Cyber Blue – FRC 234
FRC Legal Motor Testing / Drive Systems
August - December, 2017

Background

For many years, most *FIRST* Robotics Competition (FRC) robots had standardized around a drive system that used four CIM Motors, which were available from multiple FRC-focused retailers. The Robot Rules allowed only four CIM Motors to be used on the robot, which led to this standardization. Commercial Off-The-Shelf (COTS) gearboxes had been developed to make it easier for teams to use these motors in their robots. These gearboxes came in many ratios, with multiple output shafts, and allowed for single-speed and two-speed drive systems.

In 2013, up to six CIM Motors were allowed on robots. A new motor, the VEXPro miniCIM was also introduced to FRC. Up to four miniCIMs were also allowed on the robot.

In 2015, the rules were changed to allow an unlimited number of miniCIMs on the robot. Up to six CIMs were still allowed.

In 2016, a new motor, the West Coast Products RS775Pro was introduced. An unlimited number of these motors were allowed on the robot.

These changes began a sort of arms-race in drive train design for FRC. Teams worked to get the maximum amount of power out of their robots, and the new motors and rules allowed for increased torque, and higher speeds with faster acceleration. This also allowed single-speed robots to add power to their drive trains, which meant the robot could be geared for a faster top speed and still be traction limited.

After the success of many top teams, including the 2014 World Championship performance by Team 254, many teams saw a more powerful drive train as a path to increased competitiveness. COTS gearboxes supporting three motors per drive side also provided more teams the ability to use these higher-power drive systems without the need to design and manufacture custom gearboxes.

In the fall of 2014, Team 234 performed a design of experiments based test comparing various drive train motor combinations. These results were posted to the FRC community via whitepaper (https://www.chiefdelphi.com/media/papers/3071).

In March 2017, Team 2451 posted a photo of their custom 775Pro drive gearbox. This gearbox used four motors, which allowed eight motors in the drive train. The lessons they learned and shared through the season, in addition to the success they had during the season, led to a flood of 775Pro powered drive train designs posted to Chief Delphi over the summer and fall of 2017.

In the summer of 2017, Team 234 decided to complete another Design of Experiments based test to add test-backed comparison data to the anecdotal data that was available. This testing included the 775Pro as a motor option for the drive train and took advantage of the increased data capture capability of the new FRC control system. All testing was completed by the students and mentors of FRC Team 234. This report summarizes the testing results. The full data set can be located at https://tinyurl.com/FRC234MotorTestData.

Test Objectives

The primary objective of the testing was to determine acceleration rates, top speeds, power consumption, and pushing performance of the following motor combinations in an FRC robot drive train: 2 CIM, 4 CIM, 6 CIM, 2 CIM + 4 miniCIM, 4 CIM + 2 miniCIM, 4 miniCIM, 6 miniCIM, 8 775Pro, 6 775Pro.

A secondary objective was to utilize the 775Pro drive train in an off-season event to gain “real world” experience with this type of drive using COTS components.

Testing Discipline

Test Methodology

The high-level test process goals were:

1. Build an FRC legal robot drive chassis and control system that could be easily adapted for each test.
2. Minimize the changes to the robot drive chassis for each variation of the test.
3. Follow a prescribed test sequence to minimize the test process impact on the results of the test
4. Document the test steps to allow others to duplicate the tests and compare results.

To accomplish this, the following steps were taken:

1. A 6-wheel drive robot chassis was built that allowed motors to be easily changed with minimal changes to the rest of the drive system.
2. A weight bin was added to the top of the robot to enable the total robot weight to be held within one pound from test to test. Test weight was approximately 135 lbs.
3. An autonomous program was written to run each test case to minimize human interaction.
4. Data recording parameters were identified for capture and recording

Managed Variables

The following parameters were managed with each test.

This list is variables that were held constant:

- Chassis system
- Wheels
- Gearboxes, Ratios
- Control System
- Weight distribution
- Chain to front and back wheels
- Test locations
- Encoder type, location

This list is variables that changed with each test:

- Motor count and type
- Exact overall robot weight
- Battery
- Date and Time

Test Configuration

A 6-wheel drive chassis was built from 1x1 and 1x2 aluminum tube. A West Coast Products 3 CIM WCD dog-shifting gearbox (P/N 217-3433) with a 2.92 spread and a 14-tooth input gear were used. The front and back wheels were chained with #25 chain to the center wheel. The wheels were black 4-inch AndyMark HiGrip wheels (P/N am-2256_blk).

An idler wheel was added to the center of the chassis to count actual distance travelled. This was done in case a motor configuration introduced slip between the drive wheels and the floor during acceleration and provides a true, consistent measure of robot travel.

Encoders (US Digital P/N S4-250-250-N-S-B) were attached to the front wheel on each side of the drive train and to the idler wheel.

To minimize changes to the gearbox set up, VEXPro VersaPlanetary gearboxes (P/N 217-4976) with a 3:1 ratio (P/N 217-2817) were used to adapt the 775Pro motors to similar output speeds, mounting, and output shafts to the CIM and miniCIM motor. To allow four 775Pro motors to be mounted to a gearbox made for three CIM motors, a VersaPlanetary Dual Motor Input (217-3141) was used to pair two 775Pro motors into one planetary gearbox.

A weight tray was added to the top of the robot. Since the only items being changed between tests were the motors, which are centered on the robot front-to-back, the weight tray was also centered front-to-back. This would allow the weight distribution changes to be minimized from test-to-test.

The robot was controlled with an FRC-legal control system based on the 2017 rules. Victor SP motor controllers (P/N 217-9090) set to brake mode were used to control the motors.

Autonomous code was used for all test points.

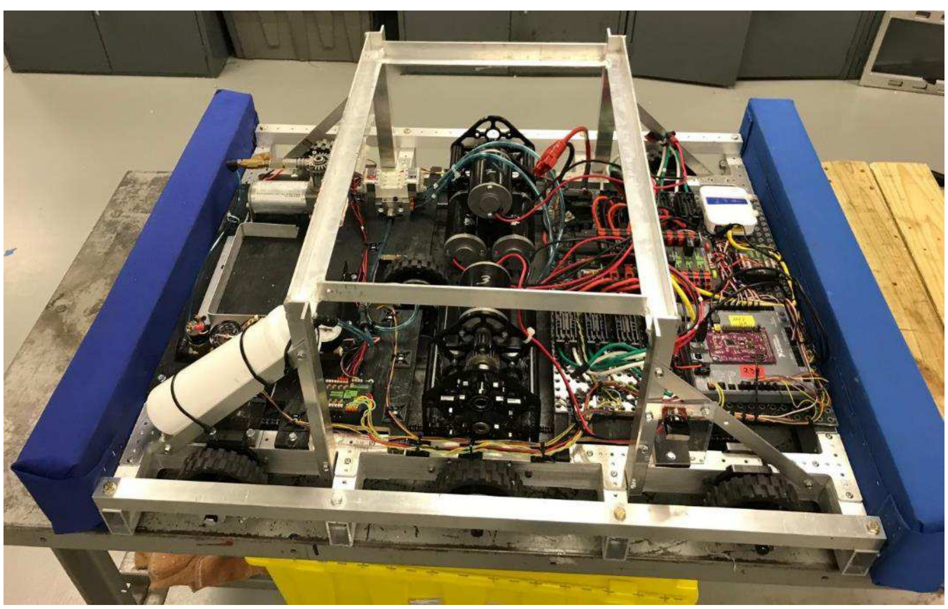


Figure 1 - Fully Assembled chassis with motors, gearboxes, idler wheel and controls. The weight tray fits into the aluminum structure and is removed for this picture.

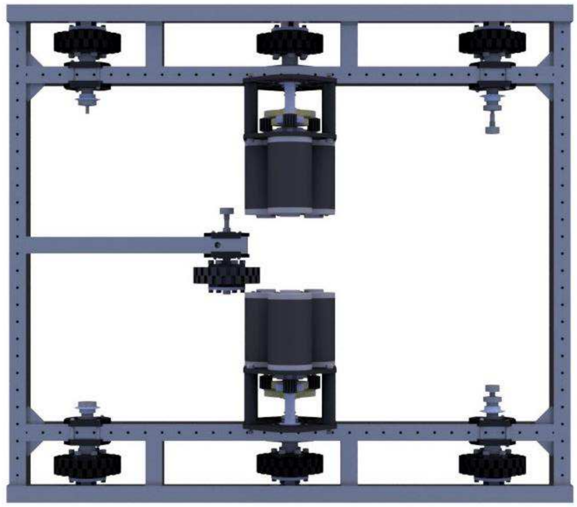


Figure 2 - Top View Render of Test Chassis with Idler Wheel Shown

Figure 3 - Ortho View of Test Chassis with Idler Wheel and Gearboxes Shown

Test Conduct and Data Recording

All tests were performed autonomously. Due to brownout conditions noticed during the tests conducted with 6 CIM motors, a short voltage ramp was added to the code so that the robot did not receive full power from the PWM immediately, but instead over a 250 ms time frame. This ramp was utilized in all tests except for the 4 CIM configuration.

Test configurations are shown in Table 1.

Table 1 – Motor Configurations

#	Config	# CIM	# miniCIM	# 775Pro	Notes
1	4 CIM	4			
2	6 CIM	6			
3	4C + 2M	4	2		
4	8 775 @80 6 775 @80			8	Used for Boiler Bot Battle (off-season event), not this testing
5	8 775 @80			8	Limited to 80% input voltage
6	6 775 @80			6	Limited to 80% input voltage
7	6 775 @100			6	Full Power
8	6 MINI		6		
9	4 MINI		4		
10	4M + 2C	2	4		
11	2M + 2C	2	2		
12	2 CIM	2			Only ran Test 2 for comparison purposes

Many FRC teams use the John V-Neun Design Calculator to estimate performance of robot drives and mechanisms. The estimated performance characteristics of each configuration are shown in Table 2.

Table 2 - Estimated Drive Train Performance

Config	Max Free Speed (ft/sec) High	Max True Speed (ft/sec) High	Max Free Speed (ft/sec) Low	Max True Speed (ft/sec) Low
4 CIM	22.2	18.0	7.6	6.2
6 CIM	22.2	18.0	7.6	6.2
4C + 2M	22.7	18.3	7.8	6.3
8 775 @80	20.8	16.9	7.1	5.8
6 775 @80	20.8	16.9	7.1	5.8
6 775 @100	26.0	21.0	8.9	7.2
6 MINI	24.3	19.7	8.3	6.7
4 MINI	24.3	19.7	8.3	6.7
4M + 2C	23.3	18.9	8.0	6.6
2M + 2C	23.0	18.6	7.9	6.4
2 CIM	22.2	18.0	7.6	6.2

In addition to performance information, weight and cost can be significant design factors for FRC teams. Table 3 shows an estimate of the weight and cost for each drive configuration. The reasonably astute observer will note that Team 2451 designed their own 775Pro gearbox, eliminating the need for the VersaPlanetary gearboxes. While outside the scope of this testing, this is an important distinction. Test system weight and cost includes motors, VersaPlanetary gearboxes (if needed), speed controllers, and pinion gears. A comparison plot of Power, Cost, and Weight is included at the end of this report.

Table 3 – Estimated Weight, Cost, and Power Info

Config	Test System Weight (lbs)	Test System Cost ($)	Available Power (W)
4 CIM	12.52	$384	1348
6 CIM	18.78	$576	2022
4C + 2M	17.5	$570	1778
8 775 @80	12.6	$1062	2221
6 775@80	10.14	$876	1666
6 775@100	10.14	$876	2082
6 MINI	14.94	$558	1290
4 MINI	9.96	$372	860
4M + 2C	16.2	$564	1534
2M + 2C	11.24	$378	1104
2 CIM	6.26	$192	674

Test Point Description

1. Run robot for 10 seconds “on blocks”. This test allows for a general system check to make sure all motors are working and system is performing as expected. This also allows for the robot’s theoretical maximum speed to be obtained.
2. Robot drives forward in high gear for 13,000 encoder counts (approximately 58.5 ft) and stops.
3. Robot drives forward for two seconds in low gear, then shifts to high gear. Total distance travelled is 13,000 encoder counts.
4. Robot drives forward in high gear for 13,000 encoder counts, stops, then travels backwards for the same distance.
5. Robot drives forward in low gear for 13,000 encoder counts (approximately 58.5 ft) and stops.
6. Robot drives forward in high gear for 10 ft, turns right 90 degrees, drives forward 10 ft, turns left 90 degrees (to face in the original “forward” direction), drives forward 10 ft and stops.
7. Robot pushes against a wall in high gear. Power to motors is ramped from 0% to 100% over 10 seconds.
8. Robot pushes against a wall in low gear. Power to motors is ramped from 0% to 100% over 10 seconds.

