2018 NDIA GROUND VEHICLE SYSTEMS ENGINEERING AND TECHNOLOGY SYMPOSIUM
POWER & MOBILITY (P&M) TECHNICAL SESSION
AUGUST 7-9, 2018 - NOVI, MICHIGAN

STRYKER VEHICLE ADVANCED PROPULSION WITH ONBOARD POWER

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ABSTRACT

The intent of the Advanced Propulsion with Onboard Power (APOP) system is to increase the available onboard power for the Stryker from 16kW (570A) to 120kW to support future vehicle capabilities such as directed energy, electromagnetic armor, and electronic warfare. The additional power is also used to run electrified automotive auxiliaries on the vehicle such as the main fan and the hydraulic pump more efficiently. Vehicle test results showed that the APOP vehicle had better or equivalent performance to the baseline vehicle when just the electrified automotive auxiliaries are included, but additional future loads still pose a challenge to meeting vehicle performance requirements.

INTRODUCTION

The intent of the Advanced Propulsion with Onboard Power (APOP) system is to increase the available onboard power for the Stryker from 16kW (570A) to 120kW to support future vehicle capabilities such as directed energy, electromagnetic gun, electromagnetic armor, and electronic warfare. The additional power is also used to run electrified automotive auxiliaries on the vehicle such as the main fan and hydraulic pump more efficiently. Higher efficiency and the ability to temporarily shed electrical loads (by disabling the DC/DC converters and adjusting fan and pump speeds) will be essential to mitigating the mobility effects of high electrical power loads on the vehicle.

A flat bottom Stryker Mortar Carrier Variant wheeled vehicle was tested at the General Dynamics' chassis dynamometer facility in Sterling Heights, MI, to establish a baseline benchmark. The vehicle was upgraded with an integrated APOP system and retested for comparison with the baseline vehicle. The APOP upgrades included: a 120kW permanent magnet alternating current (PMAC) generator from DRS, two bidirectional 10kW DC/DC converters from BAE, a 35kW electric main cooling fan from Marvin Land Systems, a J1772 high voltage export power connection from REMA, and an electrically-driven auxiliary hydraulic pump from Parker. The upgrades add 466 lbs. to the vehicle weight. The vehicle's powertrain consists of a Caterpillar C7 Diesel engine and an Allison 3200 SP transmission with Integrated Starter Generator. An overview of this architecture can be found in Figure 6.

The objective of the test was to evaluate the vehicle performance, efficiency, and fuel economy under different mechanical and electrical loading conditions. The baseline vehicle test was performed in Sept. 2015 and the upgraded APOP Stryker test was performed in Dec. 2016 – Jan. 2017. Both were performed on a vehicle chassis dynamometer at General Dynamics as shown in Figure 1.

Figure 1. Test Setup

TESTING CATEGORIES

Several detailed tests were conducted on the baseline vehicle and then repeated on the APOP vehicle to cover possible operations in the dynamometer or track driving environment to provide a quantitative assessment of APOP impact. Data was collected using an in house Data Acquisition system of added sensors and the engine parameters using the CAN bus. The results of the testing are shown in the following sections.

PRE-TEST AND POST-TEST PERFORMANCE CURVE

Performance curve testing was conducted three times (beginning of baseline, beginning of APOP, end of APOP) to check for vehicle performance changes during testing. The transfer case was set to the high ratio and no load was placed on the low voltage bus. The main propulsion cooling fan and the engine bay exhaust fan operated at top speed for the duration of this portion of the baseline vehicle testing because of the high vehicle loads. The fan speed and engine coolant temperature was set based on the temperature lookup specified for the APOP vehicle. Vehicle torque was measured at 100% wide open throttle for this baseline performance test.

Table 1 shows the resulting average horsepower change from each of the performance runs. A positive percentage increase in available horsepower at a given speed means more road force was available at that speed for mobility compared to the baseline. Comparing the pre-test and post-test runs of the APOP vehicle, it appears that the performance of the vehicle held relatively constant with the exception of the 40 mph test point, which saw a decrease in horsepower by approximately 8%. A comparison of the baseline vehicle performance curve to the pre-test APOP performance curve showed that the two performance curves correlated relatively well, with resulting horsepower being slightly higher on the APOP pre-test curve, but within 7% difference. In general, differences less than 2% can be considered not significant based on the measurement uncertainty and repeatability of the test.

