2022 NDIA MICHIGAN CHAPTER
GROUND VEHICLE SYSTEMS ENGINEERING
AND TECHNOLOGY SYMPOSIUM
POWER & MOBILITY TECHNICAL SESSION
AUGUST 16-18, 2022 - NOVI, MICHIGAN

PUSHING THE LIMITS WITH A FULLY GEARED, HIGH EFFICIENCY 1000HP TRANSMISSION FOR TRACKED VEHICLES

Mike Brown[1], Brent Marquardt[1], Adam McLeod[1], Harold Moore[1], Greg Szkilnyk[1]

[1]Ker-Train Research Inc., Kingston, ON, Canada

ABSTRACT

Ker-Train Research Inc. has designed, manufactured and tested the Innovative Combat Transmission (ICT), a 1000hp, 32-speed Binary Logic Transmission for tracked vehicles. The ICT was originally intended to replace the HMPT in the Bradley Fighting Vehicle (BFV) but, with the latest upgrades and improvements, also finds itself a suitable candidate for higher powered tracked vehicle applications such as the Advanced Power Demonstrator (APD) and other future vehicle programs.

Citation: Brown, M., Marquardt, B., McLeod, A., Moore, H., Szkilnyk, G., "Pushing The Limits With a Fully Geared, High Efficiency 1000hp Transmission For Tracked Vehicles," In *Proceedings of the Ground Vehicle Systems Engineering and Technology Symposium* (GVSETS), NDIA, Novi, MI, Aug. 16-18, 2022.

1. INTRODUCTION

With over 10 years of research and development, the Innovative Combat Transmission (ICT) is the latest generation of 32-speed binary logic transmissions (BLT) for tracked vehicles from Ker-Train Research Inc. (KTR). Similar to its predecessors, the Gemini III Alpha and the Gemini III Beta, the ICT was originally intended to be a drop-in replacement transmission solution for the HMPT transmission in the Bradley Fighting Vehicle (BFV), as well as an alternative option for other similar 40-50 ton tracked vehicle platforms. However, with recent upgrades and continued optimization, the ICT, now rated for a peak input power of 1000hp and continuous input power up to 785hp, has evolved into a suitable candidate for higher powered tracked vehicle applications.

The ICT was designed, manufactured and tested by KTR, with the assistance of prime contractor Allison Transmission (ATI), for the U.S. Army's Ground Vehicle Systems Center (GVSC). In August of 2021, the transmission was delivered to GVSC and is currently awaiting new control software to begin the next phase of testing.

2. KER-TRAIN CORE TECHNOLOGY

Unrivaled packaging is achieved in KTR's transmissions using a variety of unique patented drivetrain technologies, such as high power density addendum contact coplanar gearing, high efficiency PolyCone clutches, compact one-to-one torque couplings and fully geared regenerative steering differentials.

2.1. Addendum Contact Gears

KTR's high power density Coplanar gears incorporate addendum-form gear tooth flanks that are designed to provide extremely high contact ratios that result in less gear mesh stiffness variation, more torque capacity and increased efficiency when compared to traditional involute gearing. As shown in Figure 1, addendum-form gear teeth flanks mesh along an arc of congruency between the addendums of the mating gear teeth, in contrast to traditional involute teeth that mesh along a line of action.

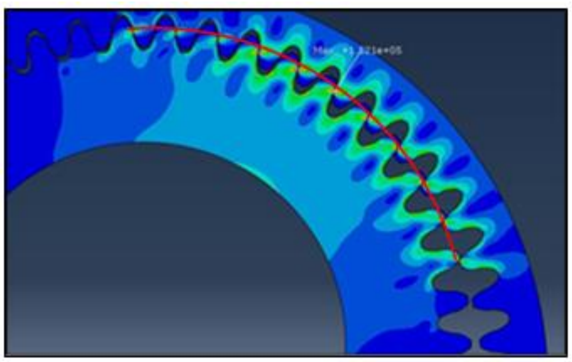

Figure 1 - Addendum-form gear tooth flanks meshing along arc of congruency (path of contact in red)

A typical coplanar arrangement, shown in Figure 2, includes a pinion, a cluster and an annulus (internal ring gear). Not shown in the picture, for clarity, is a cage that typically houses the cluster gear and provides bearing support to the other components. When either of the pinion, annulus or cage is grounded, a gear ratio is produced between the other two elements. This leads to six potential ratio configurations: three speed increasing ratios (one of which is reversing) and three speed decreasing ratios (one of which is reversing). Conversely, by clutching any two of the gear elements together, a 1:1 ratio state is created.