NOTE: 12,000 encoder counts = 50 feet

Results

This section contains general results from the tests. The data file naming convention used is C#T#, where C# corresponds to the Configuration number in Table 1 and T# is the test number from the Test Description. For Test 1, maximum speed was determined by taking an average of speeds recorded over the last half second (t=9.5 sec to t = 10 sec). For Tests 2-5, maximum speed was determined by taking an average of speeds recorded over the last half second of each 50-ft run. For Test 6, the last quarter second of each 10-ft run was averaged.

Detailed data is available -https://tinyurl.com/FRC234MotorTestData. Data Plots for Test 1, Test 2, Test 4 and Test 6 are included at the end of this report.

Minimum voltage is the minimum voltage recorded by the roboRIO during the test. The total energy calculation is calculated by multiplying the recorded battery voltage by the recorded total current at each recorded point, then multiplying that number by the time spent at that point, converted from milliseconds to seconds. Given as an equation, the Total Energy calculation is:

$$E_{TOTAL} = \sum_{i=1}^{N} I_i \times V_i \times \frac{(t_i - t_{i-1})}{1000}$$

Table 4 - Test 1 (Bench Top) Results

Config	Max Speed (cts/msec)	Max Speed (ft/sec)	Enc Cts @ 10 sec	Minimum Voltage (V)	Total Energy (J)
4 CIM	4.95	20.8	49228	8.8	2416
6 CIM	4.60	19.3	45752	6.7	3645
4C + 2M	4.57	19.2	44879	7.5	4555
8 775 @80	4.22	17.7	40755	10.6	5521
6 775@80	4.05	17.0	39361	11.2	4389
6 775@100	5.12	21.5	49749	10.4	6233
6 MINI	5.36	22.5	52860	11	2776
4 MINI	5.30	22.3	51842	11.6	2047
4M + 2C	4.96	20.8	48239	10.6	2775
2M + 2C	4.85	20.4	49095	11.4	2330

Table 5 - Test 2 (50 ft High Gear) Results

Config	Max Speed (ft/sec)	Time to End	Max Total Current	Max Avg Current	Min Voltage	Total Energy
4 CIM	17.5	3.88	266	66.5	7.3	3409
6 CIM	17.3	3.87	262	43.7	6.8	3574
4C + 2M	17.1	3.90	301	50.2	7.2	4212
8 775 @80	16.1	3.95	289	36.1	7.3	4133
6 775@80*	15.7	4.14	270	45.0	7.7	3787
6 775@100	19.7	3.66	341	56.7	7	4933
6 MINI	19.7	3.66	270	45.0	7.4	3581
4 MINI	18.7	3.89	184	46.0	8.7	2756
4M + 2C	18.6	3.73	264	44.0	7.7	3422
2M + 2C	17.6	3.97	206	51.5	8.8	3356
2 CIM	15.4	4.76	144	72.0	9.4	3316

*Data for this test was not downloaded, so the first 50 ft of C6T4 is used.

Table 6 - Test 3 (50 ft With Shift) Results

Config	Max Speed (ft/sec)	Time to End (s)	Max Total Current	Max Avg Current	Min Voltage	Total Energy
4 CIM	17.0	4.92	150	37.7	8.7	3042
6 CIM	17.0	4.90	181	30.2	8.6	3467
4C + 2M	16.8	4.94	176	29.4	8	4057
8 775 @80	16.0	5.15	167	20.8	9.4	4020
6 775@80	15.6	5.22	148	24.7	9	3783
6 775@100	18.2	4.70	207	34.5	8.2	4636
6 MINI	18.1	4.65	170	28.3	8.9	3335
4 MINI	17.6	4.75	149	37.3	10.1	3184
4M + 2C	18.1	4.73	159	26.5	9.4	3309
2M + 2C	17.1	4.90	135	67.5	9.7	2994

Table 7 - Test 4 (50 ft Down and Back) Results

Config	Max Speed (ft/sec)	Time to Stop	Time to Return	Max Total Current	Max Avg Current	Min Voltage	Total Energy
4 CIM	16.7	4.16	9.50	226	56.5	6.2	7637
6 CIM	17.3	3.96	9.22	241	40.2	5.7	7797
4C + 2M	17.2	3.90	8.98	286	47.7	5.9	9232
8 775 @80	16.0	4.04	9.16	291	36.4	5.9	9314
6 775@80	15.7	4.14	9.41	275	45.9	7.2	8970
6 775@100	19.3	3.66	8.51	307	51.2	5.1	11,980
6 MINI	18.8	3.74	8.62	273	45.5	6.7	8796
4 MINI	18.4	4.04	9.25	270	67.5	7.8	9399
4M + 2C	18.6	3.71	8.45	281	46.8	6.3	8267
2M + 2C	17.7	3.97	9.03	240	60.0	7.7	8114

Table 8 - Test 5 (50 ft Low Gear) Results

Config	Max Speed (ft/sec)	Time to End	Max Total Current	Max Avg Current	Min Voltage	Total Energy
4 CIM	6.7	8.1	145	36.1	8.4	2196
6 CIM	6.4	8.5	170	22.3	7.2	2993
4C + 2M	6.6	8.5	183	30.5	8.2	4486
8 775 @80	5.8	9.7	204	25.4	7.3	5662
6 775@80	5.8	9.6	192	32.0	9.7	4471
6 775@100	7.3	7.7	189	31.5	9.0	4677
6 MINI	7.4	7.6	127	21.2	9.8	2637
4 MINI	7.5	7.5	129	32.3	10.5	2057
4M + 2C	7.1	7.8	134	22.3	9.9	2793
2M + 2C	6.9	8.0	111	27.8	10.2	2189

Table 9 - Test 6 (10 ft Turns) Results

Config	Max Speed (ft/sec)	First 10 ft Time	Total Time	Max Total Current	Max Avg Current	Min Voltage	Total Energy
4 CIM	11.3	1.14	4.96	252	63.0	7.3	5674
6 CIM	11.6	1.18	5.06	215	35.9	7	5671
4C + 2M	11.8	1.10	4.86	276	45.5	7.1	6262
8 775 @80	11.2	1.04	5.42	295	36.9	6.9	7507
6 775@80	10.6	1.18	5.31	258	43.0	7.3	6593
6 775@100	11.4	1.13	6.63*	327	54.5	6	10,532
6 MINI	11.1	1.17	5.33	251	41.8	6.8	6451
4 MINI	10.4	1.32	5.51	205	51.3	8.9	6246
4M + 2C	11.5	1.17	5.41	257	42.8	7.2	6703
2M + 2C	10.8	1.27	5.37	219	54.8	8.2	6043

*Robot experienced brown-outs during test

Table 10 - Test 7 (Wall Push High Gear) Results

Config	Wheel Slip?	PWM value for Slip	Total Current at End	Current per Motor at End
4 CIM	No	N/A	251	62.65
6 CIM	Yes	0.9	158	31.6
4C + 2M	No	N/A	286	47.6
8 775 @80	Yes	0.75	207	25.8
6 775@80	No	N/A	252	42.0
6 775@100	Yes	0.82	100	16.7
6 MINI	No	N/A	255	42.5
4 MINI	No	N/A	231	57.8
4M + 2C	No	N/A	249	41.5
2M + 2C	No	N/A	234	58.5

Table 11 - Test 8 (Wall Push Low Gear) Results

Config	Wheel Slip?	PWM value for Slip	Total Current at End	Current per Motor at End
4 CIM	Yes	0.45	105	26.3
6 CIM	Yes	0.34	108	18.0
4C + 2M	Yes	0.32	114	19.0
8 775 @80	Yes	0.26	96	12.0
6 775@80	Yes	0.30	89	14.9
6 775@100	Yes	0.26	105	17.4
6 MINI	Yes	0.30	105	17.4
4 MINI	Yes	0.39	101	25.3
4M + 2C	Yes	0.30	76	12.7
2M + 2C	Yes	0.40	78	19.5

Summary

Conclusions

Except for the 2 CIM configuration, each configuration tested can be the basis for a suitable drive for an FRC robot. Any of the configurations tested can be created with COTS components.

Except for the voltage limiting for the 775 motors and the acceleration ramp rate, no significant control / software modifications were required to provide a suitable drive solution. These rates were based on human testing and not specifically optimized for any motor combination.

Except for the 2 CIM configuration, there was minimal difference in acceleration, top speed and total time for the 50 foot runs compared to expected speeds based on motor performance data. The configurations that used the 775Pro motors often used more energy to accomplish each test.

Tests did not show a significant amount of slip during initial acceleration from a stop, especially once the realistic ramp was added. There was slip around robot direction (forward to reverse) and orientation (turning right and left).

With the 6 CIM, 6 775Pro and 8 775Pro configurations, the quick stop / return created a brown out condition and caused erratic behavior as the control recovered (all was autonomous and the stop/return was in 1 cycle). A voltage ramp of 0-100% over 250 ms solved this problem.

The performance of the 775 configurations may be negatively impacted by the test set up used (3:1 VersaPlanetary gearboxes). The VPs reduced the efficiency of this configuration, however we believe it was minimal. The goal was to use a configuration that could be duplicated with COTS parts.

Competition Performance

In the middle of the testing sequence, the test robot was modified to compete in an off-season event. A gear collector and climbing winch was installed (almost identical to our competition robot) for the competition. The total robot weight (including batteries and bumpers) was approximately 110 lbs. The 8 x 775 drive was used for this competition. Not all motors were used in every match.

A total of 12 matches were played, and the robot was driven and operated in the same manner as our competition robot. The robot was subjected to heavy defense, pushing, pusher, aggressive play, and rope climbs.

The first match was played with only 6 motors powered, and capped at 80% voltage input. The second match was played with all 8 powered and capped at 80%. The driver noted significant issues with driving related to brown outs in this match, though the robot radio or roboRIO never rebooted. Following that match, all subsequent matches were played with only 6 motors. The driver did not complain of any issues, though review of the Driver Station logs shows occasional brown outs.

To maintain consistency in the testing, the robot configuration of controls, pneumatics, battery and weight tray locations were documented with photos and the robot was rebuilt so that the pre- and post-competition configurations were the same.