Dynamometer Speed (mph)	%hp Difference Baseline to APOP Pre-test	%hp Difference APOP Pre-Test to Post-Test
60	5.1%	-1.6%
50	6.4%	-1.2%
40	2.1%	-8.4%
30	-0.9%	-1.1%
20	4.6%	-1.0%

Table 1. Performance Curve Test Results

SCREENING TESTING

A partial factorial experiment was executed. The vehicle was tested at a number of operational points based on multiple input variables. The purpose was to determine the effects of different factors on the system performance. These points served to screen the effects of the variables on the overall system performance and provide a means to predict their impact on vehicle performance. The test variables were: high voltage (HV) electrical load (kW) (N/A for Baseline), low voltage (LV) electrical load (A), vehicle speed (mph), torque %, battery charge current (A), full low voltage current (A). The actual test points are listed in Table 4 in the Appendix. The thermostat was blocked open for the duration of this test. The main propulsion cooling fan and the engine bay exhaust fan ran in their normal operation mode for the duration of this test.

Figure 2 shows the difference between road load force on the APOP and baseline vehicle tests. Ideally, they should be nearly the same so fuel usage can be compared between the two tests. It needs to be noted that there was a limitation in the APOP initial screening data set, as Run Order #1, 7, 10, and 20 were not fully achievable during test as shown in . These four data points had in common that they specified the high value for high voltage load (59kW), and the high level for torque (88.7% throttle). With this considered, the slopes for the effect of each control variable on average fuel efficiency still correlated very closely between the baseline and APOP vehicles.

The distribution of fuel usage can be seen in Figure 3. The resulting average fuel efficiency (in hp/(gal/hr)) showed an approximately 25% lower value than the baseline vehicle, which may be offset by some correction factor due to the unachievable test points.

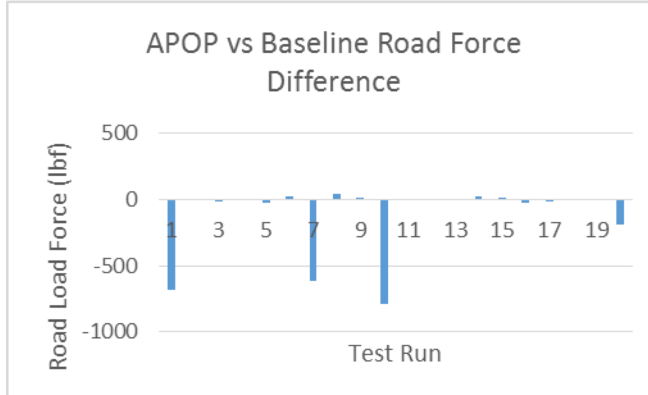

Figure 2. Screening road force difference

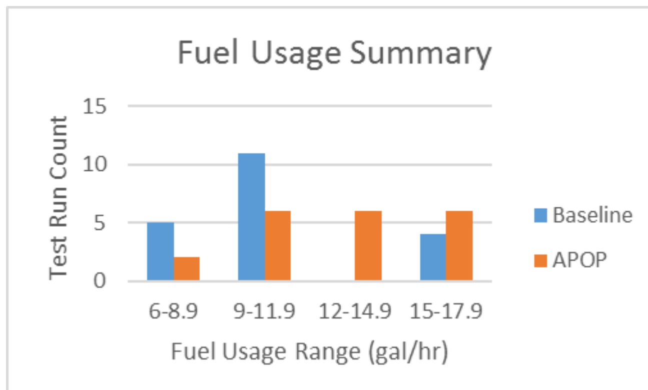

Figure 3. Fuel usage difference

FULL LOAD COOLING

A classical 1st gear / low transfer-case full load cooling test could not be run due to test facility limitations. To address this, a simulated full load cooling test was performed in 4th gear and transfer case high with the torque converter unlocked. The test points for equivalent tractive effort were chosen based on vehicle modeling and simulation data.

