NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Autonomy-Enabled Fuel Savings for Military Vehicles: Report on 2016 Aberdeen Test Center Testing

Adam Ragatz, Robert Prohaska, and Jeff Gonder
National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Technical Report
NREL/TP-5400-67665
May 2017

Contract No. DE-AC36-08GO28308

Autonomy-Enabled Fuel Savings for Military Vehicles: Report on 2016 Aberdeen Test Center Testing

Adam Ragatz, Robert Prohaska, and Jeff Gonder
National Renewable Energy Laboratory

Prepared under Task No. WFJG.1000

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

Technical Report
NREL/TP-5400-67665
May 2017

Contract No. DE-AC36-08GO28308

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Available electronically at SciTech Connect http:/www.osti.gov/scitech

Available for a processing fee to U.S. Department of Energy and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
OSTI http://www.osti.gov
Phone: 865.576.8401
Fax: 865.576.5728
Email: reports@osti.gov

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5301 Shawnee Road
Alexandria, VA 22312
NTIS http://www.ntis.gov
Phone: 800.553.6847 or 703.605.6000
Fax: 703.605.6900
Email: orders@ntis.gov

Cover Photos by Dennis Schroeder: (left to right) NREL 26173, NREL 18302, NREL 19758, NREL 29642, NREL 19795.

NREL prints on paper that contains recycled content.

Acknowledgments

The authors acknowledge that funding for the work performed within the Autonomy-Enabled Fuel Savings for Military Vehicles project is provided by the Office of the Deputy Assistant Secretary of Defense for Operational Energy (ODASD(OE)) Operational Energy Capabilities Improvement Fund (OECIF) Program. TARDEC greatly appreciates the support it has received from the Director of Innovation and staff of ODASD(OE) within the Office of the Assistant Secretary of Defense for Energy, Installations & Environment.

List of Acronyms

AMAS	Autonomous Mobility Appliqué System
ATC	Aberdeen Test Center
ATEF	Automotive Technology Evaluation Facility
CAN	controller area network
CTA	Churchville Test Area
GPS	global positioning system
kg	kilogram
kW	kilowatt
lb	pound
mph	miles per hour
MTA	Munson Test Area
NREL	National Renewable Energy Laboratory
PTA	Perryman Test Area
SAE	SAE International
TARDEC	Tank Automotive Research, Development, and Engineering Center

Table of Contents

List of Figures

List of Tables

Project Background and Objective

Research into autonomy-enabled military vehicles has historically been motivated by concerns over personnel safety and operation efficiency, with less attention given to the potential for fuel savings. However, studies have estimated that autonomy in passenger and commercial vehicles could improve fuel economy by as much as 22%–33%[1,2] over various drive cycles. If even a fraction of this saving could be realized in military vehicles, significant cost savings could be realized each year through reduced fuel transport missions, reduced fuel purchases, less maintenance, fewer required personnel, and increased vehicle range. This autonomy-enabled vehicle project targets achieving broad fuel savings in excess of 5% over conventionally operated vehicles.

The National Renewable Energy Laboratory (NREL), located in Golden, Colorado, has supported this continued effort under Interagency Agreement IAG-15-1980 by installing instrumentation and data collection systems on-board test vehicles and analyzing the collected results to determine system performance and improve on the control strategy. The information presented in this report describes the test vehicles, additional instrumentation, and the data acquisition system added by NREL and presents preliminary results from the first round of testing. These results will be used to iterate on the system design and control strategy ahead of further planned testing in 2017 and 2018.