Next Steps

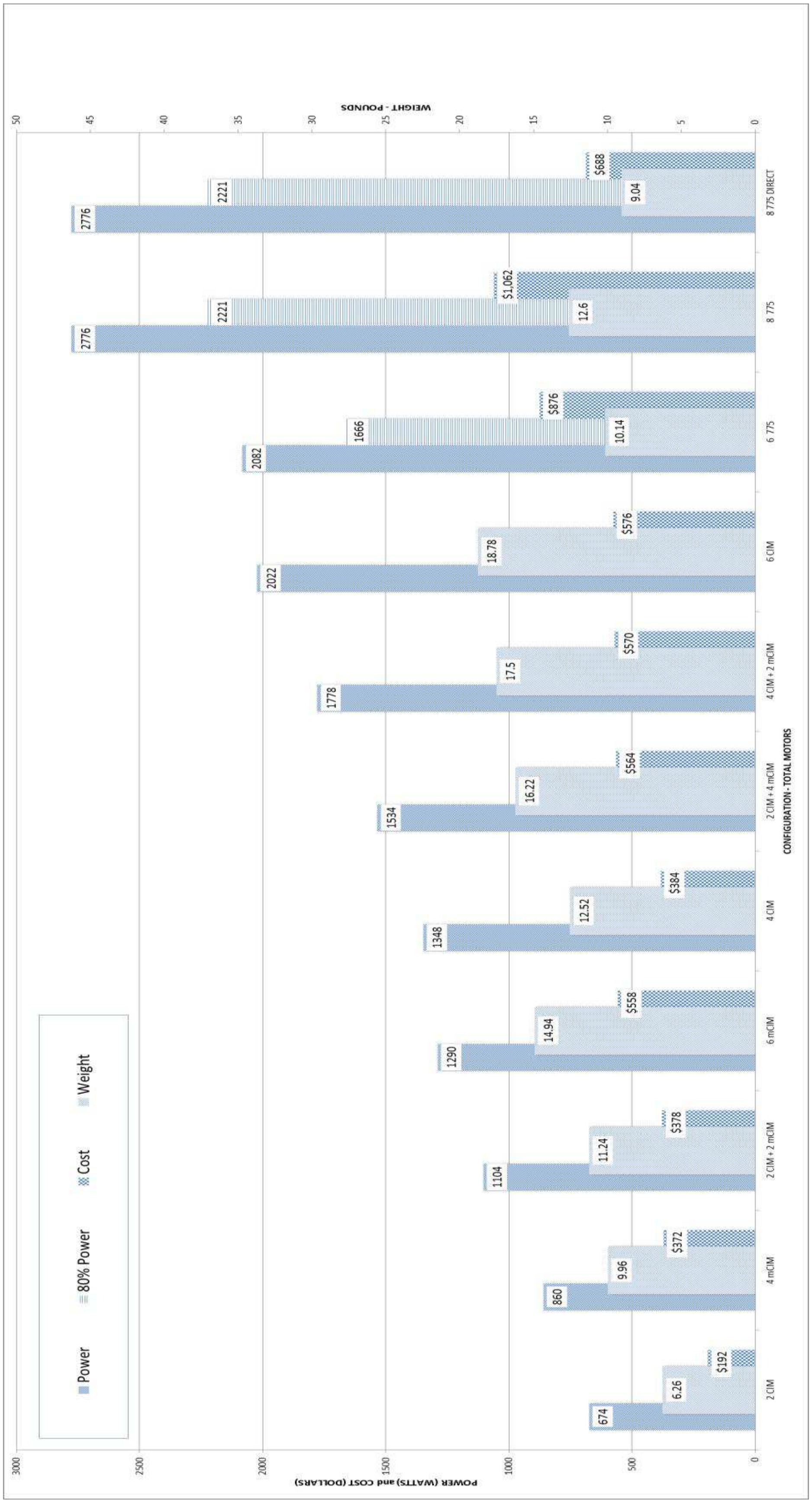
This series of tests has provided a significant level of performance data for multiple motor products and combinations. As with many test programs, it has also created new questions to be resolved.

Some potential follow-on testing could include:

- Optimization of initial acceleration to reduce wheel slip and determine if a faster actual acceleration can be achieved.
- Optimization of an auto shift point to determine if a faster actual acceleration can be achieved.
- Optimization of the 775Pro configuration power limiting and / other control logic to enable more usable power of the motor.
- Peer review of the data and summary points for other insights, verification and validation.
- Testing with gearbox specifically designed for a 775-style motor to evaluate the impact of the additional 3:1 planetary reduction on performance.
- Optimization of the 6 CIM configuration power limiting, acceleration ramps of other control logic.
- These tests were often done back-to-back, and included some driving between tests (e.g. driving back to starting line), however none of them tested the motors over an extended period. A next step could be to create a test methodology to compare motors in a single match, multi-match, and "event" scenarios.

Acknowledgements

This testing would not have been financially possible without the support of donated product from VEX Robotics. VEX Robotics donated the motors and gearboxes used for the testing, and reviewed the original test plan. This donation was based on an agreement that the results and data would be shared with the FRC community. Once testing began, the VEX team was “hands off” and had no input or influence on the test data or final results.


Power
80% Power
Cost
Weight
POWER (WATTS) and COST (DOLLARS)
WEIGHT - POUNDS
CONFIGURATION - TOTAL MOTORS
2 CIM
674
6.26
$192
4 mCIM
860
9.96
$372
2 CIM + 2 mCIM
1104
11.24
$378
6 mCIM
1290
14.94
$558
4 CIM
1348
12.52
$384
2 CIM + 4 mCIM
1534
16.22
$564
4 CIM + 2 mCIM
1778
17.5
$570
6 CIM
2022
18.78
$576
6 775
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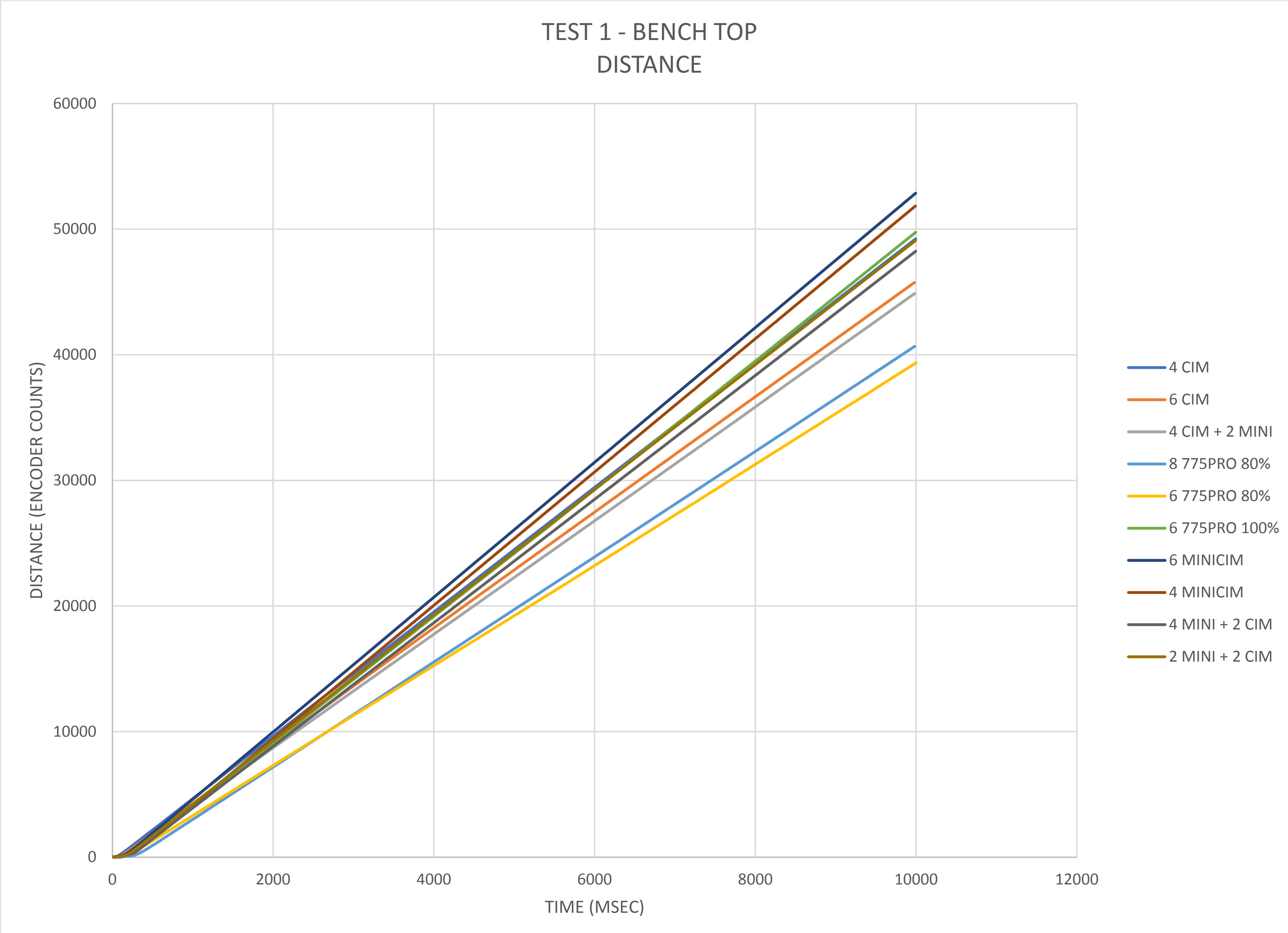
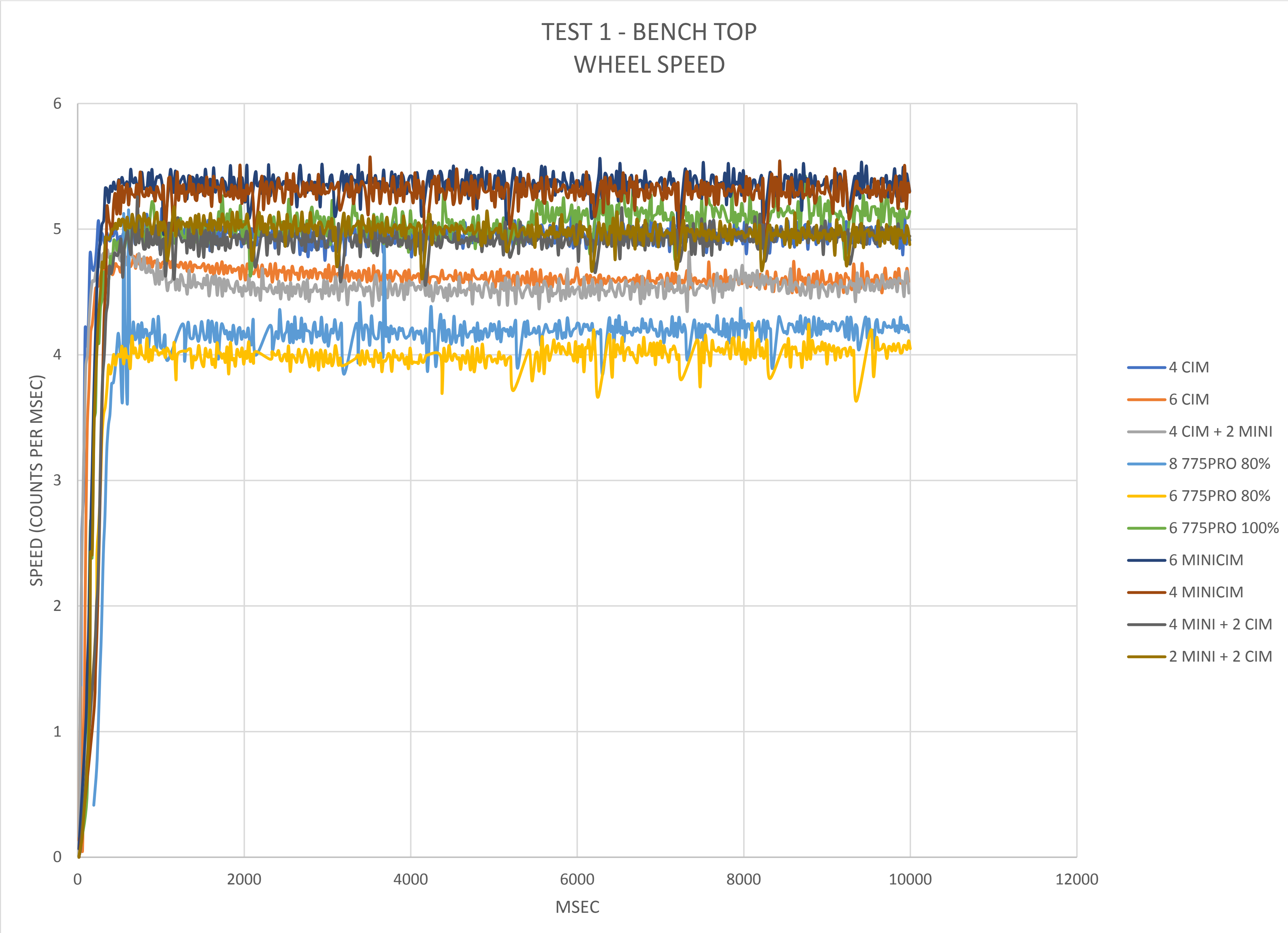
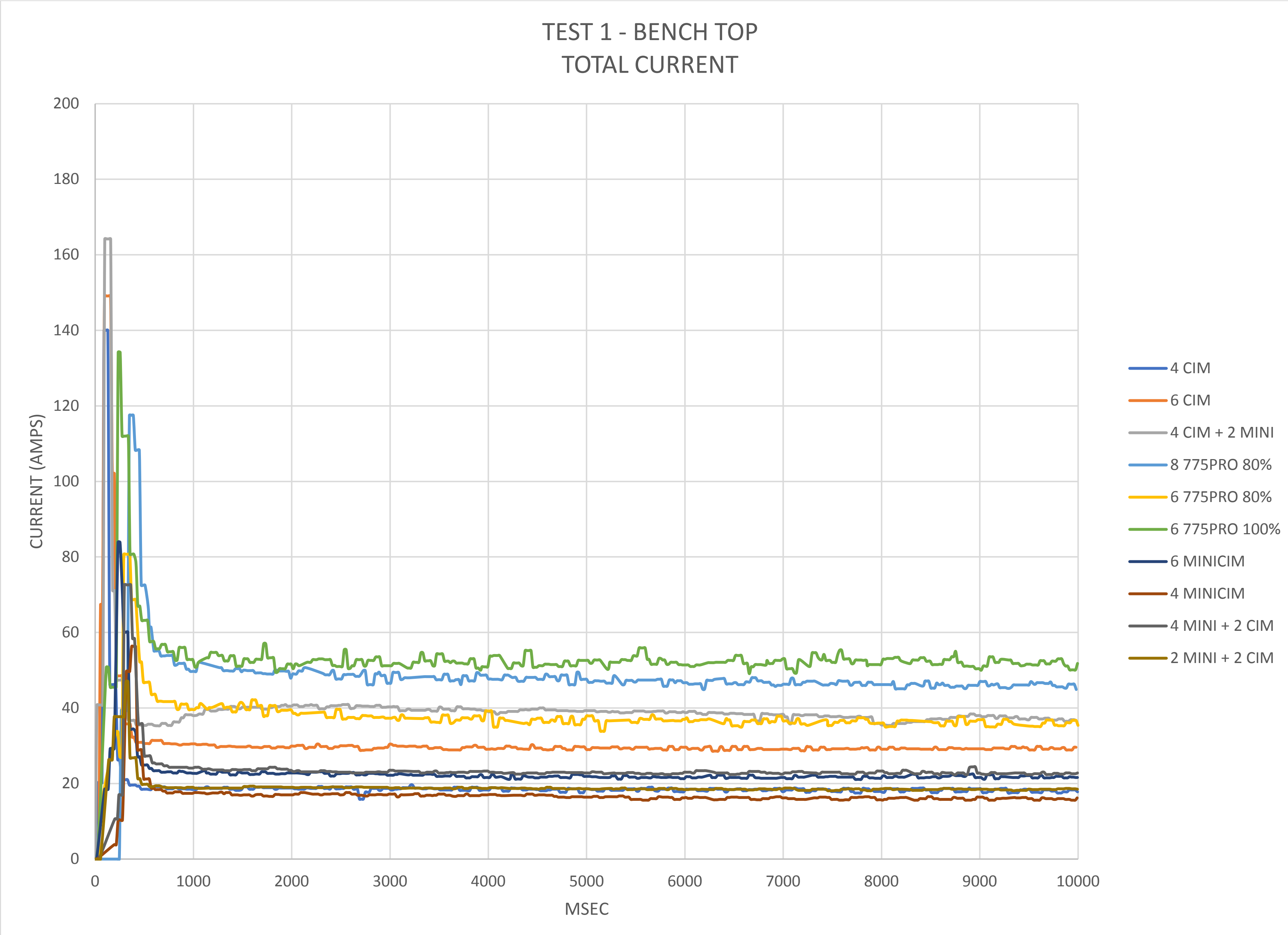

