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ADVANCED COMBAT TRANSMISSIONS - THE SAPA ACT1000, ACT850 & ACT1075

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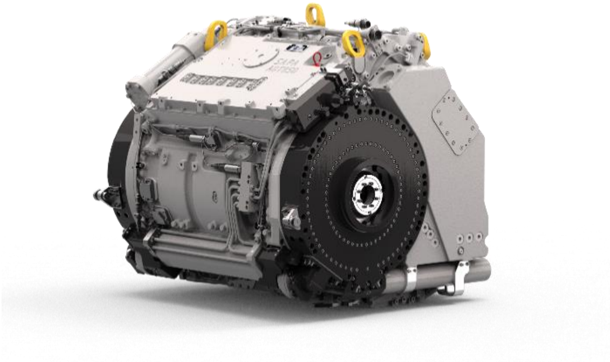

ABSTRACT

This paper describes the architecture, capabilities, and readiness of the SAPA Advanced Combat Transmission (ACT) family. The ACT850, ACT1000, and ACT1075 utilize scalable and modular technology across the product line, applicable to tracked vehicles weighing 35 thru 75 tons. The ACT family of transmissions are designed to improve the size, weight, power, and cooling (SWaP-C) characteristics of armored vehicle powertrains. Common features of the ACT family include high efficiency (>90%), low heat rejection under all operating conditions, 32 speed mechanical propulsion in forward and reverse; high efficiency mechanical steering delivering smooth agility from pivot turns thru straight paths and enabling use of lower power electric motors to provide for silent maneuverability; drive-by-wire control interface to reduce operator fatigue and training requirements; and reduced powertrain cooling, weight, and space claim impacts on the vehicle.

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1. Tracked Vehicle Mobility

Mobility is the foundational component of formation and individual vehicle combat effectiveness. Mobility enhances firepower by enabling the formation and its component vehicles to be quickly closed with the enemy and provides the agility to reposition to most effectively capitalize on the situation and lethality capabilities of the assets. Agility enhances protection by allowing the vehicle to be rapidly repositioned to improved stations or protective alignment. This repositioning may require the vehicle to rapidly traverse adverse terrain including steep grades and power sapping surfaces such as mud and/or sand, or the agility to pivot the vehicle to position better protected sections of the vehicle to the attacker.

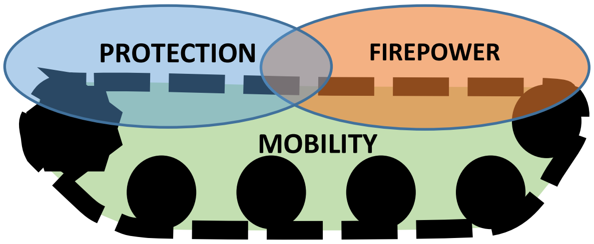

Figure 1 - Relationship between Mobility, Protection and Firepower.

Mobility margin is needed to protect for future needs to carry heavier armor and provide power allowing for future weapons systems while maintaining vehicle agility. Provisions for silent watch and vehicle maneuvering, and future adaptation to autonomous or un-manned operation should also be considered.

The mobility of a tracked vehicle is enabled and controlled by its transmission. The transmission of a tracked vehicle is unique, in that it not only manages the forward and reverse movement of the vehicle, but also provides for steering agility thru differential speed control of the port (left) and starboard (right) tracks. Provisions for vehicle parking, service, and emergency braking capabilities are usually included in the functionality requirements of the tracked vehicle transmission. For armored vehicles, all these mobility functionalities must be provided under some of the most severe installation and operating conditions encountered of any ground vehicle.

All the mobility energy applied to the tracks is managed by the transmission, making the energy efficiency of the transmission vitally important. High transmission efficiency allows more of the shaft power produced by the prime mover, whether an internal combustion engine or e-machine, to be utilized for mobility, reduces the power pack's heat rejection burden on the vehicle, and improves vehicle performance, vehicle fuel efficiency and range, thereby reducing logistic burdens and Green House Gas (GHG) footprint.