This compact coplanar arrangement allows for a large range of gear ratios in a relatively small package.

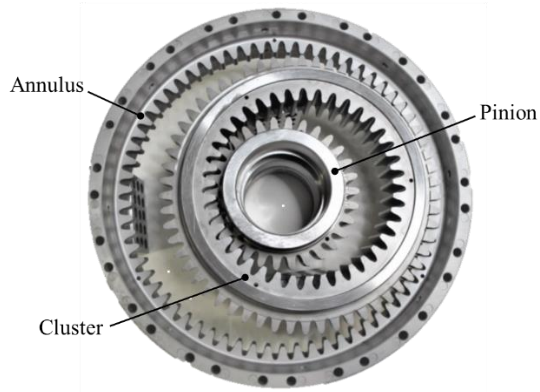

Figure 2 - Coplanar gear set (cage not shown)

In recent years, extensive functional and durability testing has been performed on the addendum contact gears that has helped to validate currently selected manufacturing tolerances and develop a suite of in-house software tools at KTR. These tools allow the designer to optimize sizing of the gears leading to increased gear life and capacity. Also, with the support of Gleason Cutting Tools Corp. and Forest City Gear, it has been shown that production tooling (hobs, shaper cutters and grinding wheels) can be designed and manufactured at an equivalent cost to production tooling for traditional involute gears.

2.2. PolyCone Clutches

KTR's PolyCone clutches are unique couplings that comprise a pair of clutch end members and a center member that are machined with concentric cones that wedge together when engaged. The wedging action increases the normal force on the mating cone surfaces, which in turn increases the tangential frictional force, thereby increasing

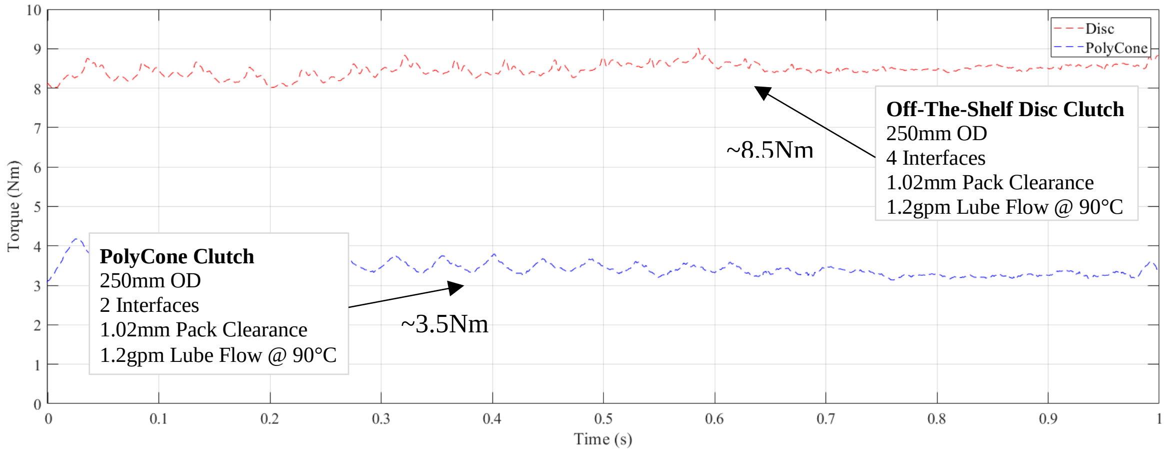

Figure 3 - Extracted test data from clutch drag test comparing disc clutch to PolyCone clutch

the torque carrying capacity when compared to a traditional flat plate friction clutch.

