

Development of a Stationary Axle Efficiency Test Stand and Methodology for Identifying Fuel Efficient Gear Oils for Military Applications - Part 1

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ABSTRACT

For existing fleets such as the U.S. military ground vehicle fleet, there are few ways to reduce vehicle fuel consumption that don't involve expensive retrofitting. Replacing standard lubricants with those that can achieve higher vehicle efficiencies is one practical and inexpensive way to improve fleet fuel efficiency. In an effort to identify axle gear lubricants that can reduce the fuel consumption of its fleet, the U.S. Army is developing a stationary axle efficiency test stand and procedure. In order to develop this capability, on-track vehicle fuel consumption testing was completed using light, medium, and heavy tactical wheeled vehicles following a modified SAE J1321 type test procedure. Tested lubricants included a baseline SAE 80W-90, a fuel efficient SAE 75W-90, and a fuel efficient SAE 75W-140. Vehicle testing resulted in reductions in fuel consumption of up to 2%. Using data collected during vehicle testing and data from vehicle simulations, a stationary axle efficiency test stand was designed and built to allow evaluation of axle hardware under loading conditions representative of real world operation. The test stand was constructed in a modular fashion capable of fitting a variety of military axles, and test method developmental work was initiated using hardware representative of the light and medium tactical wheeled vehicles used during on-track vehicle testing. Results to date have shown the stationary test stand to have excellent ability to differentiate and map axle efficiency changes between lubricants. Stationary testing has also been shown to offer a higher degree of accuracy than full-scale vehicle testing (more tightly controlled conditions), and provides efficiency results at a much lower cost than full-scale vehicle testing. This work is intended to support the future development of a Federal Test Method (FTM) to define procedures to evaluate potentially fuel efficient gear oils (FEGO) for use in military ground equipment.

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INTRODUCTION

The U.S. Army Tank Automotive Research Development and Engineering Center (TARDEC) is currently investigating the use and impact of fuel efficient gear oils (FEGO) in its ground vehicle fleet as a means to increase fleet fuel efficiency. Studies have shown that optimized axle gear lubricants aimed at increasing mechanical efficiency have the ability to reduce overall vehicle fuel consumption. This is beneficial to the U.S. Army, as new or updated lubricants are easily implemented into the existing vehicle fleet without requiring expensive or impractical vehicle retrofitting.

To determine the feasibility of using FEGO, the U.S. Army has conducted on-track vehicle testing in light, medium, and heavy tactical wheeled vehicles. Testing was completed following a

modified SAE J1321 type procedure, and the vehicles were evaluated following a city and highway type driving cycle using two fuel efficient gear oil candidates. The fuel efficient gear oil candidates included an SAE 75W-90 and an SAE 75W-140 product. Both were evaluated against a baseline SAE 80W-90 representative of axle gear oil currently fielded by the U.S. Army. This testing demonstrated potential improvements of up to 2% reduced vehicle fuel consumption, but results indicated that lubricant selection could vary depending on operating cycle and vehicle application.

Although effective in investigating gross vehicle fuel consumption changes, full-scale vehicle testing often lacks required accuracy needed to discriminate between smaller changes in efficiency. This is due to inherent variability of full scale vehicle tests which adds additional uncertainty in the fuel consumption measurement data

potentially masking real fuel consumption changes. Full-scale testing also limits the ability to provide more in-depth understanding of why specific oils perform as they do, as only a top level fuel consumption result is attained. In addition, full scale vehicle tests tend to be costly to conduct, especially in the case of specialized military equipment which can not only be difficult to obtain for testing, but also requires that testing be conducted on a closed course. Because of these limitations and the need to support additional future testing for continued product qualification efforts, a stationary axle efficiency test was desired.

No industry standardized test method currently exists outlining procedures to measure axle efficiency changes specifically as a result of lubricant changes. Several research papers were identified that have attempted to study and develop stationary axle testing methods [1, 2, 3], but evaluated hardware generally focused on light duty passenger vehicle applications. As the ability to study medium and heavy duty hardware was desired to represent the full breadth of the military vehicle fleet, the requirement for a new test stand was created. The following lists the goals outlined for the new stationary test stand:

- To the greatest extent possible, be modular in design to provide sufficient motoring and absorption capabilities to be able to test light to heavy duty vehicle military applications
- Provide improved testing accuracy and precision when assessing lubricants to improve the ability to discriminate between similarly performing oils
- Provide a lower cost alternative for quantifying efficiency impact from new lubricants compared to full-scale vehicle testing
- Support the future development of a Federal Test Method intended to be used for product qualification for the U.S. Army

Based on these goals a new test stand was designed and constructed, and developmental work was initiated using light and medium tactical wheeled vehicle hardware in an effort to relate results with vehicle testing and develop a test method to provide for future product qualification.