2. ACT Objectives

The cascade of translating warfighter needs to engineering requirements, quantifiable validation criteria, and testing protocols is a particularly challenging task [1]. Additional challenges are presented if only vehicle level performance parameters are considered. Relying solely on vehicle level criteria may inadvertently lead to sub-optimal trade-offs between component selections to off-set deficiencies present in one component. For example, lower transmission efficiency is often offset by using a higher engine power rating. While this combination may yield the target vehicle acceleration and speed on grade performance, vehicle cooling load, fuel consumption, range, and GHG emissions will suffer. To avoid these unintended consequences, the vehicle level requirements must also be cascaded down to rational and cohesive system and component level performance requirements.

The cascade of requirements from warfighter to formation to vehicle to system to component should also include parameters focused on growth in capabilities, vehicle mass, electric power needs, and maneuverability that are anticipated to occur in the future.

The Advanced Powertrain Demonstrator (APD) program and objectives established in 2014 [2] by the Government reflected the anticipated integrated powertrain system level requirements of the time, based on a hypothetical 55ton tracked vehicle. The overall powertrain system requirements were then cascaded into engine, transmission, cooling, and electric power generation system specific requirement sets. This approach, while oriented towards providing a plausible demonstration powerpack, also focused on development of some key performance parameters for each of the major powerpack systems. The specific Threshold and Objective requirements deck for the Advanced Combat Transmission demonstration program, summarized in Table 1, were the basis for much of the internal product development goals for the SAPA ACT family of transmissions.

Table 1 – Sub-set of original requirements for the Advanced Combat Transmission program [2]

Parameter	Threshold	Objective	Unit
Efficiency	90	92	%
Steering efficiency	90	91	%
Forward speed	42	45	mph
Reverse speed	20	30	mph
Maximum TE	1.0		-
Continuous TE	0.7		-
0-30mph accel time	22	16	s

Additional transmission and performance objectives, beyond those of the Advanced Combat Transmission program, were targeted in the development of the SAPA ACT Family. These additional requirements, listed in Table 2, reflect the further refinement of transmission performance parameters to include considerations for agility and silent maneuverability, improved vehicle fuel efficiency and reduced GHG emissions, reduced cooling load with increased tractive effort (TE) and performance, and the ability to efficiently cope with the trend of increased vehicle weights with time.

Table 2 - Additional SAPA ACT development requirements

Parameter	Threshold	Objective	Unit
Maximum Transmission Specific Heat Rejection	15	10	% Rated Prime Mover Power
Transmission Input Power Required for 4rpm Pivot Turn @ 0.5 TE	5	4	kW Power Input/ Ton
Vehicle speed reduction while executing 100ft radius turn at 25 mph - Constant Engine Power	5%	0%	%
Impact of 10% Increase in Vehicle Weight – Constant Engine Power	7	5	Speed loss (mph) on 10% grade

3. Architecture for Efficiency

3.1. Scalable & Modular Commonality

The technology development pathway for the SAPA ACT850 and ACT1075 transmissions is shown in Figure 2.

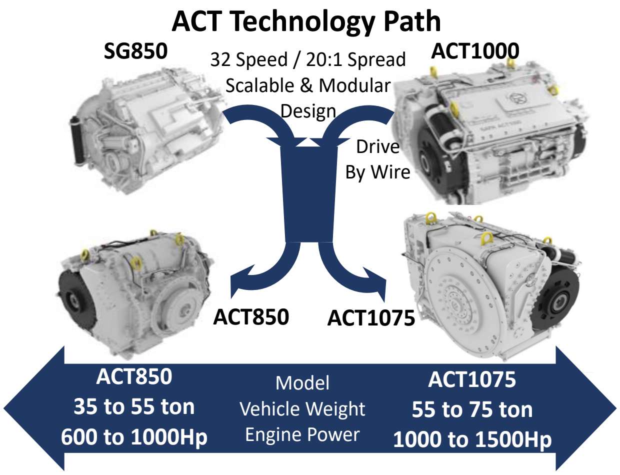

Figure 2 - ACT technology path and application range

The ACT850 and ACT1075 represent a merger of base technologies developed for the SAPA SG850 (32 speed, 20:1 ratio spread modular based design) with the refinements and Drive-By-Wire capabilities embodied from ACT1000 program requirements. The scalable and modular design approach allow two variants, the ACT850 and ACT1075, to efficiently bridge the range of vehicle weight and power inputs that normally require 4-5 discrete, historic cross drive transmission models to cover.