In addition to NREL's role outlined above, other key project contributors include:

- The Office of the Deputy Assistant Secretary of Defense for Operational Energy – provided the funding for this project.
- The U.S. Army Tank Automotive Research, Development, and Engineering Center (TARDEC), the project's principal investigator, is responsible for leading the project and implementing the custom control strategy to manipulate the original equipment manufacturer's signals onboard the vehicle.
- The U.S. Army Aberdeen Test Center (ATC) at the Aberdeen Proving Grounds – provided testing support and equipment and made the various test tracks available for this fuel economy testing.
- Argonne National Laboratory – is responsible for constructing the model-based custom control strategy and delivering it to TARDEC for implementation.
- Lockheed Martin – is responsible for the design and construction of the Autonomous Mobility Appliqué System (AMAS), the base autonomy kit for these military vehicles.
- Primus Solutions Inc. – handled custom fabrication, component installation, and vehicle logistics.

---

[1] Manzie, C., et al., 2007, "Fuel Economy Improvement for Urban Driving: Hybrid vs. Intelligent Vehicles." *Transportation Research Part C* 15, Elsevier, 1–16

[2] Wu, C., et al., 2011, "A Fuel Economy Optimization System with Applications in Vehicles with Human Drivers and Autonomous Vehicles." *Transportation Research Part D* 16, 515–524.

Test Vehicles

The test vehicles used for this autonomy-enabled fuel economy assessment were two different variants of the M915. The M915 is a military specification version of a typical over-the-road class 8 6x4 vocational tractor. The first vehicle, an M915A3, was configured as an unarmored day cab, and the second vehicle, an M915A5, was configured as an extended cab up-armored version of the M915. Both vehicles were powered by Detroit Diesel S60 series diesel engines with automatic transmissions. Each was connected to separate M872A3 flatbed trailers for the testing. The trailers were loaded with intermodal shipping containers and ballasted to near their gross combined weight ratings. Specifications are shown in Table 1.

Table 1. Vehicle Specifications

Vehicle Descriptor		
Truck Number	T12	T13
Truck Make / Model	Freightliner M915A3	Freightliner M915A5
Gross Vehicle Weight Rating	54,000 lbs. (24,494 kg)	66,000 lbs. (29,937 kg)
Gross Combined Weight Rating	105,000 lbs. (47,627 kg)	120,000 lbs. (54,431 kg)
Test Weight (Tractor + Trailer)	102,600 lbs. (46,539 kg)	111,910 lbs. (50,762 kg)
Engine Make / Model	Detroit Diesel S60	Detroit Diesel S60
Engine Power Rating	430 HP (321 kW)	500 HP (373 kW)
Engine Torque Rating	1,450 lb-ft (1,966 Nm)	1,650 lb-ft (2,237 Nm)
Transmission	Allison Automatic 4500 SP	Allison Automatic 4500 SP
Rear Ratio	4.88	5.38
Tires (Steer)	12R22.5	315/80R22.5
Tires (Drive)	11R22.5	315/80R22.5

Photos: M915A3 – R. Prohaska NREL | M915A5 - TARDEC

Data Acquisition System

Early in the project planning phase, a number of group discussions were held to determine the required data channels to capture so that all parties would be able to perform the necessary analysis. Some of these channels were available from the on-board diagnostic J1939 controller area network (CAN) bus, but other channels required adding additional instrumentation. The full negotiated required channel list is shown in Appendix A. However, the actual captured channel list exceeded the minimum requirements and is shown in Appendix B along with the channel units as recorded.

In addition to the legislated CAN channels available from each vehicle's on-board diagnostic network, NREL added thermocouples, pressure transducers, a GLONASS-enabled global positioning system (GPS), and a weather station. The system also included provisions to log the data stream from the high-accuracy AVL KMA mobile fuel flow meter installed by Primus Solutions shown in Figure 1. Data were recorded from the fuel flow meter in two ways, through a high-speed frequency-to-analog converter connected to the pulse output and an RS-232-to-CAN converter connected to the serial output. All signals were converted to a CAN where necessary and logged using a Vector GL2000 data recorder. The Vector GL2000 loggers were selected for their ability to log multiple CAN buses, which allowed for easy expansion, and the ability to connect with a Wi-Fi or cellular network for periodic data uploads. Additional specifications for the Vector GL2000 loggers are shown in Table 2. A schematic of the system is shown in Figure 2.