The full load cooling test consisted of three tractive load points and four high voltage load bank points. The tractive load points were chosen based on modeling results estimating the cooling performance of the vehicle in 4th gear. The need for 4th gear operation came from test cell limitations that would not allow a full tractive effort test in low gear. The results are summarized in Figure 4. The full three tractive load sets of points met their expected road load force points on both the baseline and APOP system with no additional HV load. The APOP with 25kW additional HV load passed the Low tractive load point, but failed to meet the expected road load force at the Medium and High points. The second load point with the additional 25kW HV load in Figure 4 shows the attempt at the Medium tractive load point, which didn't increase much above the Low tractive load point before the speed dropped and temperature limits were hit. An additional test point at the Medium tractive load was also run on the APOP system with manual optimization of the fan speed to examine its performance impact.

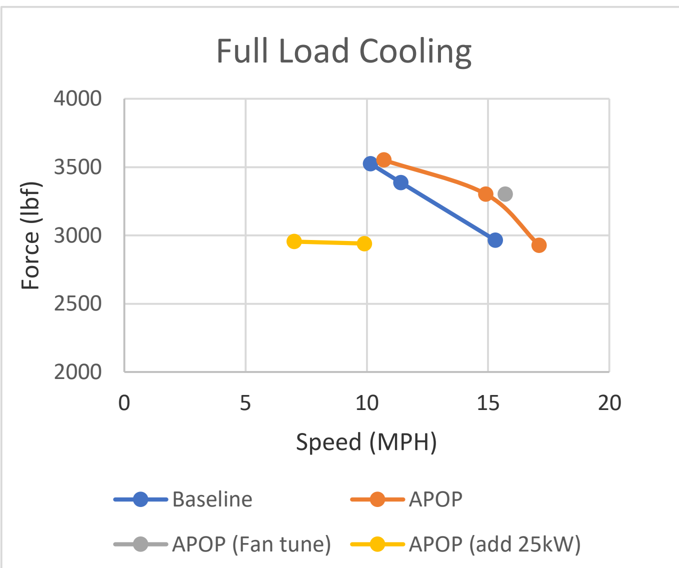

Figure 4. Full Load Cooling Overview

ON ROAD COOLING

This test simulated the vehicle at gross vehicle weight (GVW) of 52,000 lbs. with the low voltage bus loaded to 497 amps. The dynamometer controlled the load on the system to mimic the loads on the Stryker performing operations on road from 5 to 25 mph and at grades from 0 to 20%. For planned test points that the system could not achieve, the grade was held constant and the point of the maximum achievable speed was recorded. If the test point occurred around a transmission shift-point, the gear was limited to the lower gear. If the test point occurred where the transmission torque converter entered and exited lockup, the torque converter was forced out of lockup.

When in an equivalent transmission state, the APOP vehicle generally used less fuel than the baseline vehicle under lower loads. The difference narrowed as the speed and grade increased. Points that ended up in different gears or out of torque converter lockup had significant effects on efficiency as well and accounted for most points where the APOP vehicle was significantly less efficient. This highlights the importance of transmission shift scheduling in vehicle performance and brings up the question of whether adjustments should be made to the transmission shift schedule. A summary of the test results is shown in Figure 7.

ACCELERATION

This test simulated vehicle acceleration from a stand still. The low voltage bus load was set to 497 amps total. The main propulsion cooling fan and the engine bay exhaust fan were running in a normal operation mode for the duration of this test. The vehicle weight was set to 51,232 lbs.

