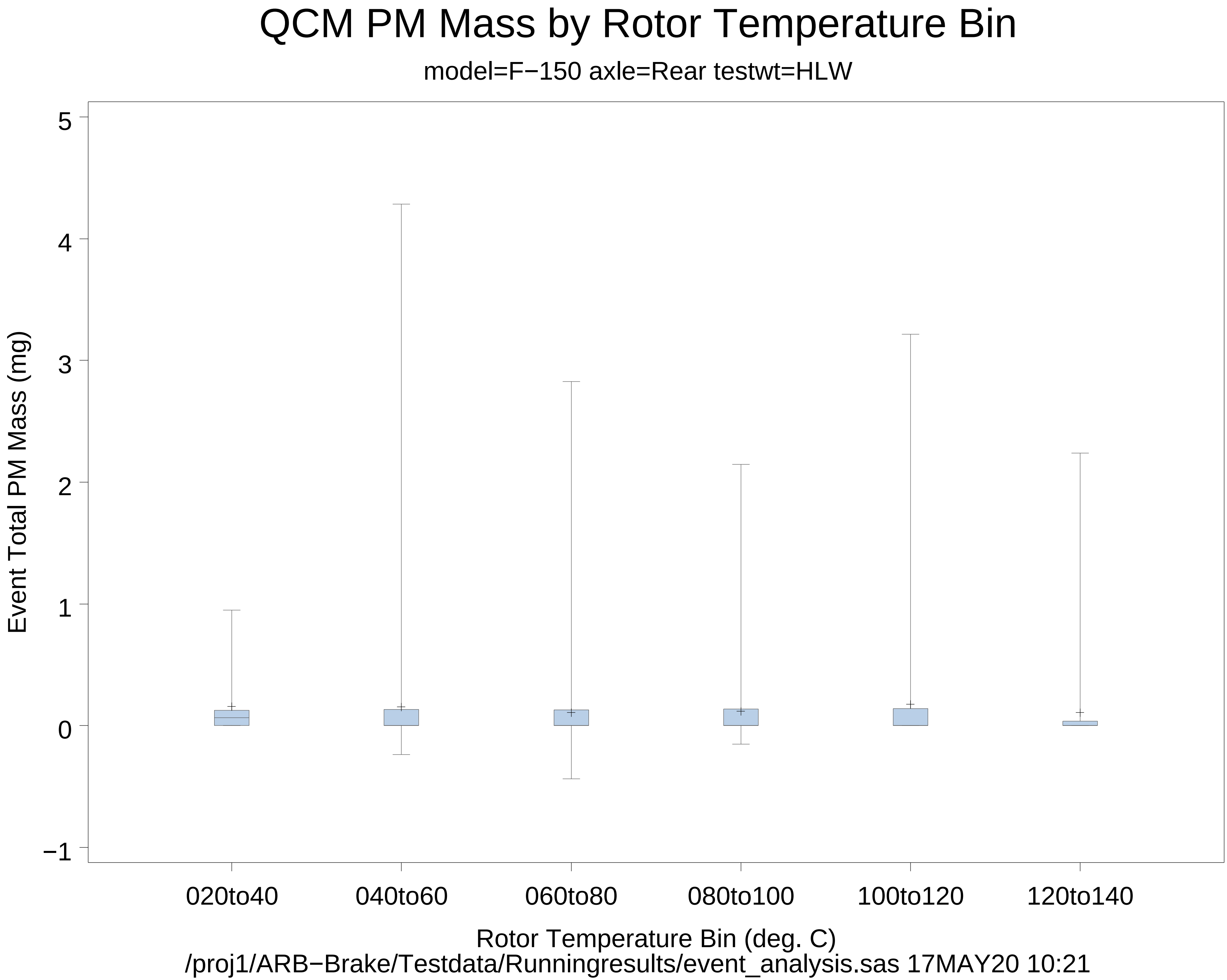
model=F−150 axle=Front testwt=HLW



/proj1/ARB−Brake/Testdata/Runningresults/event_analysis.sas 17MAY20 10:21

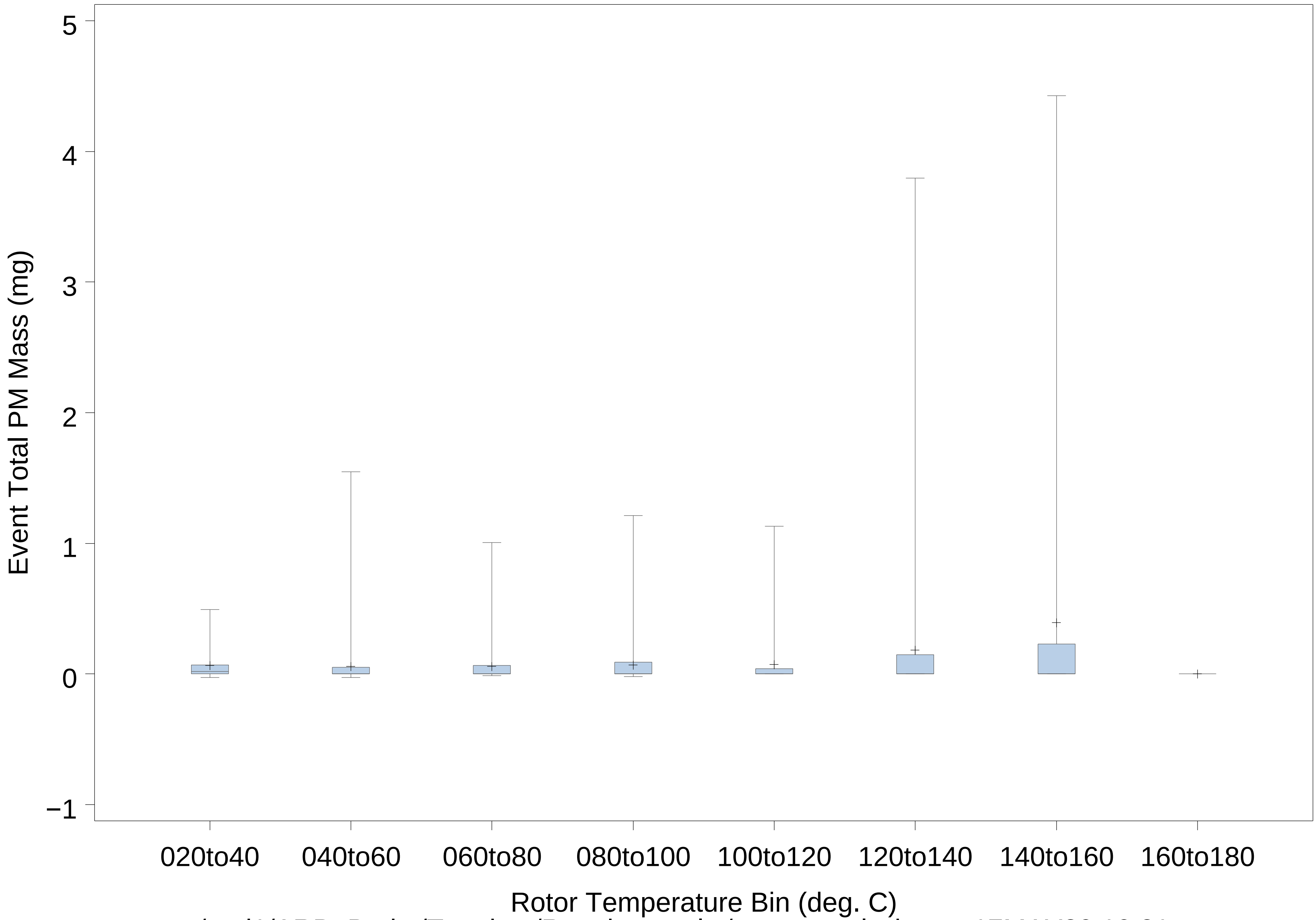


/proj1/ARB−Brake/Testdata/Runningresults/event_analysis.sas 17MAY20 10:21