VEHICLE FUEL CONSUMPTION TESTING

To quantify the potential impact on overall vehicle fuel efficiency from the use of fuel efficient gear oils, vehicle fuel consumption testing was conducted on three classes of military vehicles representative of light, medium, and heavy tactical wheeled vehicles [4, 5, 6]. Testing was conducted on the up-armored M1151A1 High Mobility Multipurpose Wheeled Vehicle (HMMWV), the M1083A1 5-ton cargo variant of the Family of Medium Tactical Vehicles (FMTV), and the M1070 Heavy Equipment Transporter (HET), respectively. Photos of these vehicles are shown in [Figure 1](#), [Figure 2](#), and [Figure 3](#). [Table 1](#) outlines the technical description of each of these vehicles.

Table 1. Vehicle Descriptions

	HMMWV	MTV	HET
Model	M1151A1	M1083A1	M1070
Engine	GEP 6.5L(T)	CAT C7	DDC 8V92TA
Trans.	GEP 4sp Auto	Allison MD3070PT	Allison CLT-754
Power	142kW (190hp) @ 3400rpm	246kW (330hp) @ 2800rpm	372kW (500hp) @ 2100
Torque	515Nm (380lbft) @ 1700rpm	1154Nm (851lbft) @ 1600rpm	1992Nm (1470lbft) @ 2100
Axle Type	Frame mounted hypoid differential, wheel end portal reduction	Beam type, hypoid differential, planetary wheel end reduction	Beam type, hypoid differential, planetary wheel end reduction
Axle Ratio	5.91:1 overall (3.08:1 differential 1.92:1 wheel)	7.8:1 overall (3.9:1 differential 2:1 wheel)	7.36:1 overall
Curb Weight	4,731kg (10,430lbs)	9,606kg (21,178lbs)	17,649kg (38,910lbs)
GVWR	6,123kg (13,500lbs)	14,061kg (31,000lbs)	39,009kg (86,000lbs) (tractor) 104,961kg (231,400lbs) (+trailer)
Approx. Tested Weight	13,000lbs	31,000lbs	44,900lbs
No. of Drive Axles	2	3	4
Approx. Axle Oil Sump Vol.	1.9L (2qt)	11.5L (12qt)	17L (18qt)



Figure 1. M1151A1 HMMWV



Figure 2. M1083A1 FMTV



Figure 3. M1070 HET

Two fuel-efficient gear oils, an SAE 75W-90 and an SAE 75W-140, were evaluated against a baseline SAE 80W-90 to determine potential fuel consumption improvement. The baseline oil was selected to be representative of typical axle gear oil currently utilized in the military fleet. With the exception of the MTV, evaluations were conducted following two different driving cycles. The first driving cycle, referred to as the “highway cycle,” consisted of steady state operation at constant speeds to represent highway or convoy type operations. Specific speeds and distances for this cycle are shown in Table 2 for each of the vehicles. The second driving cycle, referred to as the “city cycle,” consisted of a combination of stop-and-go driving and limited duration medium and high speed operation to simulate general mixed use. An example of this cycle for the light tactical vehicle is shown in Figure 4 (Note: for the MTV and HTV, the city cycle remained the same except for the maximum speed, which was adjusted consistent with the maximum speeds shown for the highway cycle). Overall testing of the vehicles was based on procedures outlined by SAE J1321 Fuel Consumption Test Procedure - Type II [7], but some deviations were made from the method that do not comply with its most recent 2012 revision (generally related to overall test route length, and greater leniency regarding tested weather conditions). In general, J1321 testing requires a minimum of two trucks, one test and one control, which are operated over a desired test cycle, and gravimetric fuel consumption is measured and used to create a test to control, or T/C fuel consumption ratio. The relative changes in the T/C ratios between baseline and test segments are used to determine fuel consumption changes as a function of the changing variable (in this case, axle gear oil).