PolyCone clutches also offer the advantage of significantly reduced parasitic losses in their disengaged state, which helps to improve overall transmission efficiency. Figure 3 shows extracted data from a clutch drag test conducted recently at Ker-Train that compared a traditional OTS disc clutch to a PolyCone clutch at a slip speed of 2500rpm. The clutch packs were designed to equivalent specifications in terms of torque carrying capacity and clutch pack clearance. The PolyCone clutch showed significantly lower parasitic losses. A similar result was found back in 2012 when a PolyCone clutch was compared to the two friction plate wet clutch in the 1-2-3-4 clutch assembly of the General Motors Hydra-Matic 6T40 transmission. In this study, all of the internal components were removed from the Hydra-Matic 6T40 transmission housing except for the clutch assembly to target clutch spin losses specifically. In the study, each of the clutches were spun up to 3500rpm over a 180 second linear ramp. The overall trend shows that the contribution of the PolyCone clutch to the parasitic losses is minimal when compared to the two friction plate clutch (Figure 5).

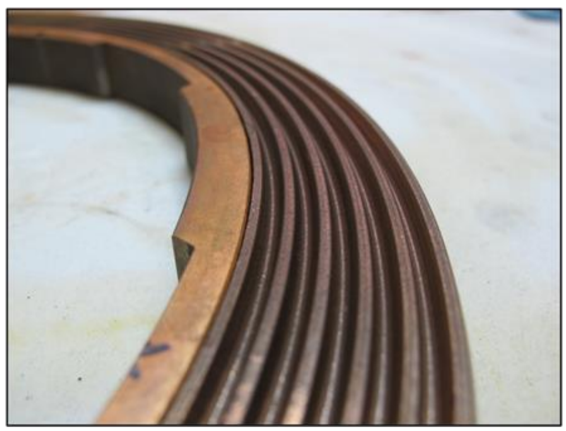

Figure 4 - Polycone clutch (side of center member)

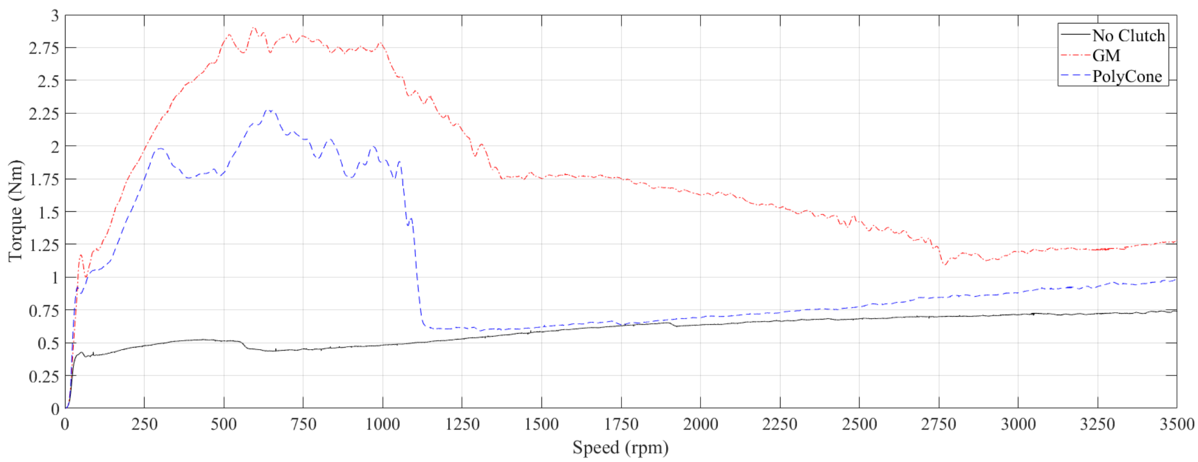

Figure 5 - GM Hydra-Matic 6T40 1-2-3-4 two friction plate clutch vs. KTR PolyCone clutch

2.3. One-To-One Torque Coupling

KTR's one-to-one torque couplings typically include a center member and a pair of side members with a plurality of congruent holes that are disposed about each member's rotational axis at a radius. Cylindrical rollers extend through the holes of the center member into the holes of the side members and allow the transfer of torque from one rotational axis to another without a change in rotational speed or direction. A one-to-one torque coupling is generally used in conjunction with a single coplanar addendum contact gear set or integrated directly into the coplanar gear set to produce a small gear ratio on a single rotational axis (Figure 6).