The ACT Family share a design consisting of three scalable modules, shown in Figure 3.

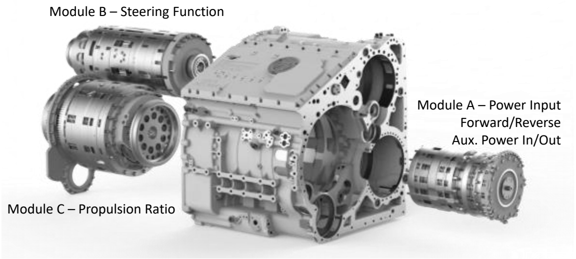

Figure 3 - ACT modular design

Module A allows customized adaptation of various engine speed and power ratings, facilitates input capabilities for auxiliary power devices such as electric motor inputs for traction use including silent mobility, and provides output(s) to drive electric generators and/or hydraulic pumps as required by the vehicle configuration requirements. Module A also provides vehicle Forward/Reverse functionality, and ready adaptation to 'T', 'L' or 'U' engine/transmission configurations.

Module B provides steering agility thru efficient, mechanical based differential speed control of the left and right transmission sprocket outputs.

Module C provides 32 mechanical speed ratios for efficient vehicle propulsion. This high number of ratios is provided through a simple series of five planetary gear sets selected by electronically modulated clutches. Together with Module A, all 32 ratios are available in forward and reverse vehicle motion.

The modular architecture and design approach used for the SAPA ACT family integrates technology commonality, enabling common training, operations, maintenance, and logistics which result in consistent performance in each application.

3.2. Elimination of Torque Converter

To satisfy objectives for starting on grade, acceleration, and maximum sustained vehicle speed on grade, tracked vehicles require transmissions having an overall ratio spread of ~20:1.

Historic tracked vehicle transmissions utilize 3-6 mechanical speed ratios and a torque converter to provide the torque amplification required to compensate for the reduced number of gear ratios for starting and high tractive effort operation. While the torque converter provides the torque amplification needed during low vehicle speed operation to compensate for the relatively high '1st' gear ratio, to deal with the relatively large step between the other 3-6 ratios, and during operating regimes requiring high tractive effort such as higher than design vehicle weight, operating in sand, mud, or on grades, it does so with efficiencies typically in the 60-70% range. The 30-40% of the energy not transmitted to the sprocket is rejected as heat that the vehicle cooling system must dissipate. While strategies to lock-up the torque converter at or very near 'steady-state' operating points can improve the instantaneous efficiency of a torque converter equipped transmission, the conditions allowing lock-up may be rare, especially in cases where vehicle weight has increased beyond that of the original design point of the transmission and/or in challenging terrain such as mud or sand.

The ACT family does not use a torque converter, but instead uses 32 transmission ratios to mechanically provide the 20:1 transmission ratio spread needed for mobility.

This architecture combination yields many advantages in mobility, efficiency, and vehicle cooling load while reducing sensitivity to soil or terrain and any increased vehicle weight that may occur in the future.