Table 2. Highway Cycle Profile

LTV Conditions	Vehicle Speed	Distance
1	40.2 kph (25mph)	36.2 km (22.5 miles)
2	88.5 kph (55 mph)	36.2 km (22.5 miles)
MTV Conditions		
1	40.2 kph (25mph)	36.2 km (22.5 miles)
2	80.5 kph (50 mph)	36.2 km (22.5 miles)
HTV Conditions		
1	40.2 kph (25mph)	36.2 km (22.5 miles)
2	64.4 kph (40 mph)	36.2 km (22.5 miles)

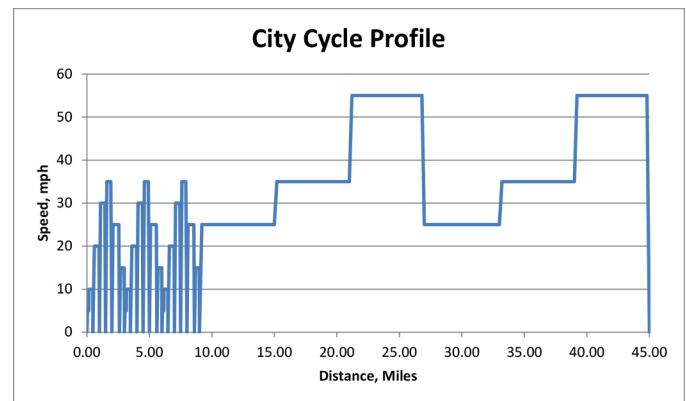


Figure 4. City Cycle Profile

Table 3 summarizes the fuel consumption improvement results for the 75W-90 and 75W-140 gear oils for the vehicle testing (Note: only one result is shown for MTV using 75W-140 fluid. Other vehicle testing was conducted with the MTV that supported fuel efficiency gains from lubricant changes, but results were combined with other powertrain fluid changes, so only the single axle result for the MTV is shown).

Table 3. Fuel Consumption Improvement versus baseline SAE 80W-90

	SAE 75W-90	SAE 75W-140
HMMWV, city	+0.71% +/- 1.82%	+2.17% +/- 1.09%
HMMWV, highway	+0.57% +/- 0.35%	+1.41% +/- 0.83%
MTV, city	Axle Only Evaluation Not Completed	
MTV, highway	+1.82% +/- 1%*	-0.84% +/- 1%*
HET, city	+1.89% +/- 1.1%	-2.75% +/- 1.62%
HET, highway	+0.75% +/- 0.77%	-1.89% +/- 0.31%

*confidence interval based on standard +/- 1% specified in pre-2012 SAE J1321 procedure. All other confidence intervals reported were calculated following post-2012 J1321 revision statistical analysis procedures.

As shown, an indication of positive improvement (i.e. fuel consumption reduction) was noted for the SAE 75W-90 oil for the HMMWV and HET vehicles on both the highway and city driving cycles. This suggests that the SAE 75W-90 is likely a good candidate to provide fleet wide fuel savings. However, for the SAE 75W-140, a different response was noted between the light duty application versus the larger medium and heavy tactical wheeled vehicles. In this case, the lighter HMMWV showed a positive improvement from the SAE 75W-140 on both driving cycles, while the heavier MTV and HET showed an almost equal detriment in fuel consumption for both. This result was unexpected as both the SAE 75W-90 and SAE 75W-140 were advertised as improved efficiency fluids, but the response from the 75W-140 was rationalized as churning losses due to the higher viscosity. Overall results brought into question the light and heavy class vehicles and how they differentiated the higher viscosity 75W-140 fluid differently. This was to be investigated further with the stationary axle stand.

TEST STAND CONSTRUCTION

The following sections outline the construction of the stationary axle test stand.

Determining Required Stand Loading Conditions

The first step required in creating the test stand was to identify all required loading conditions for the axles to be tested. For the MTV axle, J1939 CAN-BUS data was captured during on-track vehicle testing to record the transmission shaft output speed, gear selection, and driver requested torque at all operating conditions for the city and highway driving cycles. Using this data along with detailed powertrain power/torque data and the MTV's advertised 30/70 front/rear torque split, axle pinion input conditions were identified for each mode of the driving cycles. All conditions were calculated for the rearmost axle of MTV, as it was targeted for use on the test stand to avoid complications related to the articulation of the front steering axle, and the intermediate axle's differential pass through.

For the heavy and light vehicles, direct data from the vehicle testing was not available. To establish conditions for the test stand design for the heavy tactical wheeled class, TARDEC conducted computer based vehicle simulations for a Palletized Load System (PLS) vehicle that defined required wheel output torque values over the same specified driving profiles (note: the PLS platform simulated shares many powertrain component similarities with the HET). These simulated output torque values and speed profiles were then used to back calculate the required input pinion condition at the axle pinion. Similar to the MTV, conditions were identified specifically for the rearmost axle for simplicity. For the light duty HMMWV, maximum possible powertrain loading was determined to be well below the nominal requirements of the medium and heavy vehicles, so only verification of required input pinion speed (based on vehicle speed, wheel diameter, and gear ratio) was needed.