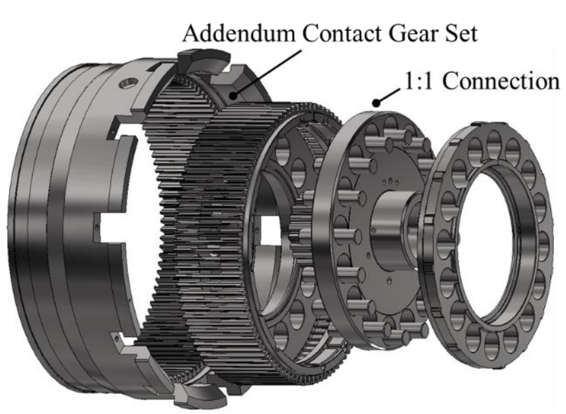

Figure 6 - Exploded view of a 1:1 connection integrated into a coplanar gear set

2.4. Regenerative Steering Differential

KTR's regenerative steering differential (Regen) is a fully-geared assembly comprising two input members and two output members. Typically, each input member is connected to the output of an independent transmission (a Main transmission and a Bias transmission, respectively – see Figure 8) and the output members are connected (directly or indirectly) to the final drives of the vehicle. The kinematics of the regenerative steering differential are such that when a speed differential exists between the two input members, a speed differential is created between the two output members. Therefore, steering is achieved by varying the speed differential between the outputs of the Main and Bias transmissions or conversely, between the two input members of the Regen.

From a tracked-vehicle perspective, in a straight drive scenario when the output speeds of the Main and Bias transmissions are equal, the components within the regenerative steering differential act as a solid coupling, thereby creating little to no losses. In a turn scenario, the negative drag torque that is produced on the inner track is regenerated from the slower inner track to the faster outer track directly through the output members of the regenerative steering differential without passing through either of the input members. This is particularly advantageous in terms of efficiency and maximum power output at the sprockets, as the negative drag torque does not put any extra load requirements on the components within the independent transmissions driving the input members, but instead helps to drive the outer track throughout the turn. The gears within the Regen have been designed to allow loads up to 0.9 tractive effort to weight per side at one time, which represents an extreme loading condition that is significantly higher than any of the realistic duty cycle loadings that were provided.

KTR has two different versions of the regenerative steering differential that function identically from a kinematic standpoint: a version with addendum contact gearing and one-to-one torque coupling as well as a version with a 3-pinion-cluster planetary-style arrangement.

3. BINARY LOGIC ARCHITECTURE

A binary logic transmission (BLT) architecture is formed with an interconnected series of gear modules, each of which can operate in one of two possible states: an engaged gear ratio state or a disengaged 1:1 ratio state. Typically, the state of each gear module is controlled by a binary clutch pack comprising two separate PolyCone clutches that are activated by either hydraulic pressure or spring force.

The total number of gear modules, *n*, defines the total number of ranges in the transmission by the exponential relationship shown in Equation 1. Given a desired overall transmission ratio, *R*, an equal step ratio, *X*, shown in Equation 2, is created between each successive range. Furthermore, the gear ratio of each gear module is defined by Equation 3, where *i* represents the i^{th} gear module.

$$Number\ of\ ranges = 2^n \qquad (1)$$

$$Step\ Ratio = X = R^{\frac{1}{2^n - 1}} \qquad (2)$$

$$Gear\ Module\ Ratio = X^{2^{(i-1)}} \qquad (3)$$

Overdrive ratios can also be created by inverting a given module ratio (essentially swapping input and output members) and switching the engaged ratio state with the disengaged 1:1 ratio state for that particular module. Table 1 shows an example of a 32-speed binary logic transmission design with a relative overall ratio spread of 20:1 $\left\{\frac{14.967}{0.748} = 20\right\}$, but with the first and second gear modules providing overdrive ratios. The step ratio between ranges remains the same, but the ratio of each range is now shifted with the latter of the ranges providing overdrive ratios.