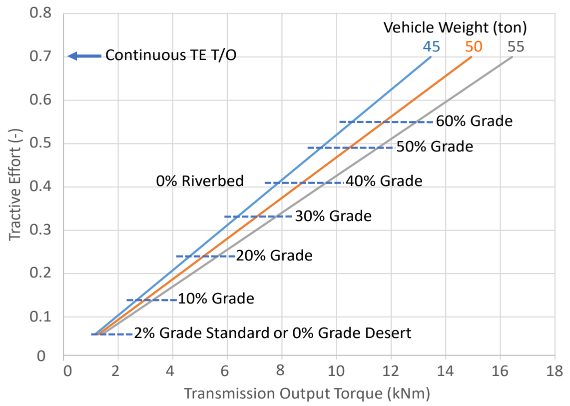

Figure 4 - Tractive effort v. transmission output torque

Figure 4 shows the impacts of grade (used as a quantifiable surrogate for soil and terrain impacts) and vehicle weight on the relationship between tractive effort requirements and transmission output torque. This relationship was used to investigate the sensitivity of transmission efficiency and torque converter strategy on vehicle performance as vehicle weight in increased at various grades.

Figure 5 compares the operational impacts of increasing vehicle mass from an original 45ton design specification to 55ton using 10% and 20% grades as examples and surrogates for non-optimum soil and terrain.

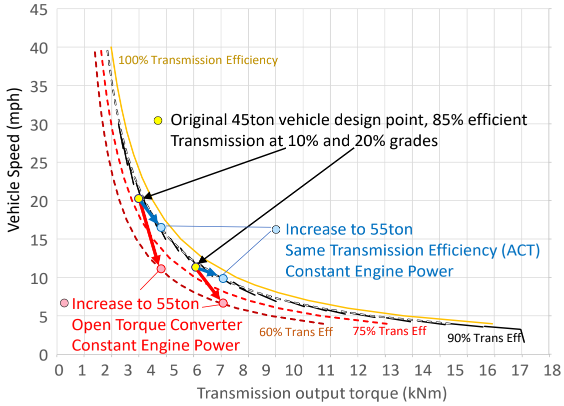

Figure 5 - Vehicle speed v. transmission output torque

This 10ton weight increase would typically require the torque converter of a conventional transmission to 'open' to provide the increase in tractive effort required, causing the overall efficiency of the transmission to shift from a normal design point of ~85% (yellow points) to 65% (red points). At constant input power the vehicle speed would slow from 20mph to 10.5mph at 10% grade, and from 10.6mph to 6mph at 20% grade.

As shown in Figure 5, the ACT transmissions would not loose efficiency, staying very near 90% efficiency over the ratio and input power ranges depicted, and the impact of the 10ton increase in vehicle mass on ACT equipped vehicles would be ~4.5mph (from 20mph to 15.5mph) at 10% grade and ~1mph (from 10.6mph to 9.8mph) at 20% grade – both significant operational improvements over the conventional transmissions. Generally, the more severe the operating conditions (vehicle mass increase, soil or terrain), the smaller the relative impact will be on ACT equipped vehicle performance.

The improved efficiency of the ACT results in reduced transmission heat rejection and vehicle cooling load. Figure 6 shows measured transmission heat rejection, as a percentage of engine rated power, over a range of transmission output speed and torque conditions representing expected ranges of vehicle speed and tractive efforts.

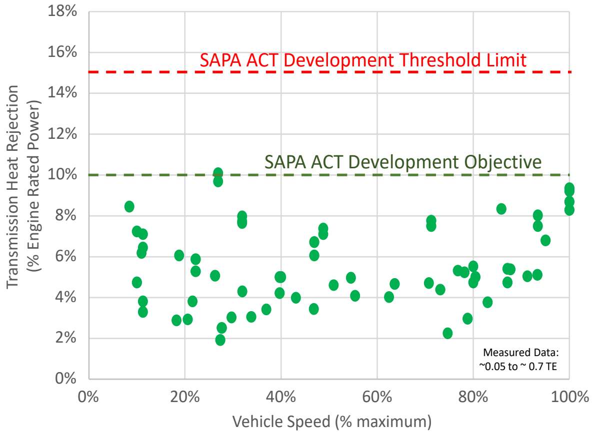

Figure 6 - Measured transmission heat rejection

The ACT development objective of heat rejection less than 10% of the engine rated power was attained over most operating conditions, and in no case was the threshold development goal not met. The reduced heat rejection of the ACT transmission allows for lower cooling fan power consumption and more of the engine power to be delivered to the vehicle tracks for increased mobility.