Component Selection & Layout

Based on the test conditions identified, all stationary axle stand components could be selected. It was desired to configure the stand in a T-type arrangement versus an L-type arrangement, as the T-type stand was expected to provide the most realistic operating conditions during the efficiency evaluations. In a T-type arrangement both wheel end outputs of the axle are coupled together and absorbed, as compared to an L-type stand, where one wheel end output is fixed sending all power through the differential gears to a single wheel end output.

For the input motor a VFD controlled 186kW (250hp) AC motor was identified to be sufficient in providing the required loading conditions for each of the desired test axles. As part of the T-type test arrangement, two 7.259:1 speed-increasing gear boxes were specified to convert the low speed high torque output of the tested axle into a higher speed but lower torque output that could then be coupled to an absorbing unit. Based on the output speed and torque of the gear boxes, a second 186kW (250hp) AC motor (configured as a generator) was specified for absorption to provide for improved low speed control instead of an eddy current type absorbing dynamometer. Figure 5 shows the general layout of the stationary axle efficiency test stand.

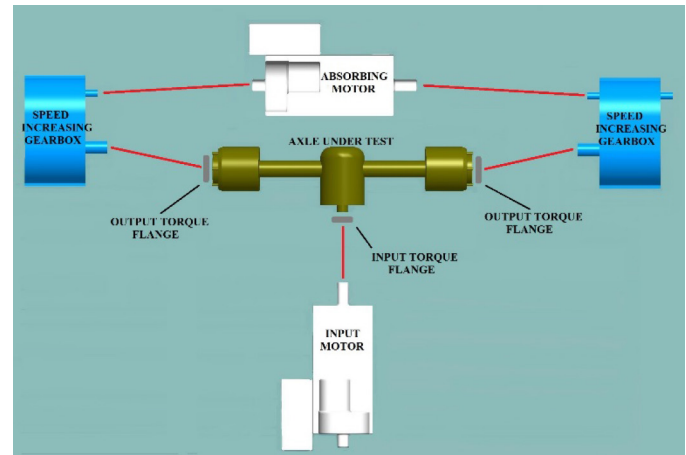


Figure 5. General Layout of Stationary Axle Efficiency Test Stand

For input and output speed measurement, incrementing encoders were integrated into the input motor and absorber units. For torque measurement, inline measurement directly at the axle's input and outputs (where applicable) was targeted to reduce any influence from the rest of the test stand components that could potentially skew the efficiency calculations. To accomplish this, flange type digital torque meters were specified, and special fixturing was machined for each axle application to mount the torque flange meters at the axle. Figure 6 shows a completed photo of the stationary axle test stand.

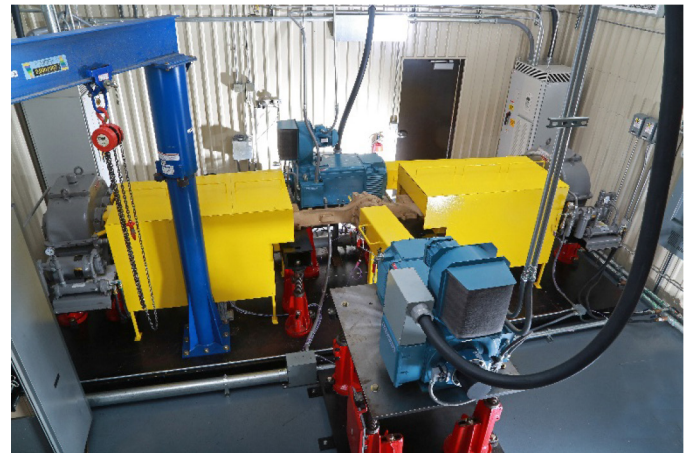


Figure 6. Completed Stationary Axle Efficiency Test Stand

Temperature Control

Temperature of the differential gear oil during operation has a substantial influence in the overall mechanical efficiency of the axle. Regarding temperature control during efficiency type testing, two general schools of thought are identified. The first considers that during real-world operation the axle will naturally stabilize to a temperature which will vary depending on the lubricant being used, its resulting efficiency in the axle, and the ambient temperature. As such, efficiency testing should be configured in such a way to allow the axle to achieve its own desired steady state temperature during the test process. This would require the ability to supply a fixed cooling rate to the axle gear oil during testing, providing some nominal cooling level to control temperature. The second school of thought allows the axle temperature to reach its own steady state temperature.