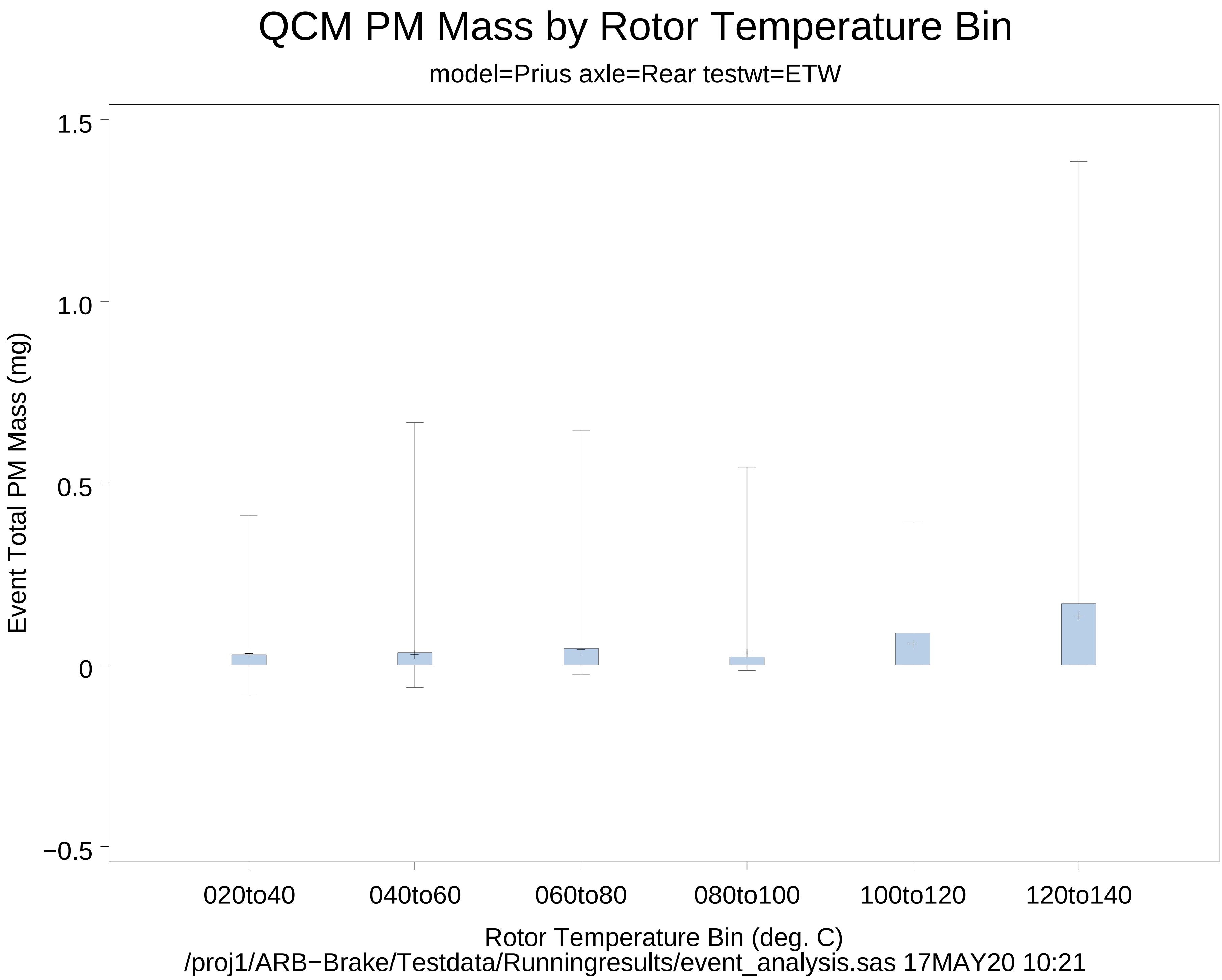

QCM PM Mass by Rotor Temperature Bin
model=F−150 axle=Rear testwt=HLW
Event Total PM Mass (mg)
5
4
3
2
1
0
−1
020to40
040to60
060to80
080to100
100to120
120to140
Rotor Temperature Bin (deg. C)
/proj1/ARB−Brake/Testdata/Runningresults/event_analysis.sas 17MAY20 10:21