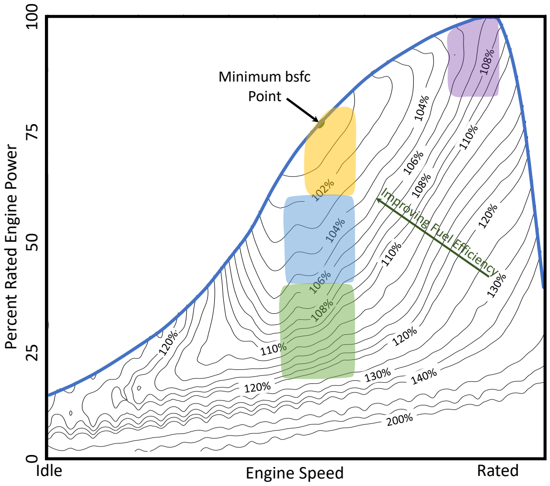

Figure 7 - ACT enabled engine fuel efficiency operation

Figure 7 illustrates a typical engine fuel consumption map in normalized speed and power space. Contours of constant fuel efficiency relative to the minimum bsfc point are shown. For example, the 102% contour depicts the operating points where the bsfc is 102% of the minimum bsfc point.

Also shown in Figure 7 are four engine operating regions as targeted by the transmission/powertrain control strategy. The purple region encompasses operation during (or near) full throttle acceleration demands from the vehicle driver. The SAPA transmission control unit (TCU) selects gear ratios and shift points to maintain the engine power delivery at or very near peak power during these events, and the impact on engine efficiency is accepted to attain maximum vehicle acceleration.

The green region depicted in Figure 7 represents vehicle operation on firm terrain and 0-2% grade. The blue region and yellow regions represent higher tractive effort vehicle operation in increasingly severe conditions of soil and/or grade. Transmission gear selection logic, enabled by the 32 speeds of the ACT family, allow the engine operation to be placed as near as feasible (allowing for some torque margin and/or ambient condition engine de-rate) to the best engine efficiency operating speed torque point for the vehicle power required.

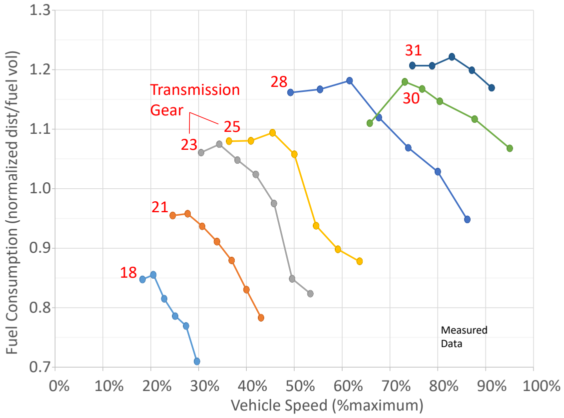

Figure 8 - Vehicle fuel consumption impact

Figure 8 shows a sample of the combined impact of the ACT family efficiency, transmission operating strategy, and engine efficiency capability on vehicle fuel economy. Fuel economy test data, on a volume of fuel consumed per distance basis, versus vehicle speed for representative gear selections between gear 18 and gear 31 were evaluated at 0% grade (refer to the green region on Figure 7) and normalized to the numeric average of all the test data for portrayal. The results shown in Figures 7 and 8 were used to determine the optimal combination of engine rpm and requested throttle to maximize fuel economy through the vehicle speed range at this grade and steeper grades as part of the calibration development.

3.3. Mechanical Steering

The transmission of a tracked vehicle provides differential track speed to deliver steering maneuverability. Conventional tracked vehicle transmissions use variants of fluid couplings, typically a hydrostatic system combination of a hydraulic pump and hydraulic motor. While effective in providing steering capabilities, the reduced efficiency and increased power requirement of these systems, when combined with the propulsion TE power needed, often exceeds the available engine power and ultimately results in a loss of vehicle speed while turning as vehicle inertia is used to provide at least a portion of the steering energy input required. In some cases, maneuvers such as stationary pivot turns are not even possible because there is no vehicle kinetic energy to recover, and the available engine power is not sufficient to overcome the input power requirement of the transmission during stationary pivot turns.