Table 1 - Binary Logic Design (with overdrive)

Range	X^{-1}	X^{-2}	X^4	X^8	X^{16}	*Ratio*
1	1	1	1.472	2.166	4.694	*14.967*
2	0.908	1	1.472	2.166	4.694	*13.588*
3	1	0.824	1.472	2.166	4.694	*12.336*
4	0.908	0.824	1.472	2.166	4.694	*11.200*
⋮	⋮	⋮	⋮	⋮	⋮	⋮
29	1	1	1	1	1	*1.000*
30	0.908	1	1	1	1	*0.908*
31	1	0.824	1	1	1	*0.824*
32	0.908	0.824	1	1	1	*0.748*

Having a large number of ranges with equal ratio steps between successive ranges lets a BLT operate in a CVT-like manner allowing the power source (engine or motor) that is driving the transmission to be operated under its most efficient conditions.

4. ICT OVERVIEW

The ICT, shown assembled in Figure 7, is a fully geared, drive-by-wire capable, 32-speed transmission with a ratio spread of 14.32:1 to 0.75:1 in both forward and reverse, a maximum total output torque capacity of 16,000lbf-ft and a maximum output speed of 3785rpm.

Figure 7 - Innovative Combat Transmission

Figure 8 shows a general overview of the ICT's key components and subsystems.

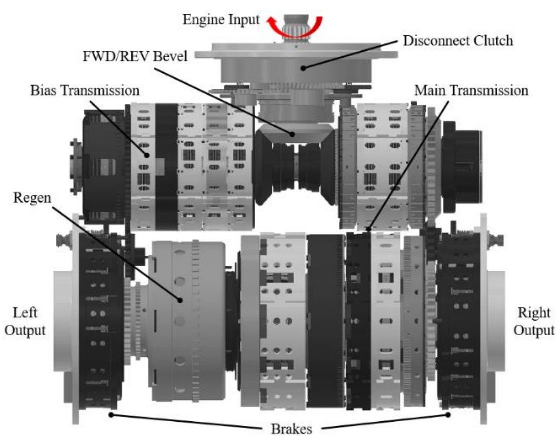

Figure 8 - Key ICT subsystems

The Main and Bias transmissions are independent 32-speed binary logic transmissions with the former providing the main propulsive effort and the latter supplying differential torque for steering. Each transmission contains five gear modules with corresponding PolyCone clutch packs that are operated using a series of electronically controlled solenoid valves that change the gear module states to achieve the desired overall ratio (dependent on vehicle and transmission controller inputs). The fully-geared regenerative steering differential accepts the outputs from the Main and Bias transmissions and provides two independent track speeds for maneuverability.

4.1. Upgrades and Improvements

Using the exact same space claim as its predecessor, the Gemini III Beta, KTR has been able to increase the peak power rating of the ICT to 1000hp (from 900hp) through refined sizing methods, optimization of key structural components and core technology testing of the Coplanar gears and PolyCone clutches.

Other notable improvements include:

- The addition of an input disconnect clutch. This allows the transmission to be decoupled from the engine, promoting minimal spin losses in the neutral state while also allowing for full stall capabilities.
- More balanced bearing structures within the input bevel as well as the gear modules in the Main and Bias transmissions.
- Caliper-style PolyCone clutch configuration in certain modules to reduce axial loads through components when the clutch is engaged.
- Balance dam optimization in the rotating clutch packs.
- Redesign of the input bevel location. This allowed it to grow radially, thereby increasing its capacity.

4.2. Original Application Target

As mentioned in the introduction, the original intent of the ICT was to replace the relatively inefficient HMPT transmission in the BFV. KTR worked with specifications provided by GVSC (space claim, hardware mounting locations, etc.) to ensure a true drop-in solution. The ICT currently exceeds power, speed-on-grade, and range coverage specs while also being compatible with existing external features on the BFV, such as the V903 engine interface, the PTO, identical brake connection points and hull mounting features. Figure 9 shows the ICT as a drop-in solution in a BFV hull.