Plots of the 60 mph acceleration times for each of the 10 runs on baseline, APOP and a second APOP test with load shedding on the 10^{th} run are shown in Figure 5

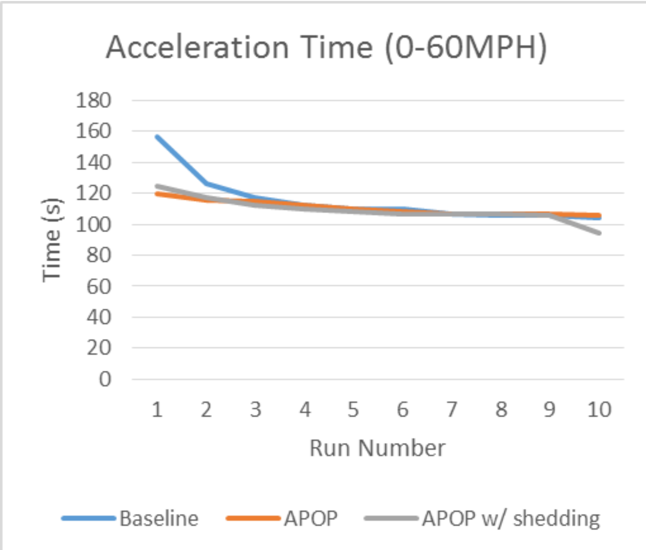

Figure 5. Plot of acceleration times (0-60MPH)

This test was run once for the baseline vehicle and twice with the APOP vehicle. The second acceleration test with the APOP vehicle included a load shedding run for the final test run.

The acceleration times were fairly similar between the baseline and APOP vehicles. The significantly faster acceleration for the APOP vehicle on the first two runs were likely due to variations in the starting conditions for the vehicle despite similar warm-up procedures. In general, the best comparisons can be made from the acceleration times in the later runs when the vehicle performance had stabilized. At those points, the acceleration performance was nearly identical.

For the load shedding run (APOP w/ shedding, Run 10), the DC/DC Converters were placed in standby so the low voltage electronics ran on battery. This removed roughly 14kW of LV electrical load from the vehicle. The load shedding run was 10 seconds faster compared to the baseline vehicle, which is a 10% improvement. During the load shedding run, the battery voltage initially dropped to 23.2V and decreased to 22.9V by the time the vehicle passed 60MPH. This left a fair amount of head room as the utilization equipment can perform down to 20V (MIL-STD-1275E).

CRUISING RANGE

This test was derived from a specific Stryker requirement: "The Stryker equipped with the APOP upgrade, without add-on armor, shall cruise a minimum range of (T) = 330 miles at a continuous, sustained, speed of 40 mph on a hard dry level surface (primary, paved roads) without refueling [exclusive of onboard fuel storage cans]" The thermostat was blocked open for the duration of this test on the baseline vehicle, with the main propulsion cooling fan and the engine bay exhaust fan running in a normal operation mode for the duration of the test. For the APOP testing, the electric fan ran according to the engine coolant temperature-based temperature lookup specified for the APOP vehicle.

Table 2. Cruise Range Comparison shows the net results of both the baseline and APOP vehicle tests. The fuel rate values in both cases are almost the same which lead to similar fuel economy values.

	Average Fuel Economy MPG	Traveled Distance Miles	Total Fuel Consumption Gallons
Base	5.25	330	62.86
APOP	5.15354	330	64.03

Table 2. Cruise Range Comparison

The Cruise Test was run at a rolling dynamometer following all the test steps. The system worked flawlessly in both the setup and test period. Critical parameters from the embedded controllers and the Data Acquisition system were monitored and recorded. The relatively low mechanical and electrical load on the vehicle kept the engine and the APOP system heat generation well within the threshold limits.

HIGH IDLE HIGH ELECTRICAL LOAD

This test checked the export power capability of the vehicle while at a high idle. It also examined the cooling of the power electronics under those conditions. The high idle point for the vehicle was set to 1800RPM using the CAT maintenance tool based on the generator power curves. The LV load was set to 497A total.

Engine Speed	HV Export Electrical Load	Total HV Load	Fuel Usage
(RPM)	(kW)	(kW)	(L/h)
1800	23	40	20.8
1800	46	65	26.1
1800	59	78	29.0

Table 3. High Idle Electrical Load Points

The vehicle operated without any problems during the high idle high electrical load test. Even with the high electrical load and no mobility load during operation, the engine coolant temperature still determined the fan speed, so the electronics cooling loop has sufficient capacity. This also means that high cooling fan speeds were not required to operate at high export power, leading to more efficient overall operation.