The ACT family eliminates the losses associated with fluid coupled maneuvering systems by efficiently providing mechanical and seamless differential speed control of each track. As shown in Figure 9, pivot turns are enabled with relatively low power input (<5kW/ton @ 4rpm & 0.5TE) required. Smooth turns, without vehicle speed reductions, are also enabled.

Figure 9 -Pivot turn power requirements

4. Drive by Wire Operator Interface

The ACT family concept architecture provides inherent drive and steer by wire capability. Realizing a complete Drive by Wire (DBW) system required only the conversion of the braking actuation system. The inherent DBW capacity of the ACT also includes redundancies in actuation, making the ACT full DBW system very simple and reliable. The SAPA ACT DBW system does not require complex and potentially unsafe robotized systems that also need additional electrical power, affecting pack efficiency.

Based on the above description, the ACT team has developed a full DBW system that satisfies the various needs and requirements of the different vehicle OEMs, the Army, and the Warfighter. This DBW capability was recently demonstrated on the AMERCA platform [3]. Figure 10 shows the unmanned vehicle equipped with the SAPA DBW system, and Figure 11 shows the remote operator station used to control (propulsion, steering and braking) the vehicle.

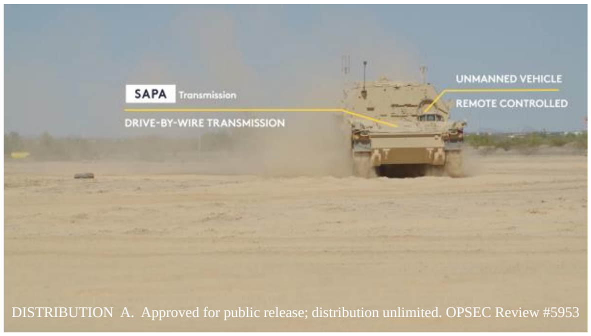

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Figure 10 – AMERCA DBW demonstration vehicle [3]

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Figure 11 - Remote operator station [3]

5. Vehicle Electrification

Utilizing the flexibility and capabilities of the transmission's modular design approach, ACT transmissions are ready for current and future applications of electrical energy to defense vehicles for propulsion and power generation. Hybridization, silent mobility, active protection, high energy weapons, advanced communications and sensors, and other needs require flexible bi-directional electrical power interfaces. Through Module A, the ACT family can accommodate electrical machines operating as a generator to provide the vehicle systems with electrical power, as a motor providing tractive effort, or both. As shown in Figure 12, these electrical machine input/output points can be flexibly located to adapt to specific vehicle application requirements.

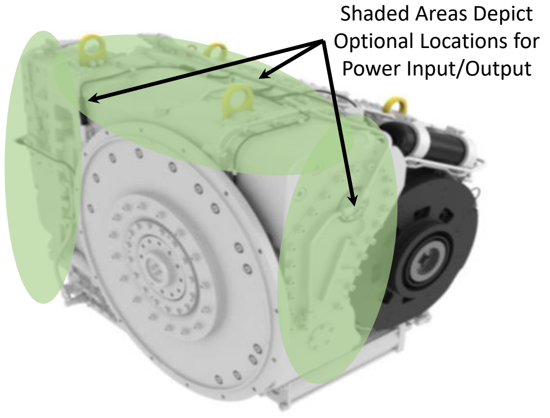
Shaded Areas Depict
Optional Locations for
Power Input/Output

Figure 12 - Accessory power input/output location options

The high efficiency of the transmission and mechanically based steering are key factors enabling use of realistically sized electric motors to provide silent mobility capabilities. As shown in Figure 9, the ACT Family enables 4rpm pivot turns using input power less than 5kW/ton vehicle weight. This reduced power input enables application of reasonably sized electric motors and battery packs to facilitate improved, and silent, on station vehicle agility.