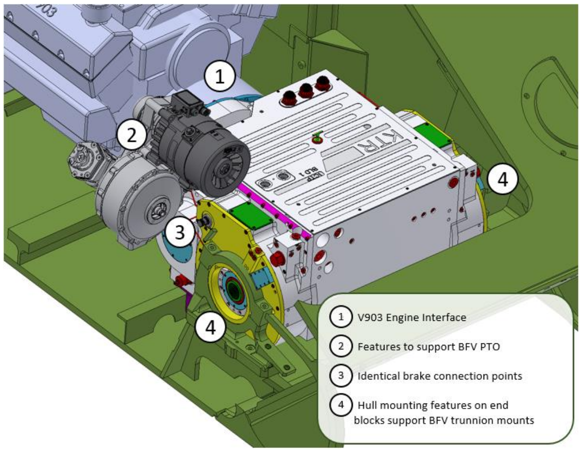

Figure 9 - ICT installed in the BFV

4.3. Future Application Targets

Realizing GVSC's ever increasing interest and funding in Cummins Inc.'s 1000hp Advanced Combat Engine (ACE), KTR has included provisions in the design of the ICT that will allow the transmission to pair seamlessly with the ACE. This compatibility makes it a suitable candidate for other higher powered tracked-vehicle applications such as, but not limited to, the Advanced Powertrain Demonstrator (APD). Figure 10 shows a conceptual view of the ICT/ACE pairing in a BFV hull.

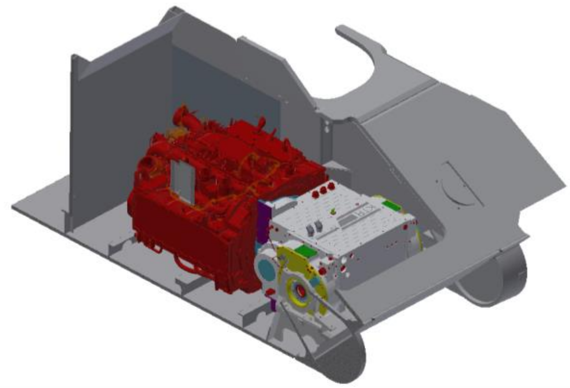

Figure 10 - ICT paired with the Advanced Combat Engine (ACE)

5. INTEGRATION FLEXIBILITY

The ICT has many features that make it easily adaptable for a variety of power packs and vehicle layouts.

The current ICT design has T-input configuration, in which the input bevel gear assembly can be tailored for different engine speed variations if desired. A conceptual view of an alternative U-input configuration is shown in Figure 11. The U-configuration has a potential advantage of better packaging with an opposed piston engine, such as the ACE, thereby reducing the overall length of the power pack in the engine compartment. One of the two outer engine cranks can be connected to the input shaft of the transmission. The transfer gear ratio can be altered to accommodate different engine speeds (similar to the input bevel in the T-configuration). Also, with the input bevel removed, the components along the input axis can be shifted to one side creating a potential location for running an accessory system such as compressor, generator or multispeed drive, thus creating an extremely compact power pack.

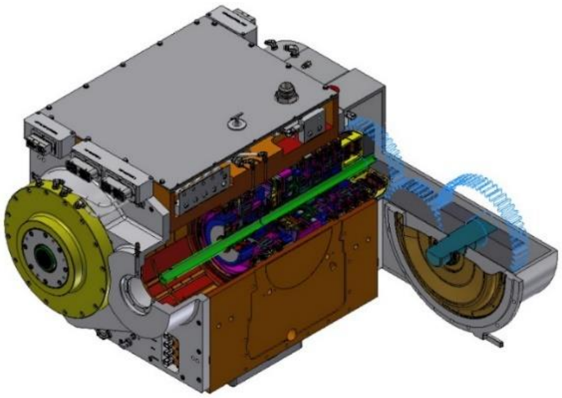

Figure 11 - Conceptual view of a U-input configuration

A flexible PTO design also supports multiple PTO drive locations and the ability to drive more than one PTO if desired. Figure 12 shows four potential PTO configurations with a transmission in a T-configuration.