QCM PM Mass by Rotor Temperature Bin

model=Prius axle=Front testwt=ETW



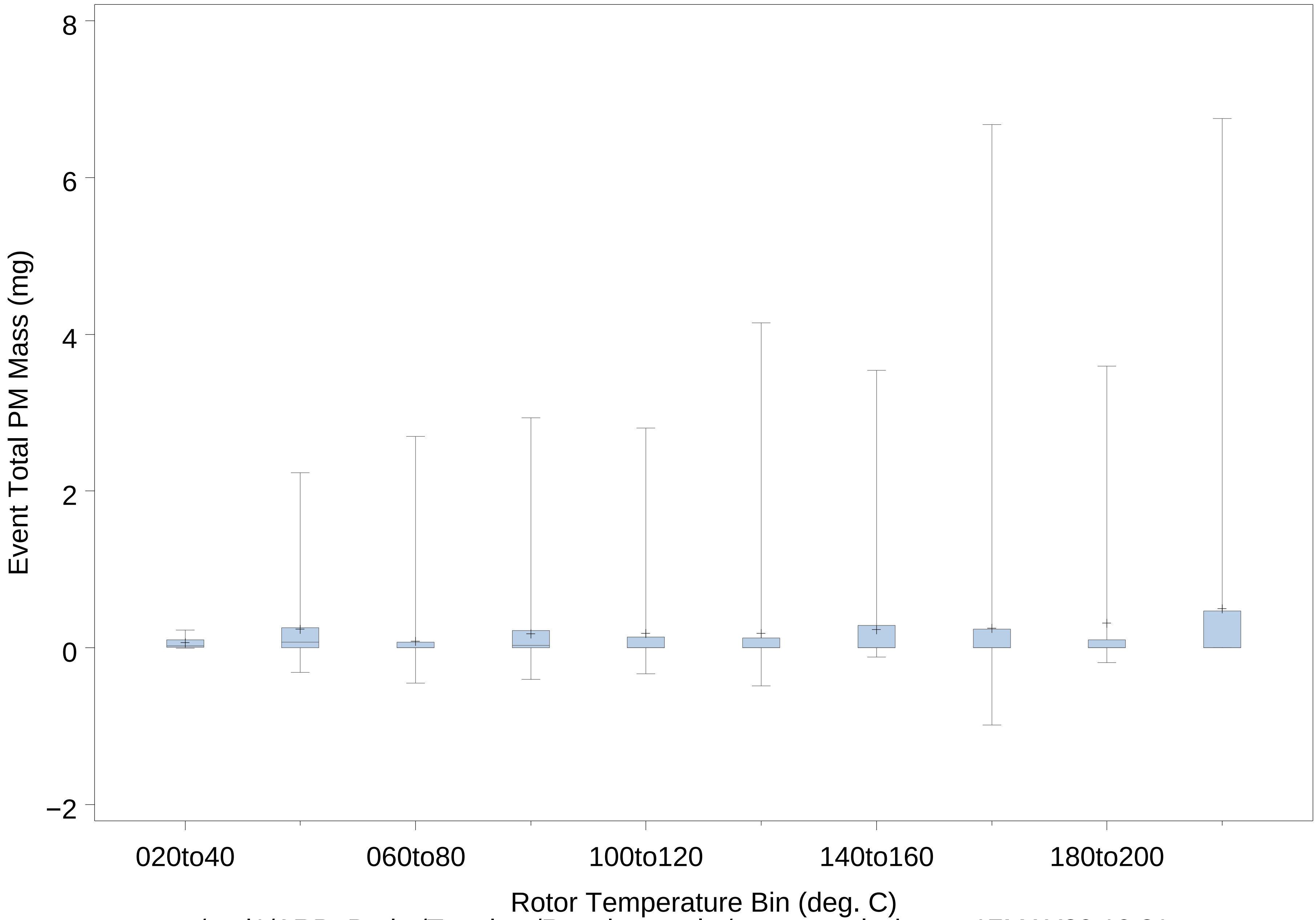
/proj1/ARB−Brake/Testdata/Runningresults/event_analysis.sas 17MAY20 10:21



QCM PM Mass by Rotor Temperature Bin
model=Prius axle=Rear testwt=ETW
Event Total PM Mass (mg)
1.5
1.0
0.5
0
−0.5
020to40
040to60
060to80
080to100
100to120
120to140
Rotor Temperature Bin (deg. C)
/proj1/ARB−Brake/Testdata/Runningresults/event_analysis.sas 17MAY20 10:21