Avoiding fluid couplings for accessory drives also reduces heat generation and provides the ability to use the transmission hydraulic system to provide generators and controllers their critical cooling needs.

6. Validation Testing Capability

SAPA has invested in sophisticated US based development and testing capabilities as shown in Figures 13 and 14. Vehicle weights from 30 to 75 tons can be simulated in the laboratory for testing and validation, and the system is capable of testing powerpacks with transmission output power up to 1100hp continuous and 1350hp during accelerations. Accounting for system impacts, these power absorption levels allow testing of power packs using engines up to 1500Hp.

The current data acquisition system can acquire 64 channels of independent temperature, pressure, and flow data, in addition to CAN data, proprietary controller data channels, fuel flow, and dyno speed and torque data.

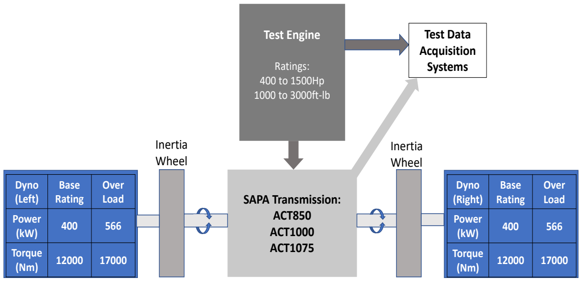

Figure 13 - SAPA Shelby Township dyno test schematic

Figure 14 - SAPA Shelby Township powertrain test cell

The SAPA test system can execute load cycles, acceleration testing, road profiles, steering testing, and braking testing. These testing and data acquisition capabilities provide for a complete quantification and validation of pack and component power, torque, efficiency, fuel consumption, temperatures and pressures, and heat rejection, so customers can easily confirm the benefits of the ACT to their application(s).

7. Manufacturing

SAPA will manufacture the ACT transmissions in the US. The 110,000 sq ft SAPA Transmission facility in Shelby Township, MI will be used for transmission assembly and product testing. SAPA will enable, utilize, and validate its domestic supply base, depicted in Figure 15, to provide transmission components that meet the rigorous quality requirements of the ACT units and the US Army. SAPA also has internal component machining, manufacturing, and validation capability, ensuring that component supply will not be adversely affected by transient supply disruptions that may occur at any supplier. Low-rate initial production (LRIP) can commence December 2023.

Figure 15 - SAPA manufacturing supply chain sites

8. Conclusion

The SAPA ACT family of transmissions provides the US Army's tracked vehicles of today <u>and tomorrow</u> with increased mobility, agility, efficiency, and performance.

ACT technology and in-use efficiency characteristics benefit existing tracked vehicles by improving fuel economy, range, maneuverability, and performance and by reducing GHG emissions, heat rejection, and cooling system requirements. The ACT family's common modular designs would also reduce the maintenance, logistic and training burdens of current tracked vehicles.

Tomorrow's tracked vehicles will not only benefit from the parameters listed for today's vehicles, but also from the reduced sensitivity of the ACT to the impacts of increased vehicle weight. The ACT family also provides inherent adaptability to electrification for silent maneuverability, hybridization, transient power boost, and increased electric power generation. Finally, the ACT family enables, through 'built in' DBW capabilities, fielding of optionally manned, unmanned or remotely operated tracked vehicles.

9. REFERENCES

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[2]"Request for Project Proposals Under GVS OTA W15QKN-14-9-1002-RPP3 – Research Area 2.2 Advanced Combat Transmission," Army Contracting Command – New Jersey to National Center for Manufacturing Sciences (NCMS) for the National Advanced Mobility Consortium (NAMC), 30 December, 2015.

[3] Aliotta, J., "Autonomous Mobility Extended Range Cannon Artillery (AMERCA) video demonstrating remote crew station, teleoperation, and waypoint navigation", CCDC/GVSC, 1 November, 2021, https://www.dvidshub.net/video/822439/amerca-video (DISTRIBUTION A. Approved for Public Release, distribution unlimited. OPSEC Review #5953.