TEST 1 - BENCH TOP
DISTANCE
DISTANCE (ENCODER COUNTS)
60000
50000
40000
30000
20000
10000
0
0
2000
4000
6000
8000
10000
12000
TIME (MSEC)
4 CIM
6 CIM
4 CIM + 2 MINI
8 775PRO 80%
6 775PRO 80%
6 775PRO 100%
6 MINICIM
4 MINICIM
4 MINI + 2 CIM
2 MINI + 2 CIM



TEST 1 - BENCH TOP
WHEEL SPEED
SPEED (COUNTS PER MSEC)
MSEC
0
1
2
3
4
5
6
0
2000
4000
6000
8000
10000
12000
4 CIM
6 CIM
4 CIM + 2 MINI
8 775PRO 80%
6 775PRO 80%
6 775PRO 100%
6 MINICIM
4 MINICIM
4 MINI + 2 CIM
2 MINI + 2 CIM


TEST 1 - BENCH TOP
TOTAL CURRENT
CURRENT (AMPS)
200
180
160
140
120
100
80
60
40
20
0
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
MSEC
4 CIM
6 CIM
4 CIM + 2 MINI
8 775PRO 80%
6 775PRO 80%
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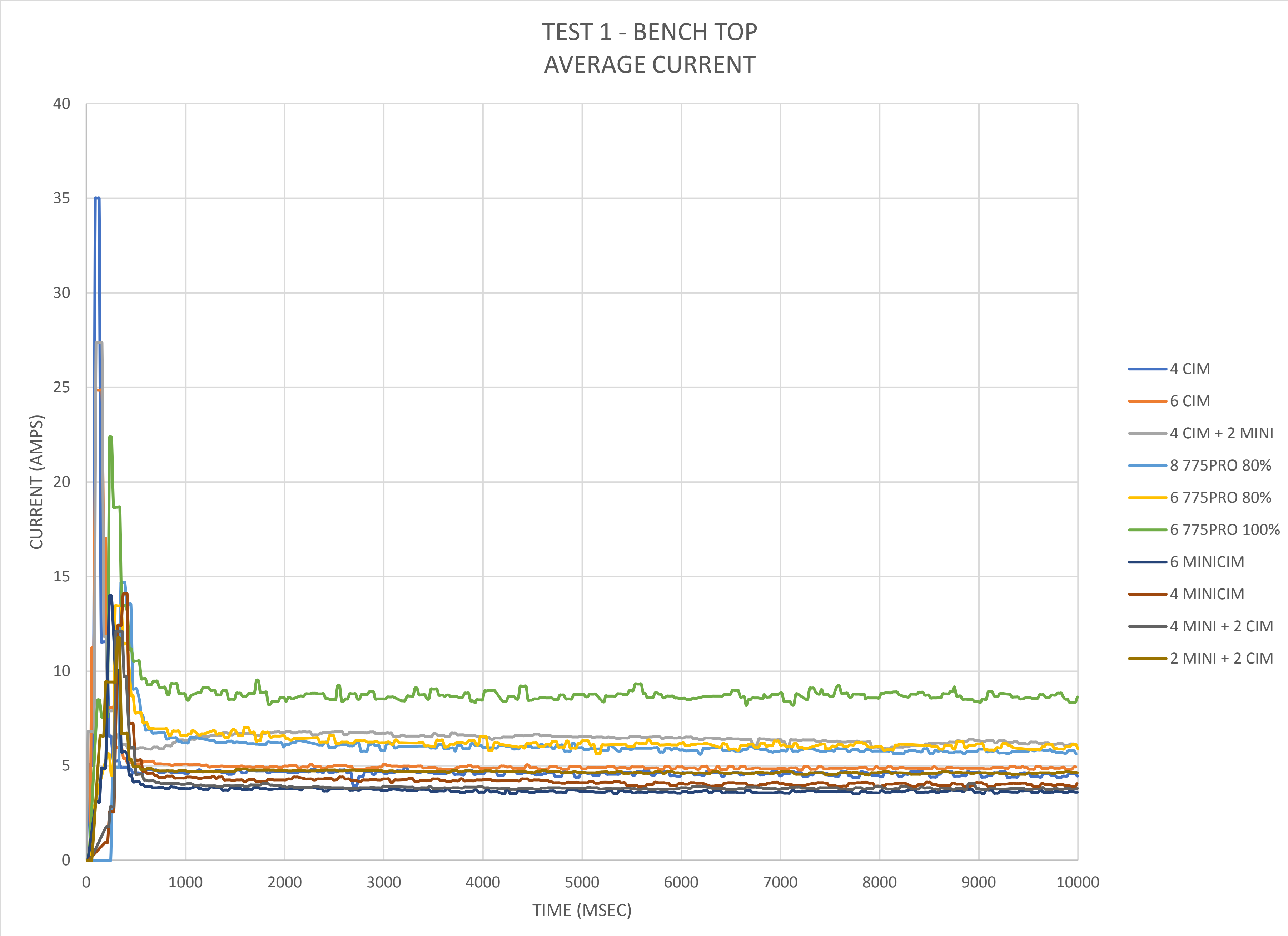
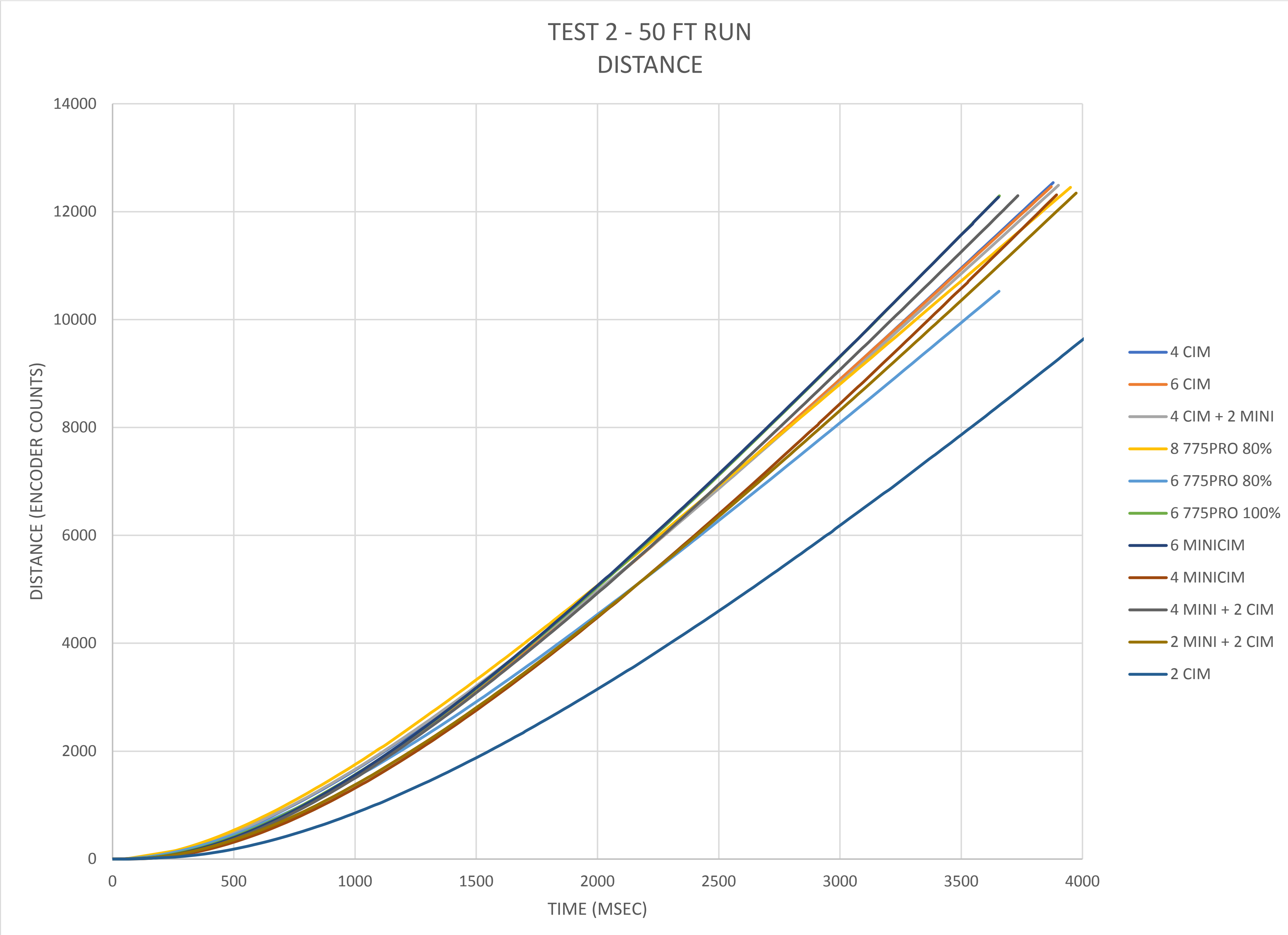
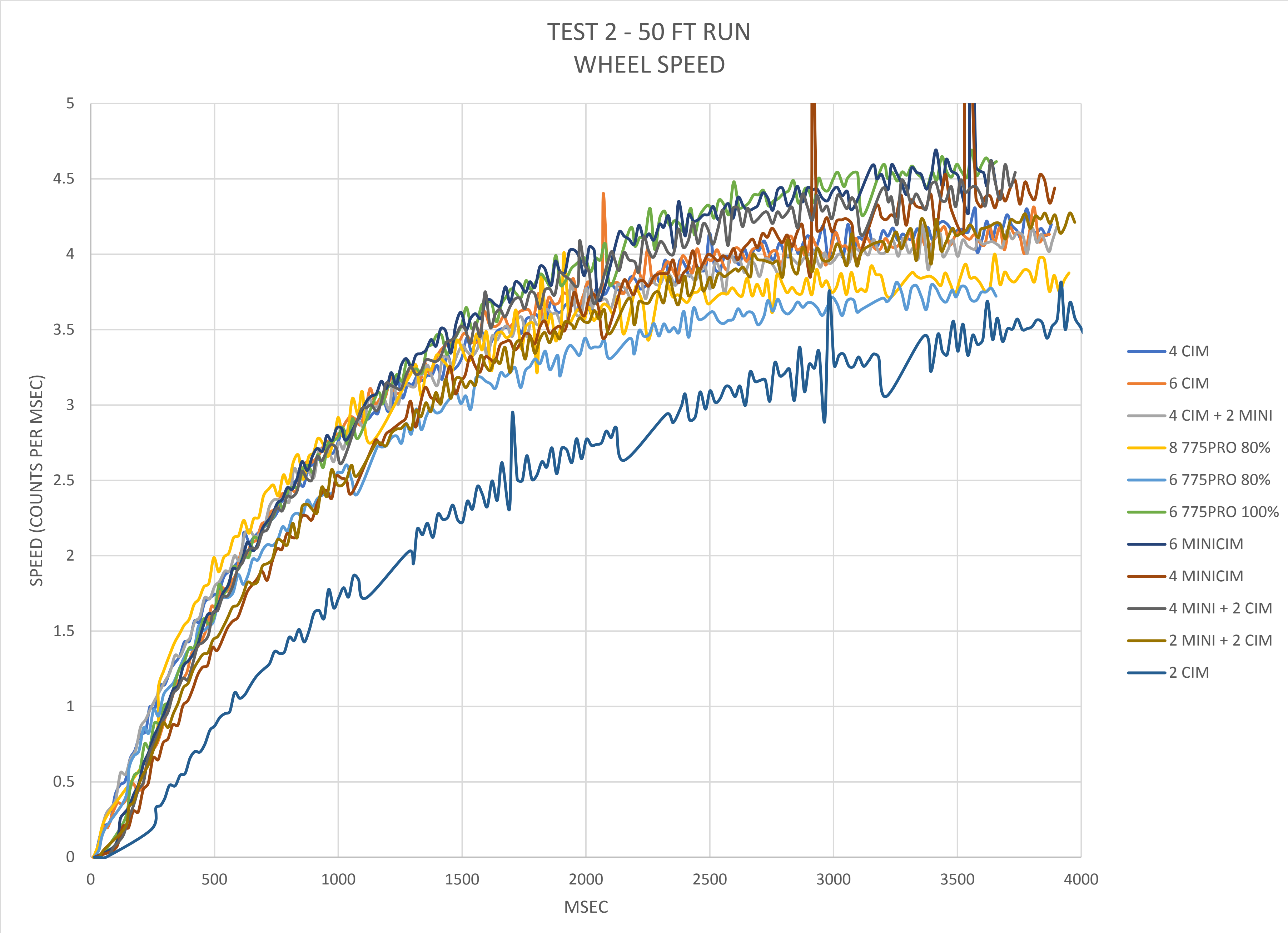
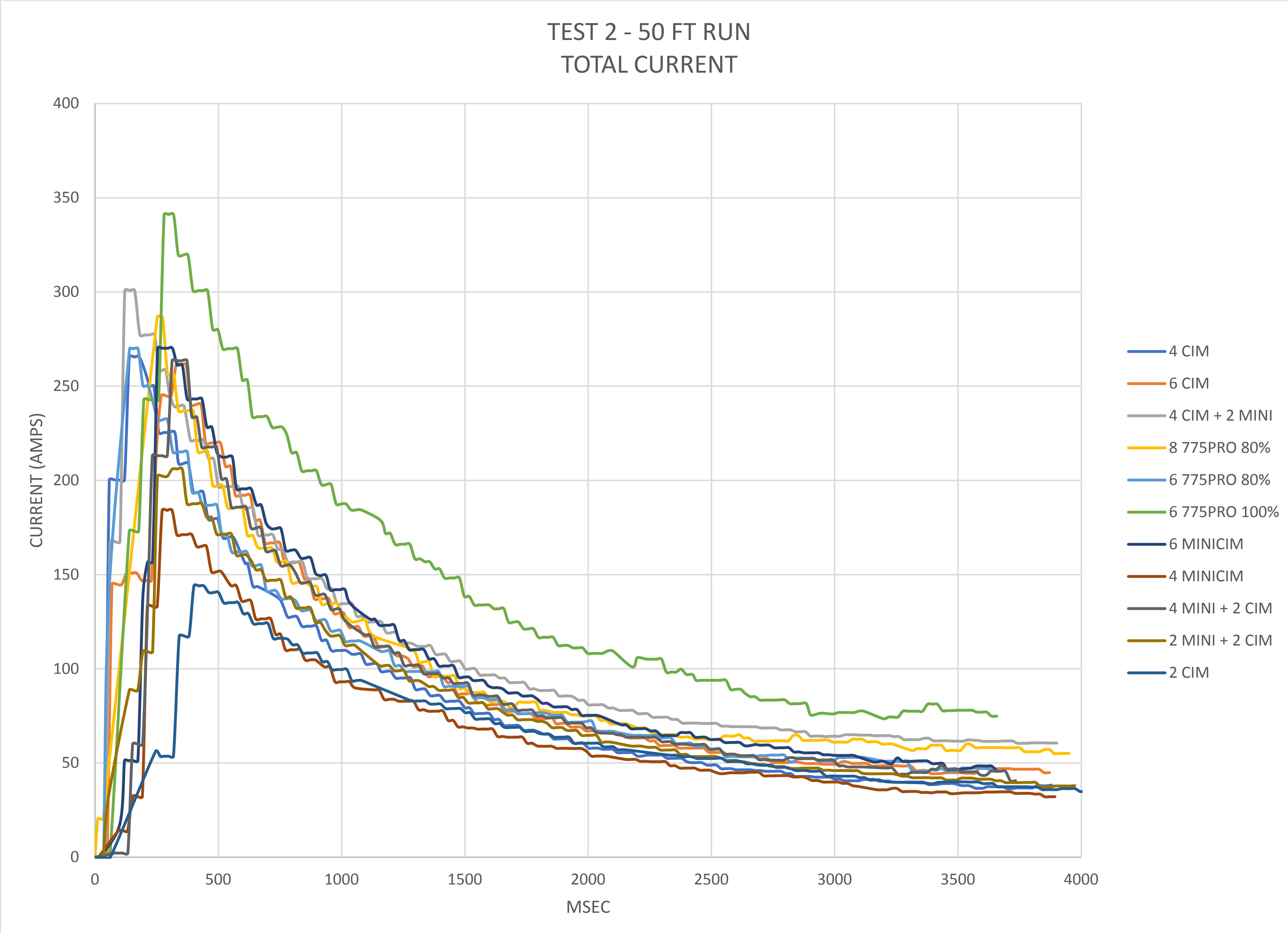
4 MINICIM
4 MINI + 2 CIM
2 MINI + 2 CIM

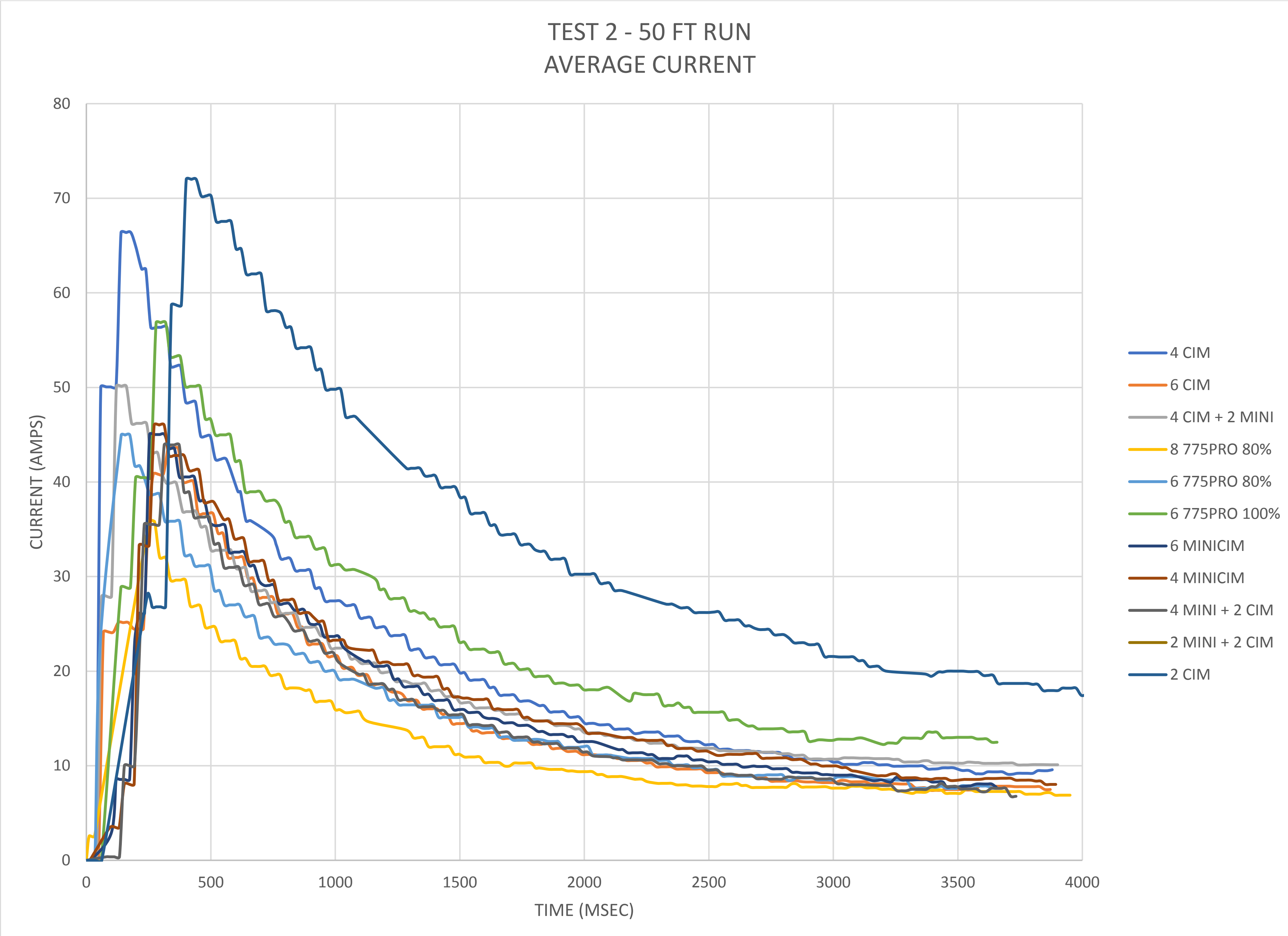

TEST 1 - BENCH TOP
AVERAGE CURRENT
CURRENT (AMPS)
TIME (MSEC)
0
5
10
15
20
25
30
35
40
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
4 CIM
6 CIM
4 CIM + 2 MINI
8 775PRO 80%
6 775PRO 80%
6 775PRO 100%
6 MINICIM
4 MINICIM
4 MINI + 2 CIM
2 MINI + 2 CIM