One area of possible future improvement is implementing an adaptive idle speed strategy. The strategy could decrease the idle speed when electrical load was low to save fuel.

CONCLUSION

Testing was completed successfully on the APOP Stryker which includes a 120kW inline generator and electrified auxiliaries on a Stryker vehicle. The APOP hardware allowed optimization of auxiliary systems and provides room for future power growth onboard the vehicle. The results of the testing show the benefits of electrification and the difficulties of handling continued electrical power growth. The APOP Stryker vehicle performed well compared to the baseline vehicle when electrical power loads were equivalent besides any electrified auxiliaries. However, continued power growth can impact fuel usage and performance, especially as the loads near the full capability of the 120kW generator.

The new high voltage systems did not have any major failures, though resettable faults were encountered. Determining ways to manage the system to better avoid potential faults would be important to create a more robust and mature system. The only failure associated with the new components was a harness issue that should be fairly straightforward to address in the future.

There are also several potential areas for future research and development based on the outcome of testing. Optimization of the fan control algorithm to allow higher operating temperatures as well as temporary load shedding should yield additional performance increases. Engine and system start-up tended to be the most sensitive time for the equipment, so further investigation of these difficulties could aid future programs.

REFERENCES

[1]Y. Abdallah, K. Boice, J. Tylenda, “APOP Stryker Vehicle Test Report”, TARDEC, 2017.