QCM PM Mass by Rotor Temperature Bin

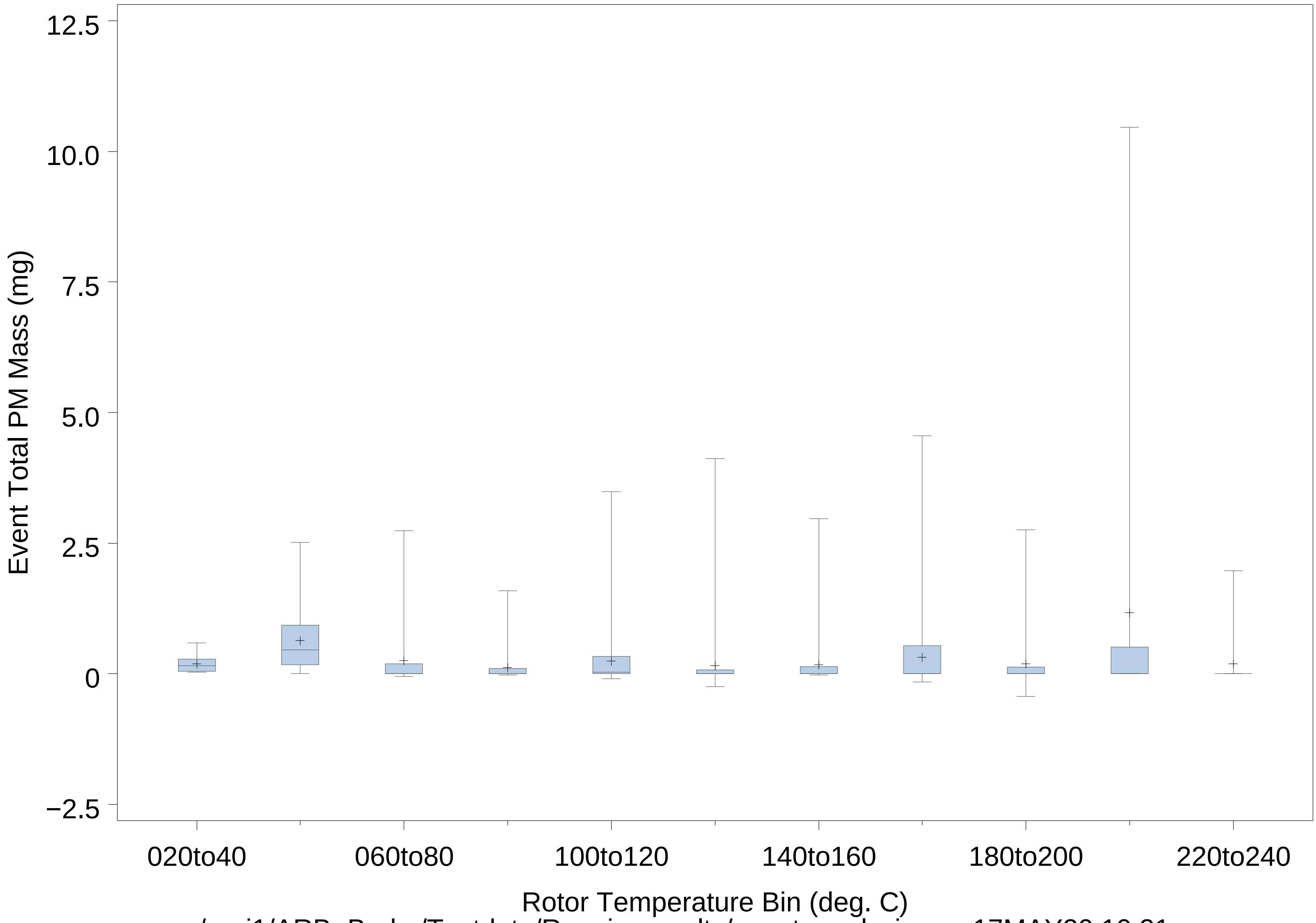
model=Rogue axle=Front testwt=ETW



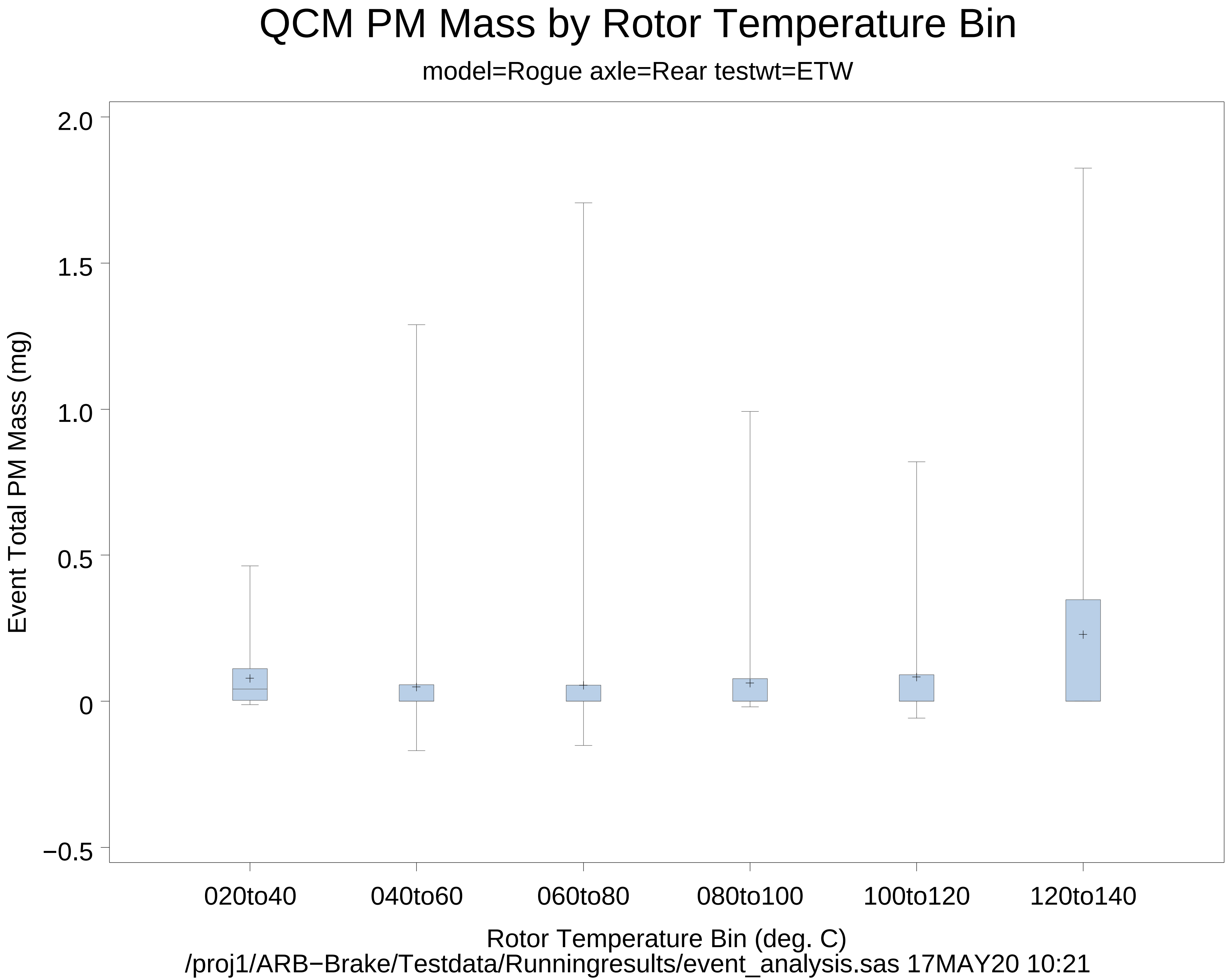
/proj1/ARB−Brake/Testdata/Runningresults/event_analysis.sas 17MAY20 10:21