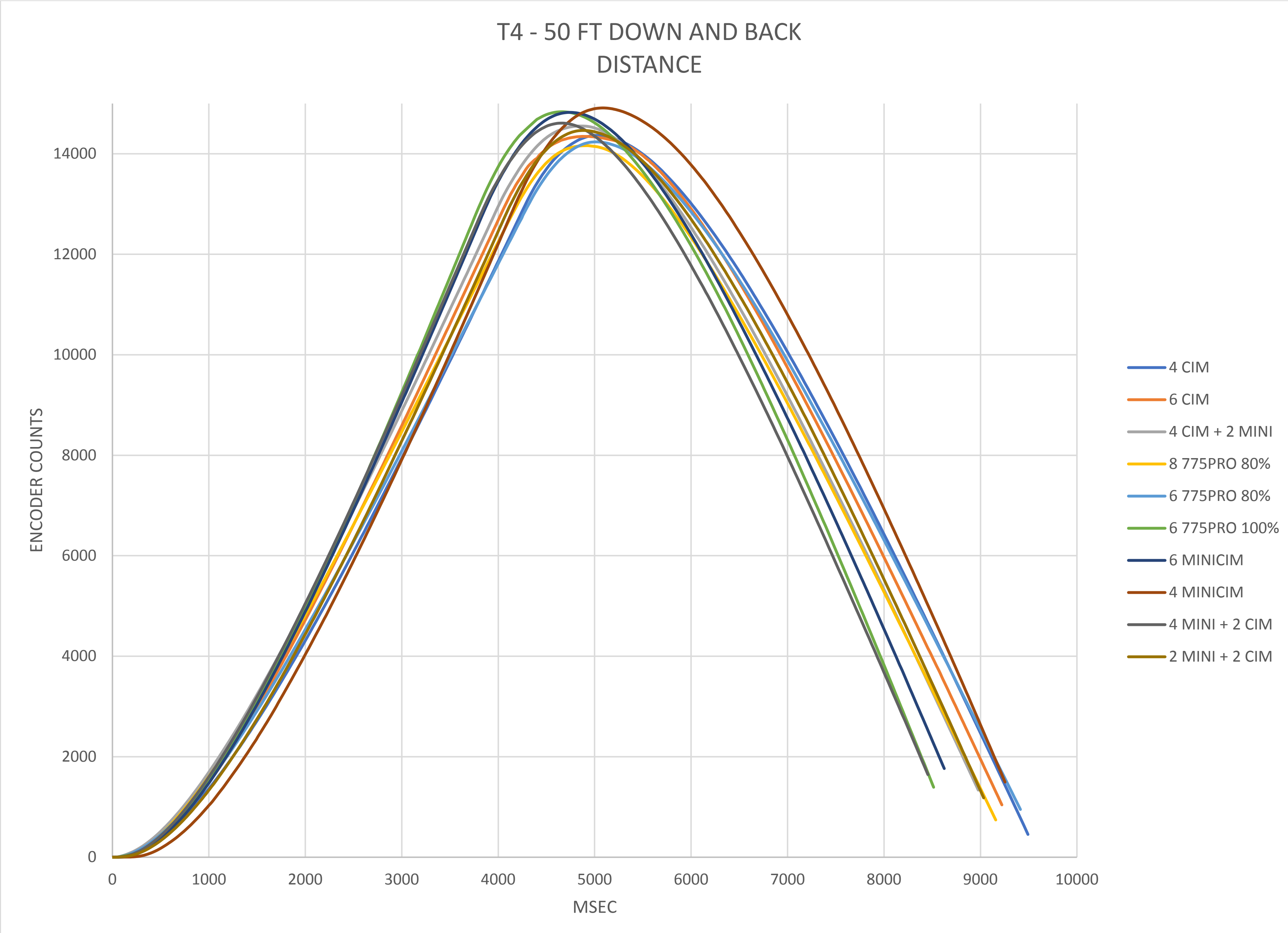
TEST 2 - 50 FT RUN
DISTANCE
14000
12000
10000
8000
6000
4000
2000
0
DISTANCE (ENCODER COUNTS)
0
500
1000
1500
2000
2500
3000
3500
4000
TIME (MSEC)
4 CIM
6 CIM
4 CIM + 2 MINI
8 775PRO 80%
6 775PRO 80%
6 775PRO 100%
6 MINICIM
4 MINICIM
4 MINI + 2 CIM
2 MINI + 2 CIM
2 CIM


TEST 2 - 50 FT RUN
WHEEL SPEED
SPEED (COUNTS PER MSEC)
MSEC
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
500
1000
1500
2000
2500
3000
3500
4000
4 CIM
6 CIM
4 CIM + 2 MINI
8 775PRO 80%
6 775PRO 80%
6 775PRO 100%
6 MINICIM
4 MINICIM
4 MINI + 2 CIM
2 MINI + 2 CIM
2 CIM

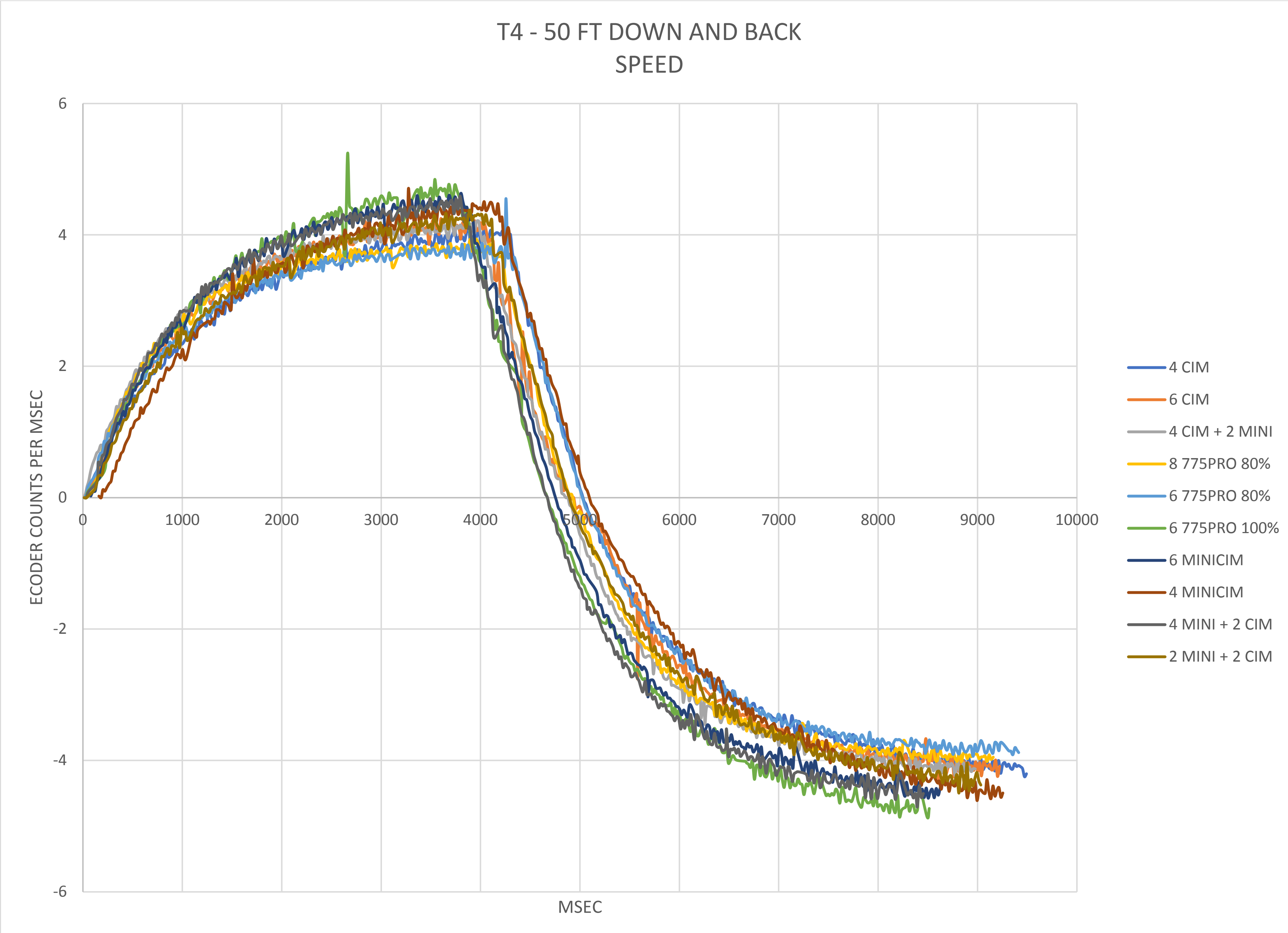

TEST 2 - 50 FT RUN
TOTAL CURRENT
CURRENT (AMPS)
400
350
300
250
200
150
100
50
0
0
500
1000
1500
2000
2500
3000
3500
4000
MSEC
4 CIM
6 CIM
4 CIM + 2 MINI
8 775PRO 80%
6 775PRO 80%
6 775PRO 100%
6 MINICIM
4 MINICIM
4 MINI + 2 CIM
2 MINI + 2 CIM
2 CIM