Figure 1. AVL KMA Mobile, 1 – Measuring Module, 2 – Conditioning Module
Photo by AVL

Table 2. Vector GL2000 Specifications

Technical Data	Description
CAN channels	CAN1 – 2: 2x fixed high-speed, wake-up capable CAN3 – 4: 2x user-configurable
Memory	SD memory cards up to 2 GB, SDHC up to 32 GB
Display	4 user-configurable LEDs
Inputs, outputs	4 analog inputs 4 digital inputs / outputs
Wireless data transmission	3G/UMTS or WLAN 802.11b/g
Supply voltage	6 V – 30 V
Current consumption @ 12V	Sleep mode: typically < 1 mA Standby mode: typically 60 mA Operating: typically 170 mA

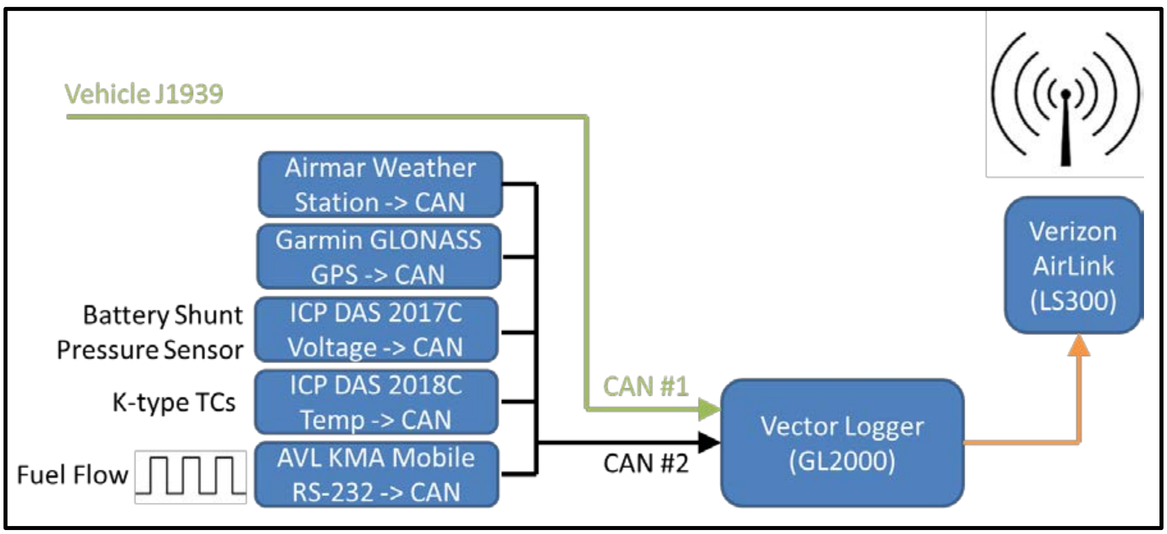


Figure 2. Data acquisition schematic

For additional information, a detailed bill of materials is included in Appendix C. A number of these modules required initial setup. Detailed documentation of the configuration settings for each module is included in Appendix D.

Fuel Economy Testing

The procedure used for this fuel economy testing followed the general guidelines of SAE International (SAE) Standard J1321 "Fuel Consumption Test Procedure – Type II."[3] The SAE J1321-supplied calculation utility was used to calculate the nominal fuel economy improvement and corresponding 95% confidence interval from the raw fuel use data where applicable. For both vehicles, there were generally three modes of operation:

- **Manual / Baseline**: In this mode, the driver handles all functions of operating the vehicle. This mode is used as the baseline condition. Speed control is maintained with manual manipulation of the accelerator pedal, brake pedal, and engine brake.
- **AMAS Cruise**: In this mode the driver still steers the vehicle, but all speed control functions are handled by the standard Lockheed Martin AMAS Cruise control system.
- **Smart Cruise**: This mode is similar to AMAS Cruise, but the AMAS Cruise control messages are manipulated by the model-based control strategy developed by Argonne National Laboratory and implemented by TARDEC. This strategy allows the actual speed to deviate more than usual from the commanded set speed in an effort to maximize fuel savings.