QCM PM Mass by Rotor Temperature Bin

model=Rogue axle=Front testwt=HLW

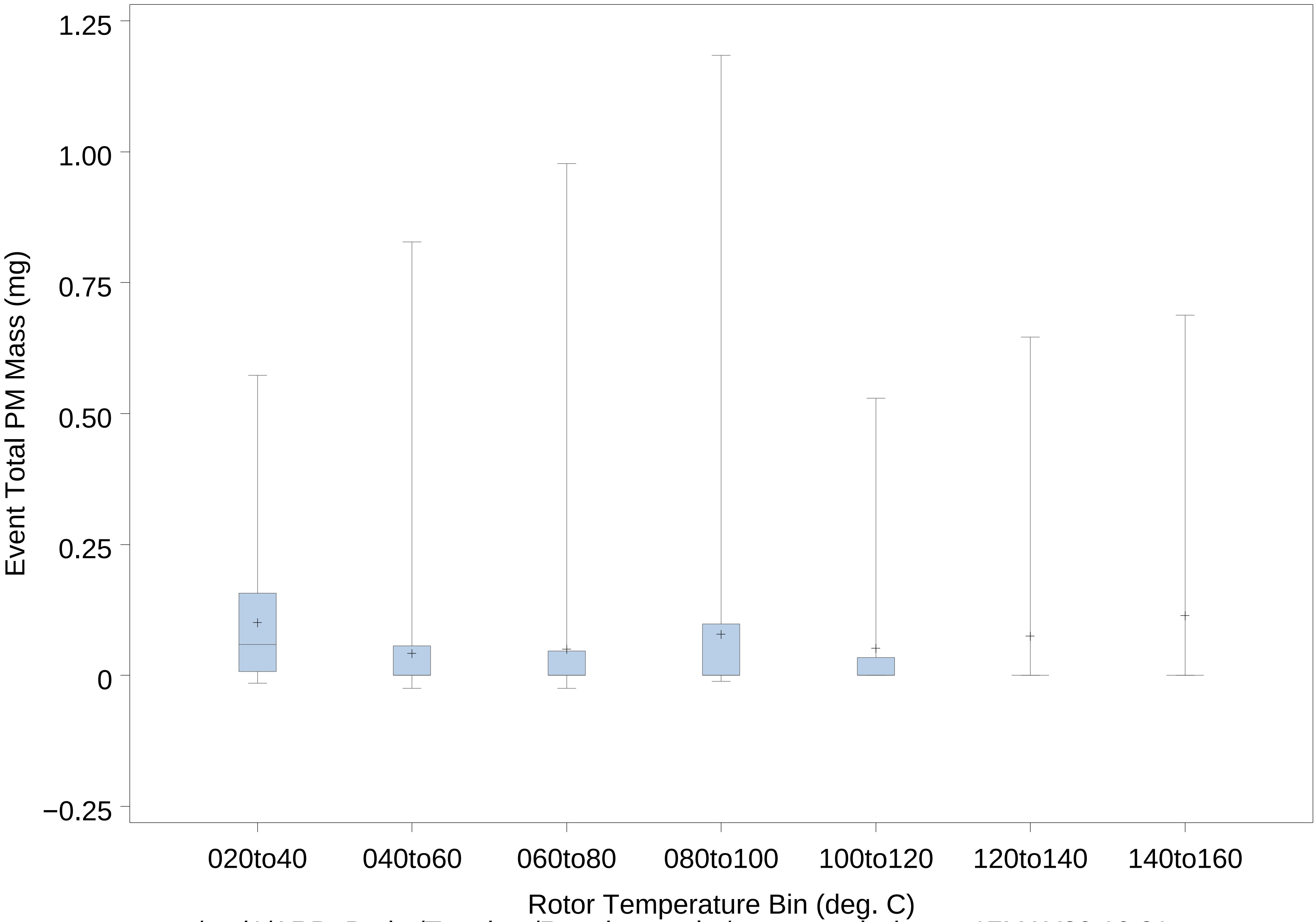


/proj1/ARB−Brake/Testdata/Runningresults/event_analysis.sas 17MAY20 10:21


QCM PM Mass by Rotor Temperature Bin
model=Rogue axle=Rear testwt=ETW
Event Total PM Mass (mg)
2.0
1.5
1.0
0.5
0
−0.5
020to40
040to60
060to80
080to100
100to120
120to140
Rotor Temperature Bin (deg. C)
/proj1/ARB−Brake/Testdata/Runningresults/event_analysis.sas 17MAY20 10:21