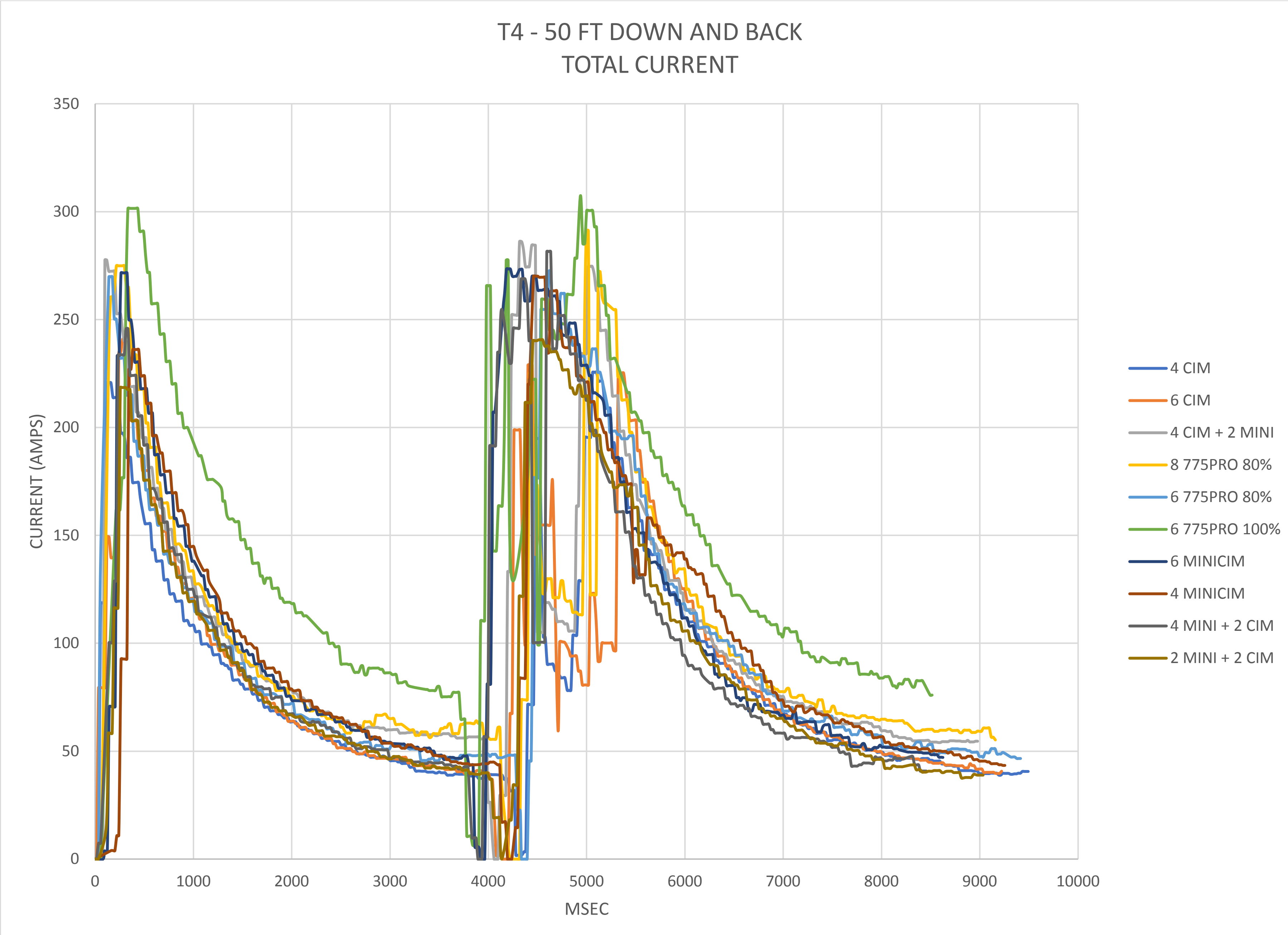


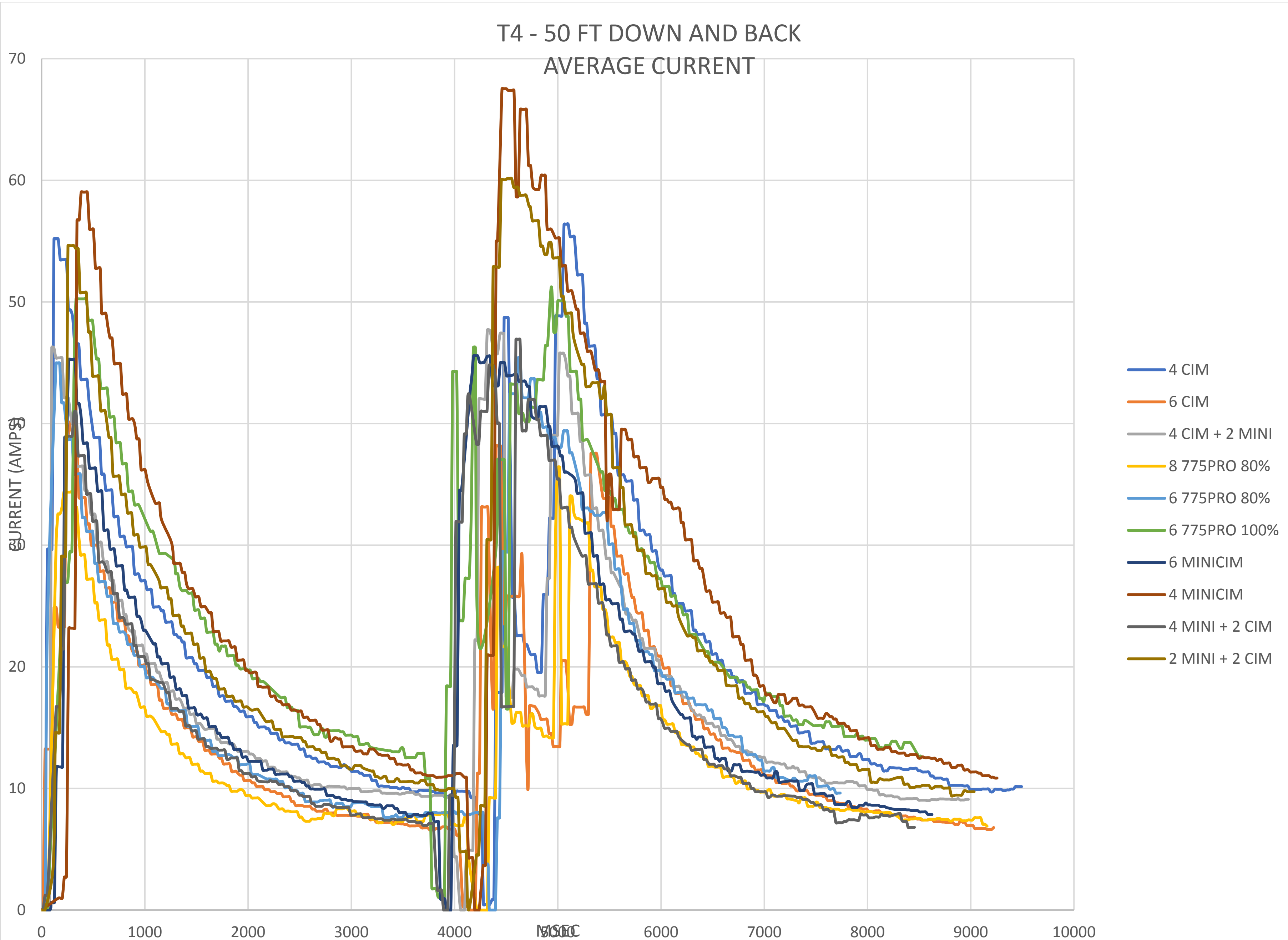
TEST 2 - 50 FT RUN
AVERAGE CURRENT
CURRENT (AMPS)
TIME (MSEC)
0
10
20
30
40
50
60
70
80
0
500
1000
1500
2000
2500
3000
3500
4000
4 CIM
6 CIM
4 CIM + 2 MINI
8 775PRO 80%
6 775PRO 80%
6 775PRO 100%
6 MINICIM
4 MINICIM
4 MINI + 2 CIM
2 MINI + 2 CIM
2 CIM



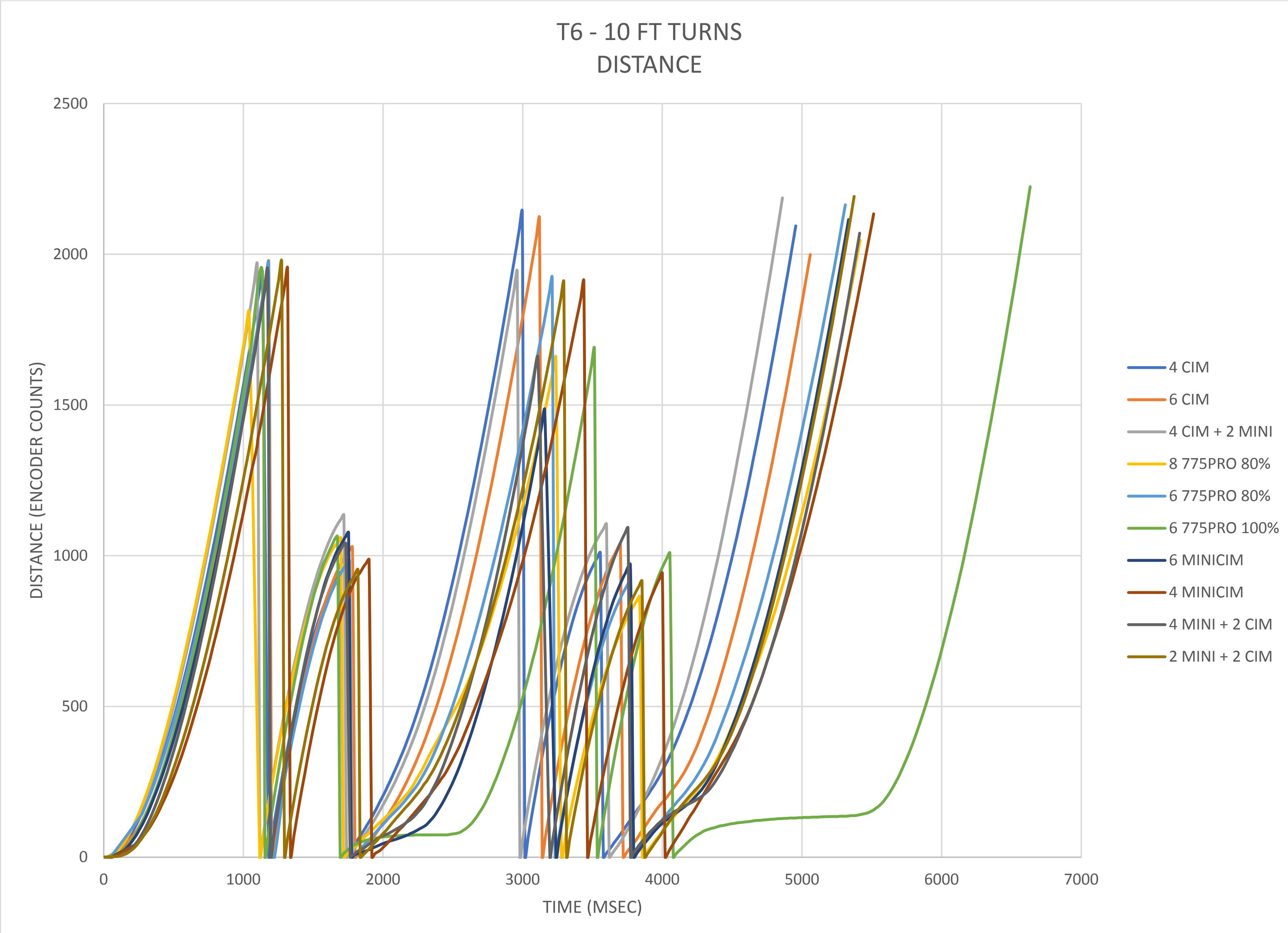
T4 - 50 FT DOWN AND BACK
DISTANCE
ENCODER COUNTS
0
2000
4000
6000
8000
10000
12000
14000
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
MSEC
4 CIM
6 CIM
4 CIM + 2 MINI
8 775PRO 80%
6 775PRO 80%
6 775PRO 100%
6 MINICIM
4 MINICIM
4 MINI + 2 CIM
2 MINI + 2 CIM