Each day of testing began with a number of warm-up laps until fuel economy and vehicle component temperatures stabilized. Testing began with three to five acceptable runs at each condition, starting with manual / baseline. If track time permitted, one vehicle remained in manual/baseline while the other vehicle went through each test condition, and then they switched conditions. This is the typical procedure for a Type II track test so the control vehicle can be used to normalize the results and account for changing environment conditions during testing. However, for some scenarios time did not allow for a full control vehicle test, and both vehicles ran through the test sequence at the same time. All testing was conducted at ATC at four different test areas. At some locations testing was repeated at various speeds and on various surfaces. The following sections describe the courses and test schedules and provide maps of each testing area.

Automotive Technology Evaluation Facility (ATEF)

The Automotive Technology Evaluation Facility (ATEF) track is a flat multi-surface, paved and gravel, 4.5-mile-long tri-oval around the Phillips Army Airfield. The paved surface has two lanes that go all the way around the airfield, with the single-lane gravel surface on the outside separated from the track by a grass median. Figure 3 shows a map of the track along with the location of crossing #1, which was used as the start and finish point for each lap. The vehicles began and ended each lap at speed, and continuously recorded data were split by lap using the geo-marker shown on the map. All testing was conducted in a counter-clockwise direction.

[3] Fuel Consumption Test Procedure - Type II, https://saemobilus.sae.org/content/j1321_201202