QCM PM Mass by Rotor Temperature Bin

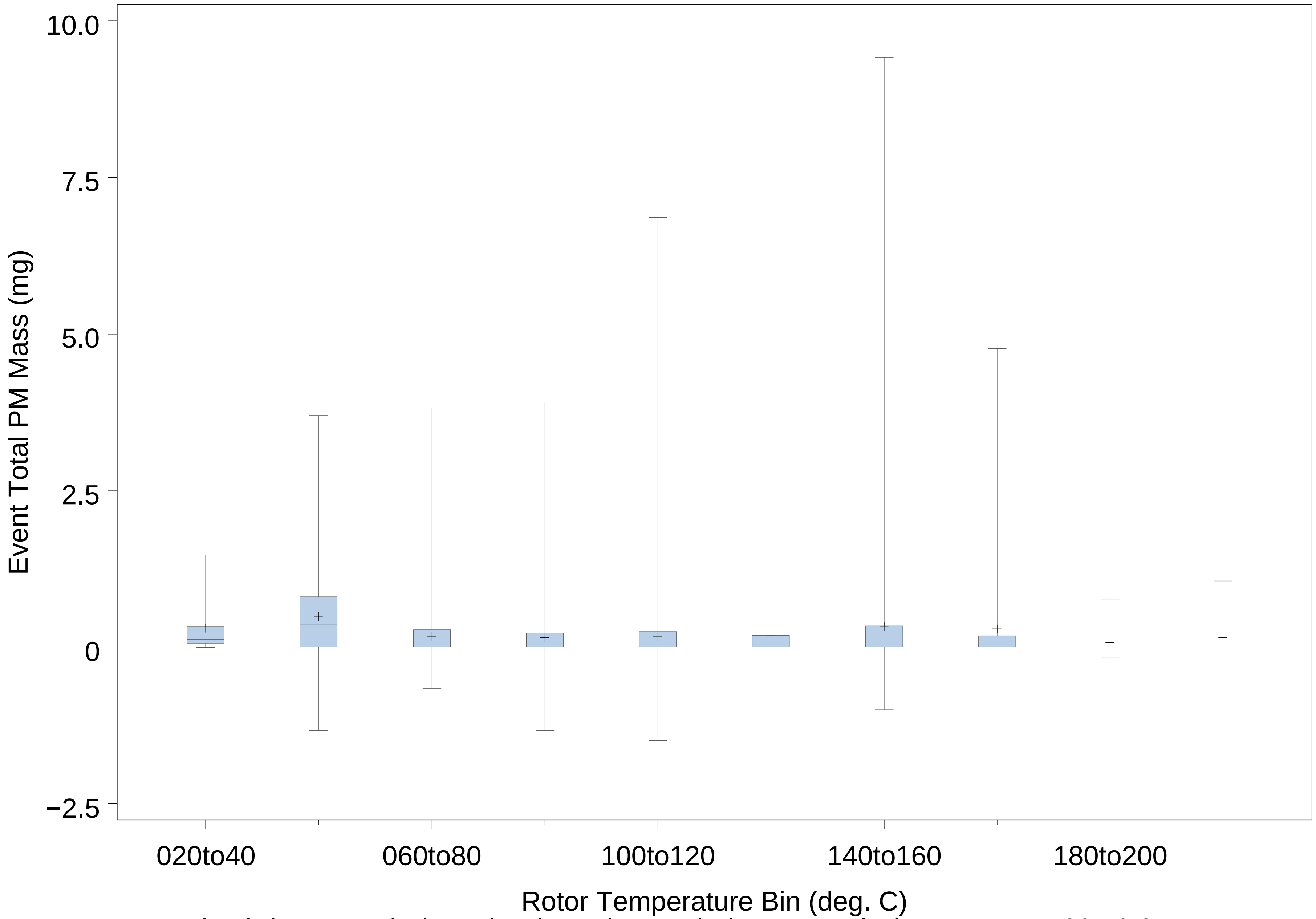
model=Rogue axle=Rear testwt=HLW



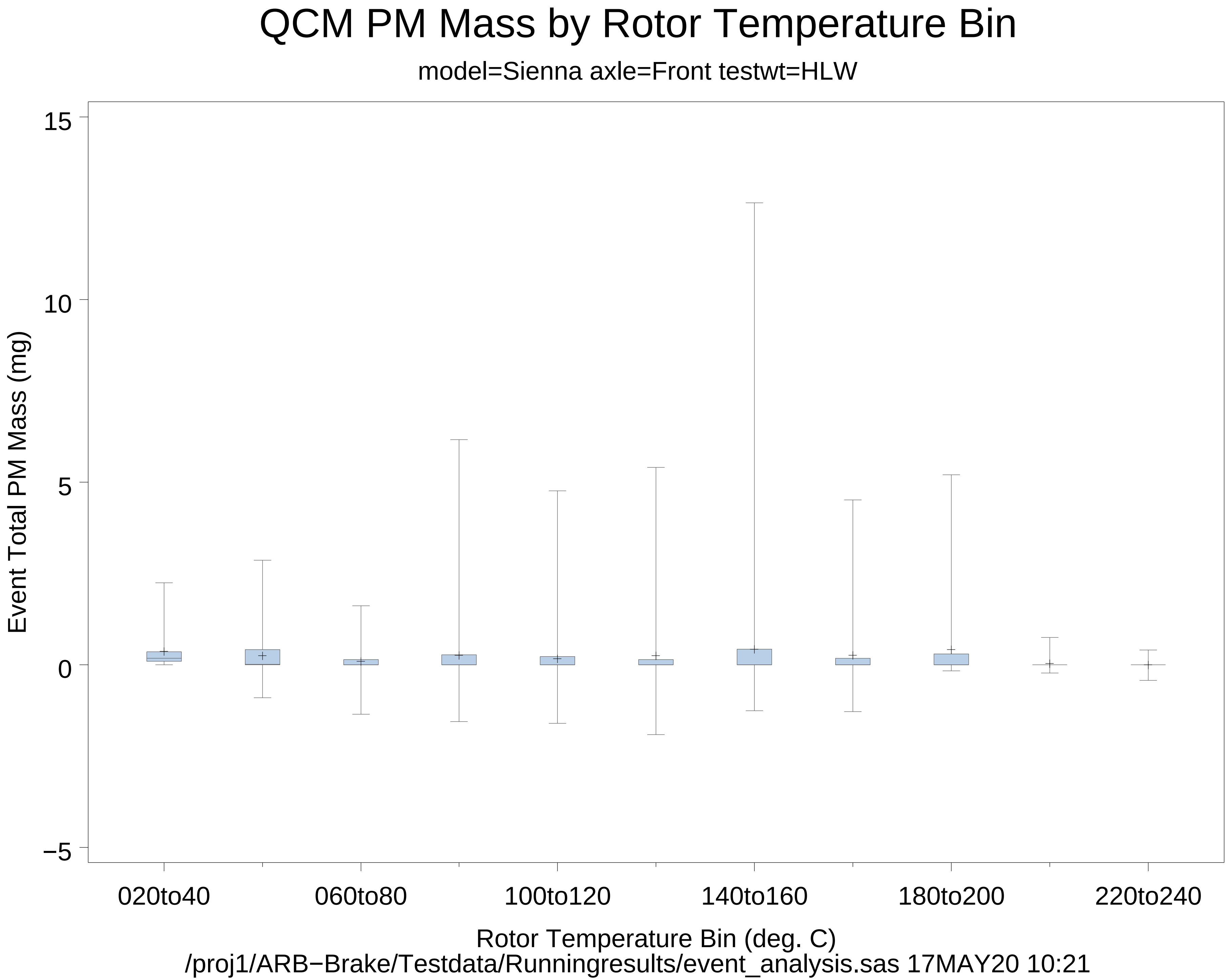
/proj1/ARB−Brake/Testdata/Runningresults/event_analysis.sas 17MAY20 10:21