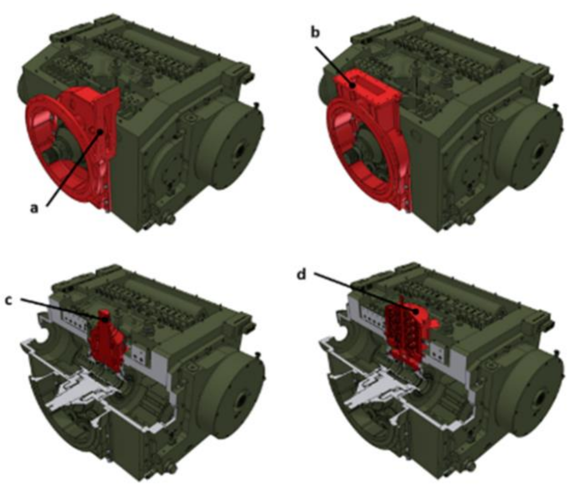

Figure 12 - Potential PTO locations

Another advantage from an installation standpoint is that the ICT can be used in front- or rear-mounted power packs due to the fact that its operation in forward and reverse is symmetric (i.e. interchangeable operation in forward and reverse).

6. TESTING

The test plan for the ICT was laid out in four phases: 1) Low power (400hp) steady-state functional testing at KTR, 2) Low power testing at KTR to prove out the controller, 3) High power (785hp) steady-state and dynamic testing at GVSC, and 4) Vehicle demonstration at GVSC.

6.1. Testing at KTR (Phase 1)

KTR's test cell is outfitted with a 400hp tandem A/C motor set that is capable of producing a maximum continuous torque of 1150lbf-ft and a pair water cooled drum brake dynamometers that can apply a maximum combined output torque of 12,000lbf-ft. A schematic of the test cell is shown in Figure 13 and a photo of the ICT being tested is shown in Figure 14.

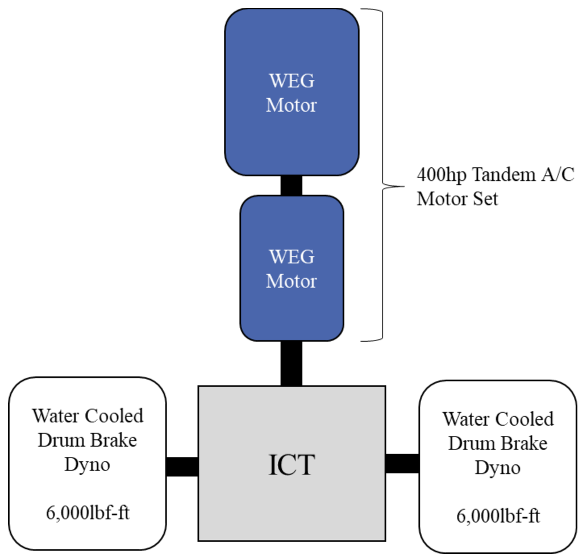

Figure 13 - Schematic of KTR Test Cell Equipment

Figure 14 - ICT in test cell at KTR

In mid-2021, the ICT was put through a series of steady state functional tests at KTR prior to being shipped to GVSC.

6.1.1 Spin Loss Testing

Spin losses were mapped out from 800rpm to 2600rpm by running the ICT in straight drive with the outputs disconnected in each of the 32 ranges.

6.1.2 Functional Loaded Testing

In this phase, the ICT was tested to peak input and output torques of 1,150lbf-ft[1] and 12,000lbf-ft, respectively. Straight drive, turn and pivot scenarios were all tested.

6.1.3 Efficiency Testing

Even though KTR's test cell is limited to an input power of 400hp, efficiency testing was conducted to give a lower bound estimate on the ICT's overall average efficiency across all 32 ranges, which was measured to be 84.1%. Its average mechanical efficiency (spin losses removed) was 92.4%. An efficiency map across all ranges is shown in Figure 15. Assuming that the mechanical efficiency in each range remains constant, the ICT's projected overall efficiency at full continuous rated power of 785hp is 88.4% and at peak rated power of 1000hp is 89.2%.