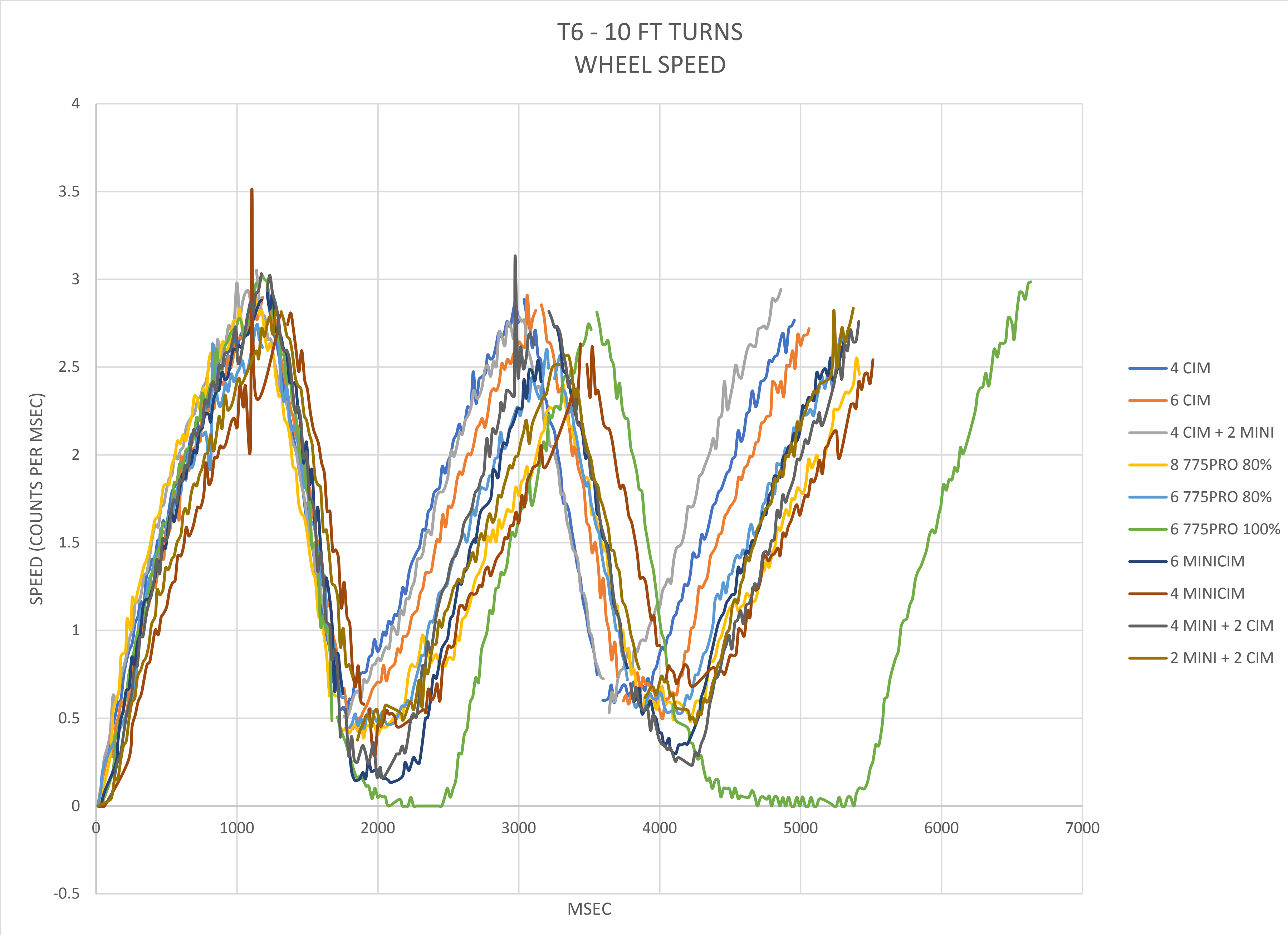

T4 - 50 FT DOWN AND BACK
SPEED
ECODER COUNTS PER MSEC
MSEC
6
4
2
0
-2
-4
-6
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
4 CIM
6 CIM
4 CIM + 2 MINI
8 775PRO 80%
6 775PRO 80%
6 775PRO 100%
6 MINICIM
4 MINICIM
4 MINI + 2 CIM
2 MINI + 2 CIM

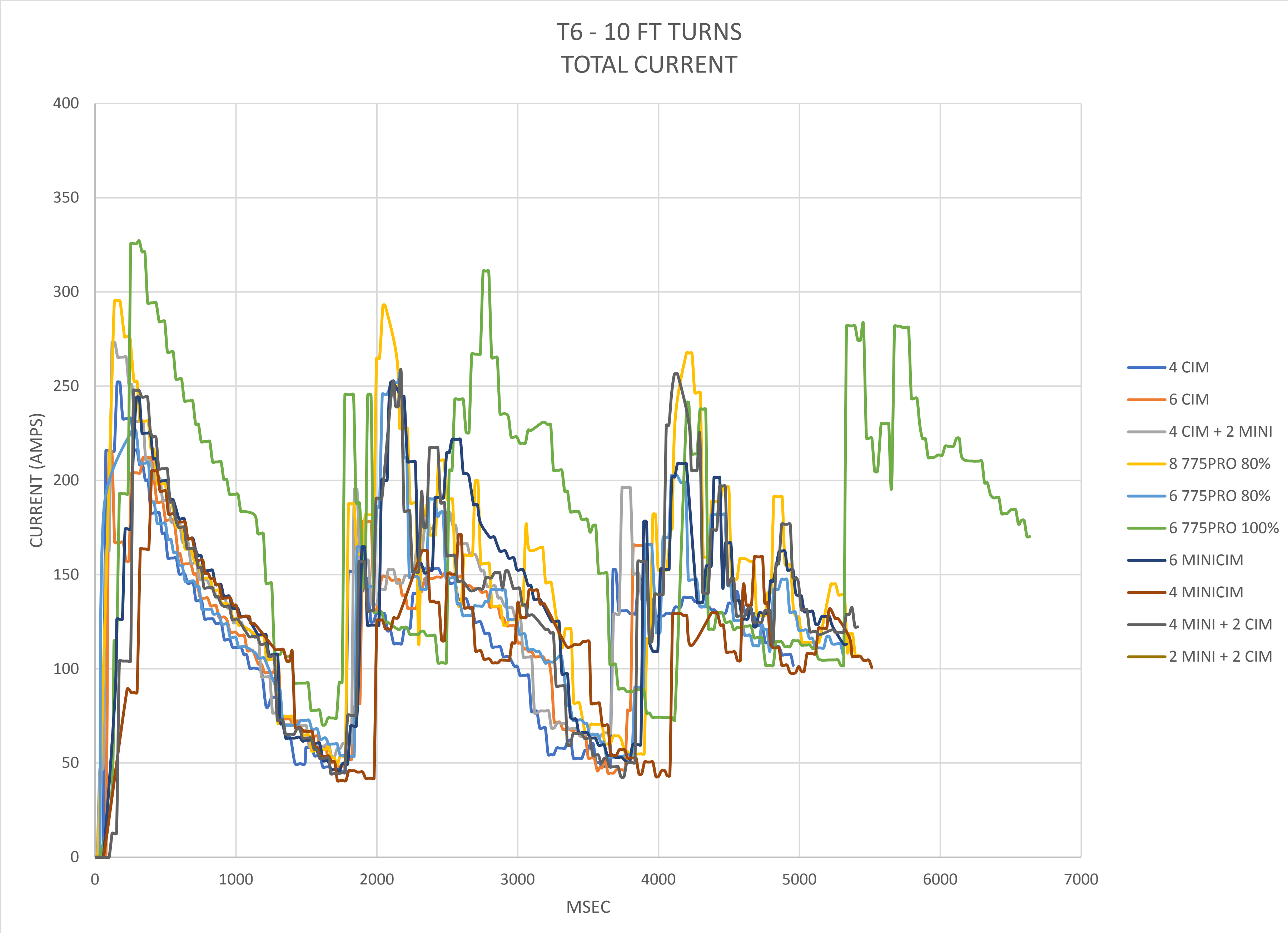

T4 - 50 FT DOWN AND BACK
TOTAL CURRENT
CURRENT (AMPS)
350
300
250
200
150
100
50
0
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
MSEC
4 CIM
6 CIM
4 CIM + 2 MINI
8 775PRO 80%
6 775PRO 80%
6 775PRO 100%
6 MINICIM
4 MINICIM
4 MINI + 2 CIM
2 MINI + 2 CIM

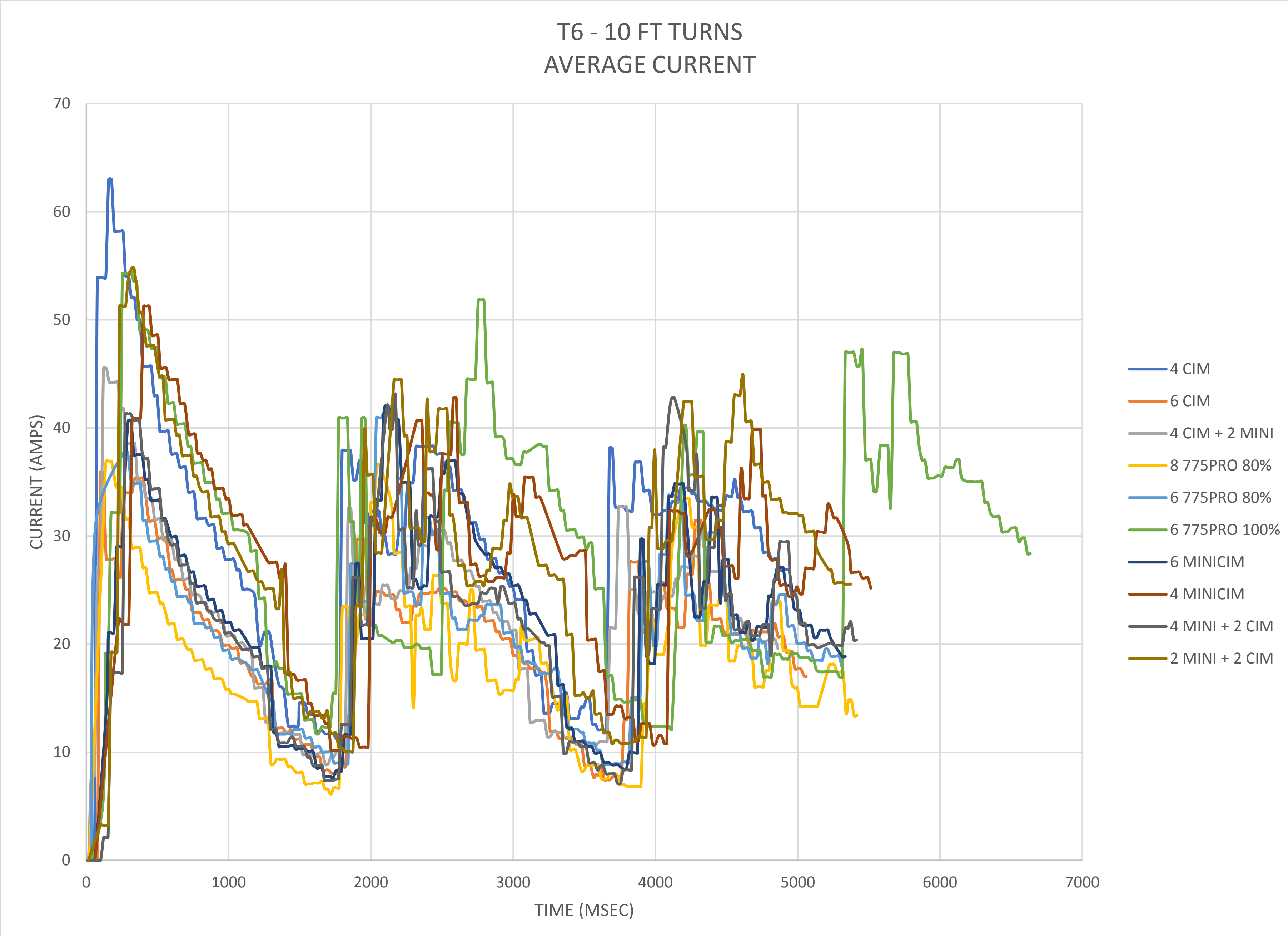


T4 - 50 FT DOWN AND BACK
AVERAGE CURRENT
CURRENT (AMPS)
MSEC
0
10
20
30
40
50
60
70
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
4 CIM
6 CIM
4 CIM + 2 MINI
8 775PRO 80%
6 775PRO 80%
6 775PRO 100%
6 MINICIM
4 MINICIM
4 MINI + 2 CIM
2 MINI + 2 CIM


T6 - 10 FT TURNS
DISTANCE
DISTANCE (ENCODER COUNTS)
2500
2000
1500
1000
500
0
0
1000
2000
3000
4000
5000
6000
7000
TIME (MSEC)
4 CIM
6 CIM
4 CIM + 2 MINI
8 775PRO 80%
6 775PRO 80%
6 775PRO 100%
6 MINICIM
4 MINICIM
4 MINI + 2 CIM
2 MINI + 2 CIM


T6 - 10 FT TURNS
WHEEL SPEED
SPEED (COUNTS PER MSEC)
MSEC
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
0
1000
2000
3000
4000
5000
6000
7000
4 CIM
6 CIM
4 CIM + 2 MINI
8 775PRO 80%
6 775PRO 80%
6 775PRO 100%
6 MINICIM
4 MINICIM
4 MINI + 2 CIM
2 MINI + 2 CIM


T6 - 10 FT TURNS
TOTAL CURRENT
CURRENT (AMPS)
400
350
300
250
200
150
100
50
0
0
1000
2000
3000
4000
5000
6000
7000
MSEC
4 CIM
6 CIM
4 CIM + 2 MINI
8 775PRO 80%
6 775PRO 80%
6 775PRO 100%
6 MINICIM
4 MINICIM
4 MINI + 2 CIM
2 MINI + 2 CIM


T6 - 10 FT TURNS
AVERAGE CURRENT
CURRENT (AMPS)
TIME (MSEC)
0
10
20
30
40
50
60
70
0
1000
2000
3000
4000
5000
6000
7000
4 CIM
6 CIM
4 CIM + 2 MINI
8 775PRO 80%
6 775PRO 80%
6 775PRO 100%
6 MINICIM
4 MINICIM
4 MINI + 2 CIM
2 MINI + 2 CIM