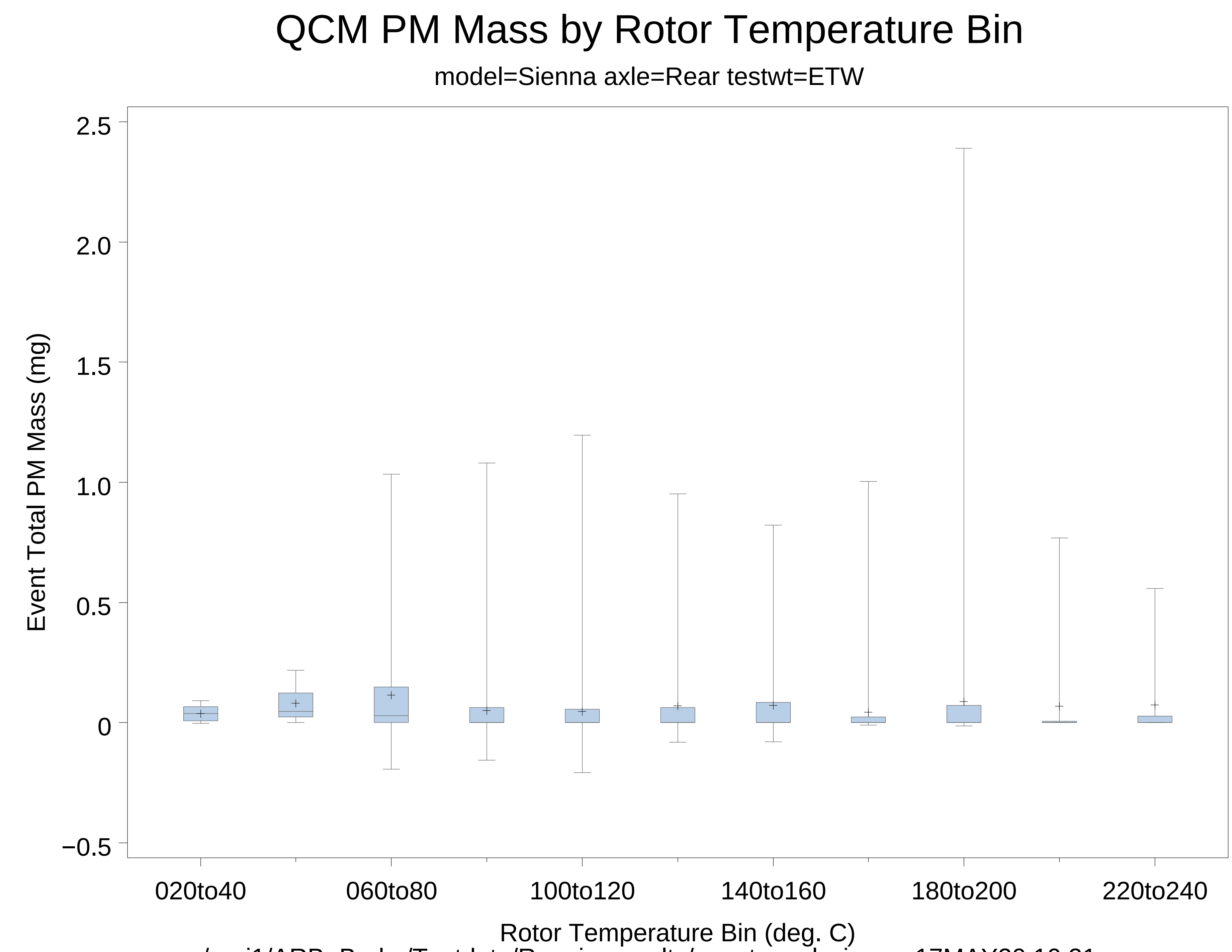
QCM PM Mass by Rotor Temperature Bin

model=Sienna axle=Front testwt=ETW



/proj1/ARB−Brake/Testdata/Runningresults/event_analysis.sas 17MAY20 10:21

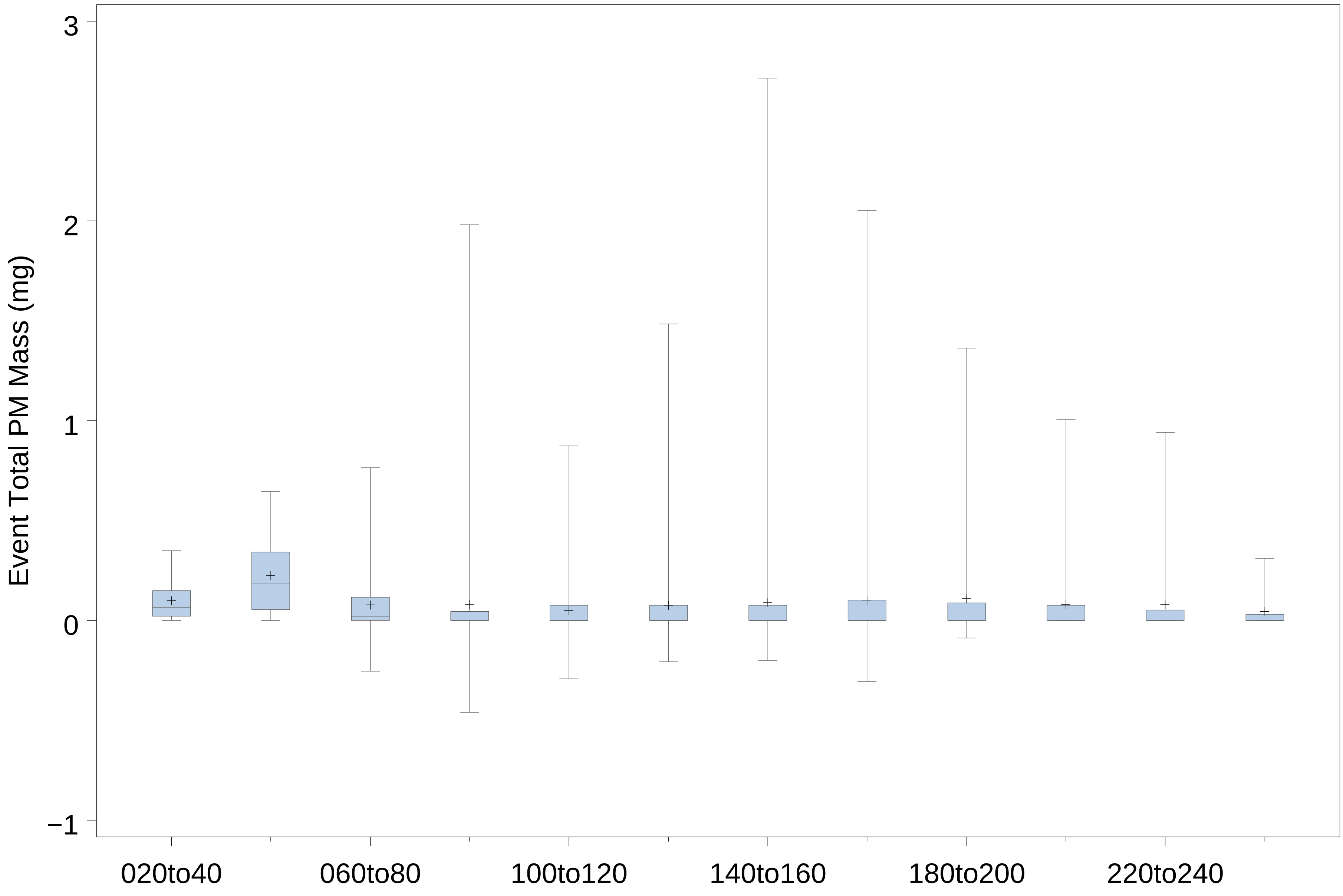

QCM PM Mass by Rotor Temperature Bin
model=Sienna axle=Front testwt=HLW
Event Total PM Mass (mg)
15
10
5
0
−5
020to40
060to80
100to120
140to160
180to200
220to240
Rotor Temperature Bin (deg. C)
/proj1/ARB−Brake/Testdata/Runningresults/event_analysis.sas 17MAY20 10:21