7. FUTURE WORK

The main focus of future work for the ICT is to complete the control software so that further testing can be undertaken at KTR and GVSC with the overall goal of testing the ICT at the vehicle level.

Several years ago, GVSC[2] controls engineers developed and integrated a pair of transmission controllers (FlexECUs) for the Gemini III Alpha with the assistance of KTR. The controllers were used to test the Gemini III Alpha in a dynamometer environment with the end goal of automatically shifting through all of the ranges (up and down) at no load, which was successfully completed.

In recent years, GVSC has been working with ETAS to develop a new state-of-the-art controller called the NextECU, which will have expanded I/O capacity and improved capabilities compared to the pair of Gemini III Alpha controllers.

It is expected that GVSC will leverage and upgrade the existing control software that was used for the Gemini III Alpha and port it over to a NextECU controller once funding becomes available.

[1] 1150lbf-ft is approximately 75% of the maximum engine torque available from a 785hp engine (V903)

[2] GVSC was known as the U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC) at the time of this development

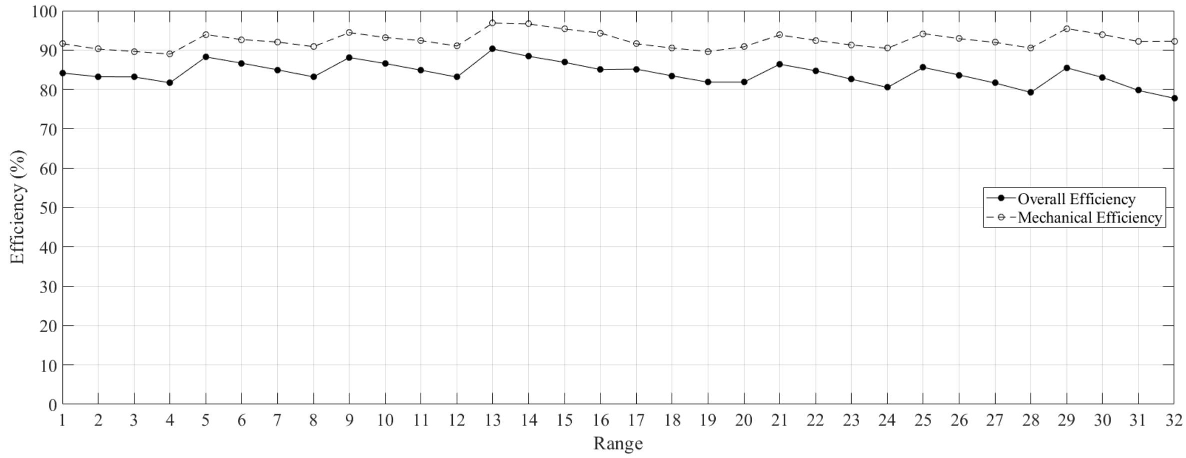

Figure 15 - ICT Efficiency @ 400hp Input Power

8. CONCLUSION

KTR's Innovative Combat Transmission has gone through multiple design iterations dating back to the original prototype of the Gemini III Alpha, culminating in a compact, high efficiency, 1000hp 32-speed binary logic transmission for tracked vehicles.

The ICT was originally intended to replace the HMPT in a Bradley Fighting Vehicle and with a tested overall efficiency of at least 84%, the ICT would dramatically increase a BFV's performance by providing more power to the sprockets while bettering fuel economy at the same time, thus improving vehicle range as well as tactical and logistical abilities.

Now rated at 1000hp, the ICT is well suited to be paired with a Cummins Advanced Combat Engine, making it an ideal candidate for higher powered applications such as the Advanced Power Demonstrator (APD).

KTR is awaiting support from GVSC controls engineers to upgrade and finalize the existing control software so that the ICT can be further tested in a dynamometer environment as well as be installed in a vehicle and tested remotely.

9. REFERENCES

[1] M. Brown and B. Marquardt, "Low Drag Performance of Ker-Train Research Inc.'s PolyCone Clutch", *Internal Report*, Kingston, January 2012.