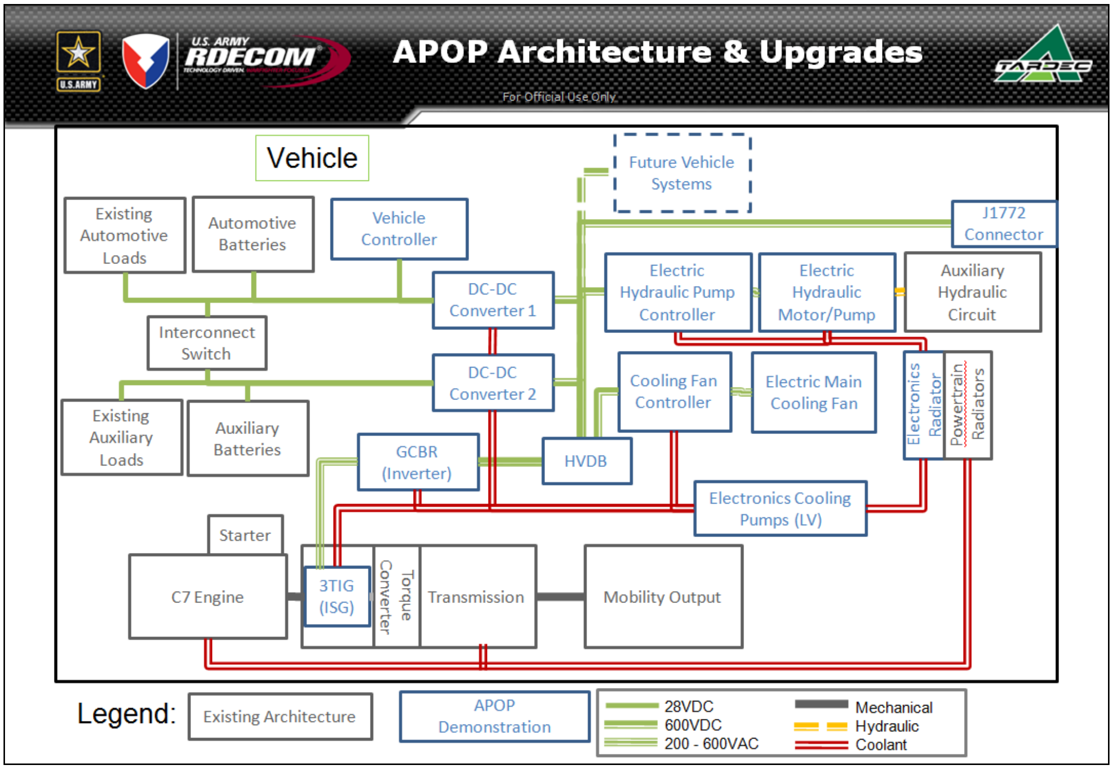

Figure 6. APOP Architecture and Upgrades

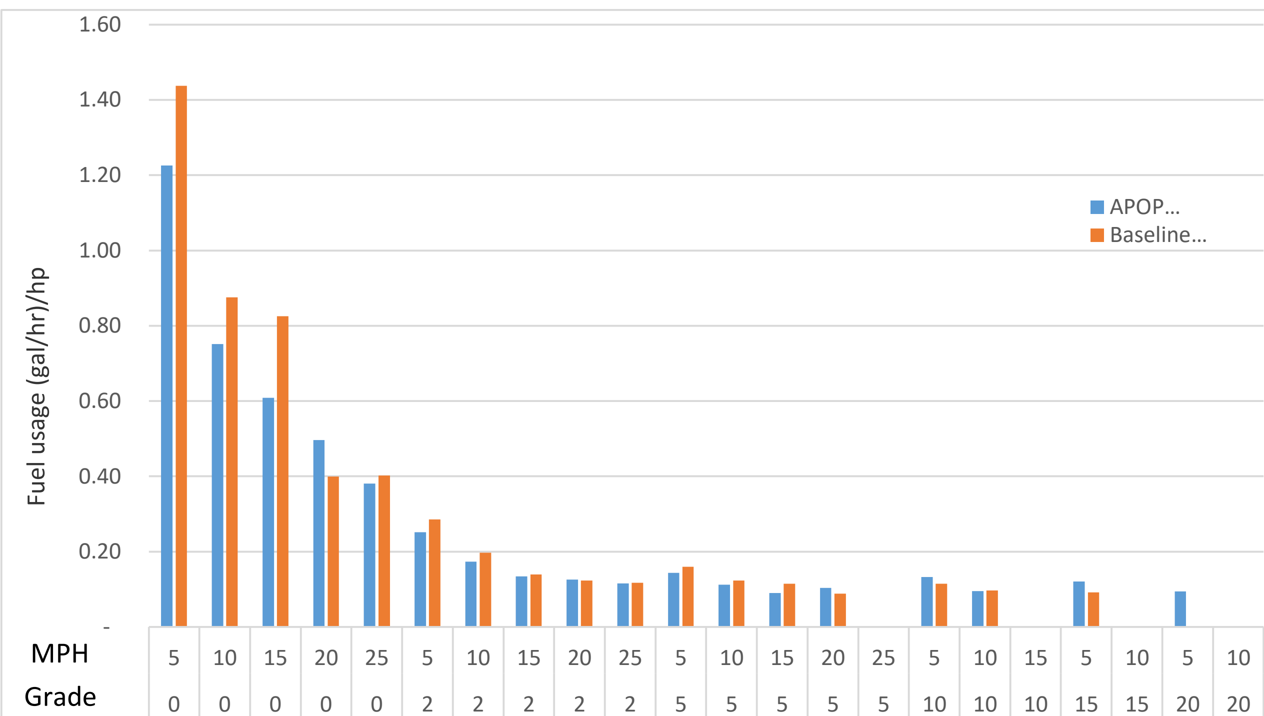

Figure 7. On road cooling results

APPENDIX

Run Order	HV Electrical Load (kW) *N/A for Baseline	Vehicle Speed (MPH)	Torque %	Load Bank Clipped Current(A)
1	69	35.6	88.7	167
2	41	24.6	65	570
3	69	13.7	55	570
4	14	35.6	41.3	167
5	14	13.7	41.3	570
6	69	35.6	41.3	570
7	69	35.6	88.7	570
8	14	35.6	41.3	570
9	41	24.6	65	516
10	69	13.7	88.7	395
11	14	13.7	41.3	395
12	41	24.6	65	516
13	14	13.7	88.7	570
14	69	35.6	41.3	395
15	69	13.7	41.3	570
16	14	13.7	88.7	167
17	14	35.6	88.7	395
18	69	13.7	41.3	167
19	41	24.6	65	516
20	14	35.6	88.7	570

Table 4. Partial Factorial Test Points