/proj1/ARB−Brake/Testdata/Runningresults/event_analysis.sas 17MAY20 10:21

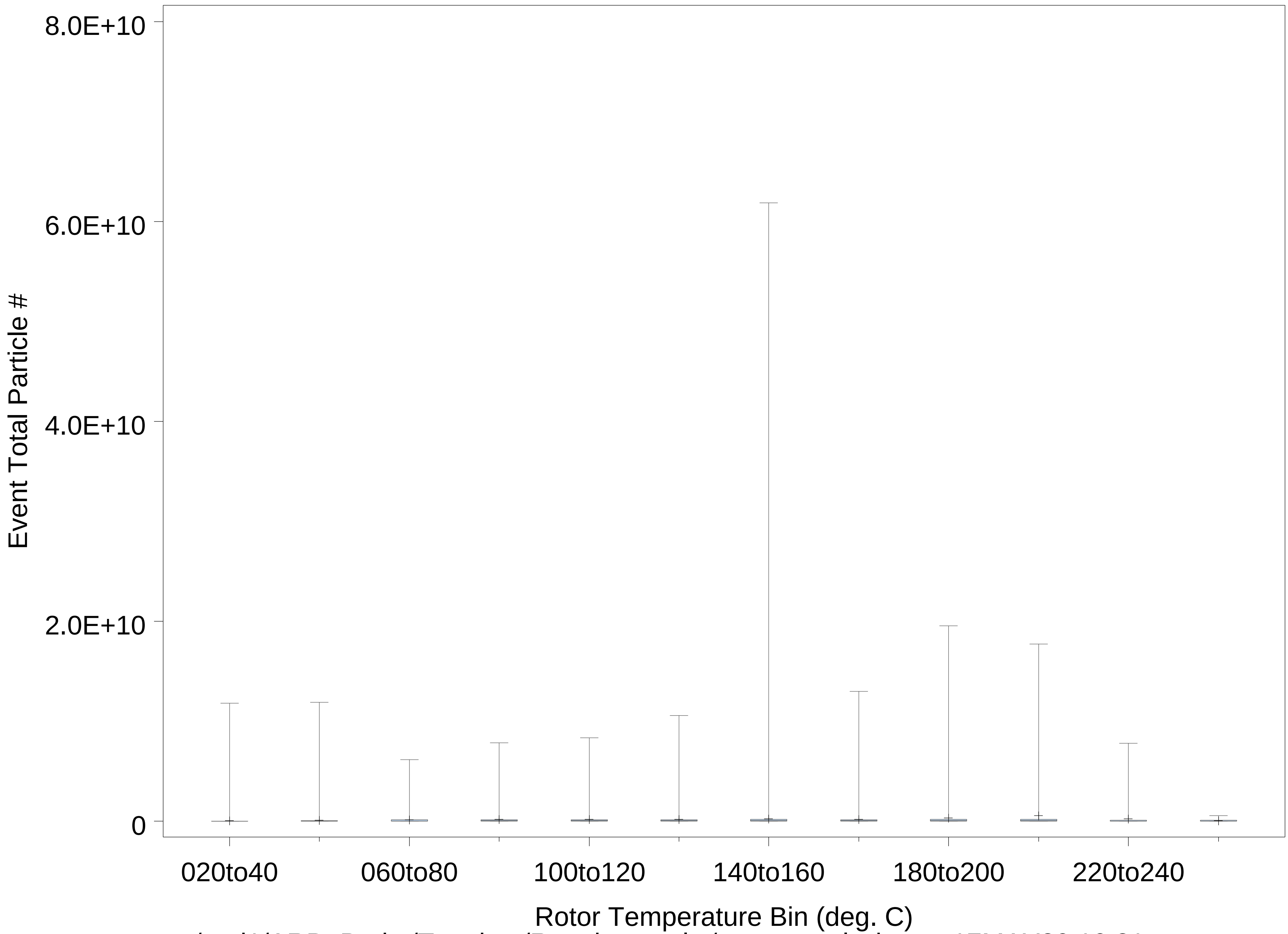
QCM PM Mass by Rotor Temperature Bin

model=Sienna axle=Rear testwt=HLW



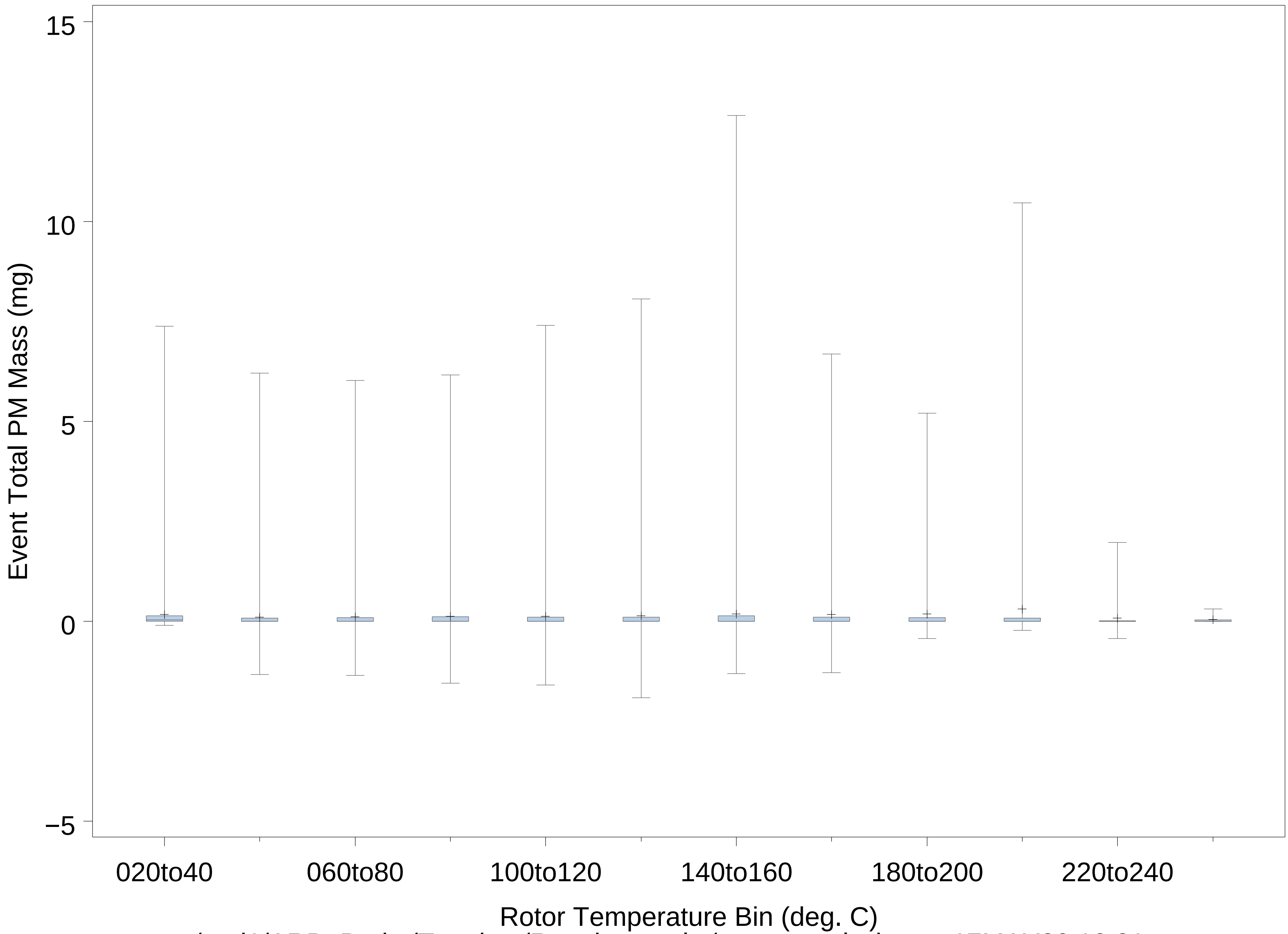
/proj1/ARB−Brake/Testdata/Runningresults/event_analysis.sas 17MAY20 10:21

Overall CPC Particle # by Rotor Temperature Bin



/proj1/ARB−Brake/Testdata/Runningresults/event_analysis.sas 17MAY20 10:21

Overall QCM PM Mass by Rotor Temperature Bin



/proj1/ARB−Brake/Testdata/Runningresults/event_analysis.sas 17MAY20 10:21

Appendix N

(Attached Spreadsheet file) California Brake Dynamometer Cycle Speed Trace

This Appendix consists of an attached spreadsheet file containing the second by second speed trace of the California Brake Dynamometer Cycle (CBDC). The file is a top-down data file with columns representing cycle time (seconds), the speed segment (by speed range in kph), the cycle speed trace (kph), the estimated brake temperature for the Camry test vehicle (degrees C above ambient), and the braking flag (1 = braking active). The braking flag indicates that the brakes are activated and deceleration is being caused by the test brakes. If a deceleration is taking place and the braking flag is not active, this is dynamometer-driven deceleration to set up for the next braking event which will start at a lower speed than the current speed. The brake dynamometer must be capable of having these “motored” decelerations to yield comparable results to the results in this study.