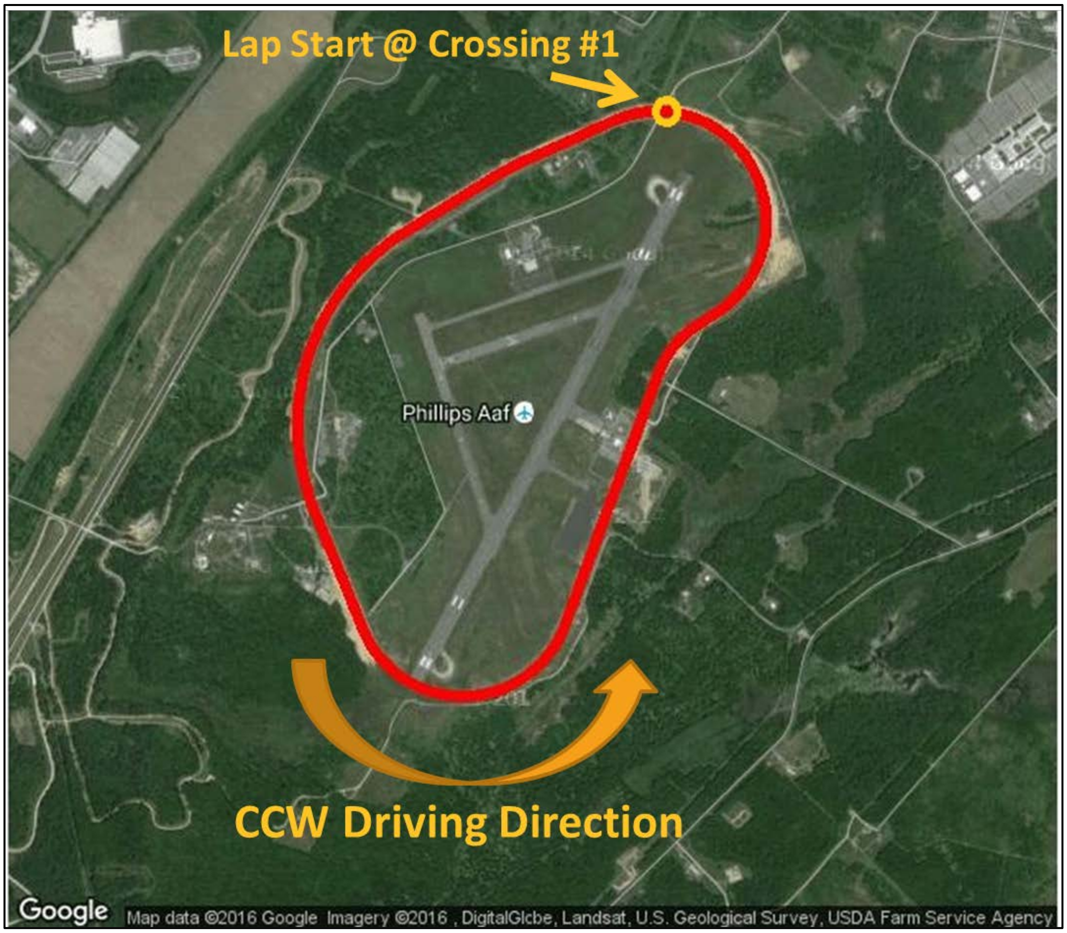


Figure 3. ATEF map, paved and gravel
© Google Maps

The test matrix for ATEF spanned three days. The first day focused on conducting a comparison of manual/baseline, AMAS Cruise, and Smart Cruise all on the paved surface. For this comparison, both vehicles where driven on the track at the same time 180 degrees apart. One vehicle continuously ran the baseline condition as the control truck as the other vehicle cycled through the various test conditions. Then, after a short break they switched. Figure 4 shows this schedule graphically.

ATEF (9/20/2016) - Morning

	Truck T12 (A3)		Truck T13 (A5)	
Lap	Baseline	Test	Baseline	Test
1	Warm-Up		Warm-Up	
2	Warm-Up		Warm-Up	
3	Warm-Up		Warm-Up	
4	Warm-Up		Warm-Up	
5	Warm-Up		Warm-Up	
6	Baseline		Baseline	
7	Baseline		Baseline	
8	Baseline		Baseline	
9	Baseline		Baseline	
10	Baseline		Baseline	
11		AMAS	Baseline	
12		AMAS	Baseline	
13		AMAS	Baseline	
14		AMAS	Baseline	
15		AMAS	Baseline	
16		Smart	Baseline	
17		Smart	Baseline	
18		Smart	Baseline	
19		Smart	Baseline	
20		Smart	Baseline	

ATEF (9/20/2016) - Afternoon

	Truck T12 (A3)		Truck T13 (A5)	
Lap	Baseline	Test	Baseline	Test
1	Warm-Up		Warm-Up	
2	Baseline		Baseline	
3	Baseline		Baseline	
4	Baseline		Baseline	
5	Baseline		Baseline	
6	Baseline			AMAS
7	Baseline			AMAS
8	Baseline			AMAS
9	Baseline			AMAS
10	Baseline			AMAS
11	Baseline			Smart
12	Baseline			Smart
13	Baseline			Smart
14	Baseline			Smart
15	Baseline			Smart

Figure 4. ATEF test matrix (9/20/2016)

The target speed for all conditions was 50 miles per hour (mph) in the straights and 40 mph in the curves. This is shown graphically in Figure 5. Although the Smart Cruise system was commanded to operate at these speeds, the model chose 45 mph and 35 mph, respectively, as more optimal operating speeds. Because of this, it was decided that the next day would begin with a manual/baseline test mimicking the Smart Cruise speeds in an effort to separate cruise control effects from speed set point effects. The schedule for day two is shown in Figure 6. Once the reduced-speed manual condition tests were finished, testing moved to the gravel course that runs on the outside of ATEF parallel with the paved course. In the interest of time, AMAS was omitted as a test condition so baseline and Smart Cruise could be compared keeping one vehicle as a control as was done previously on the paved road.

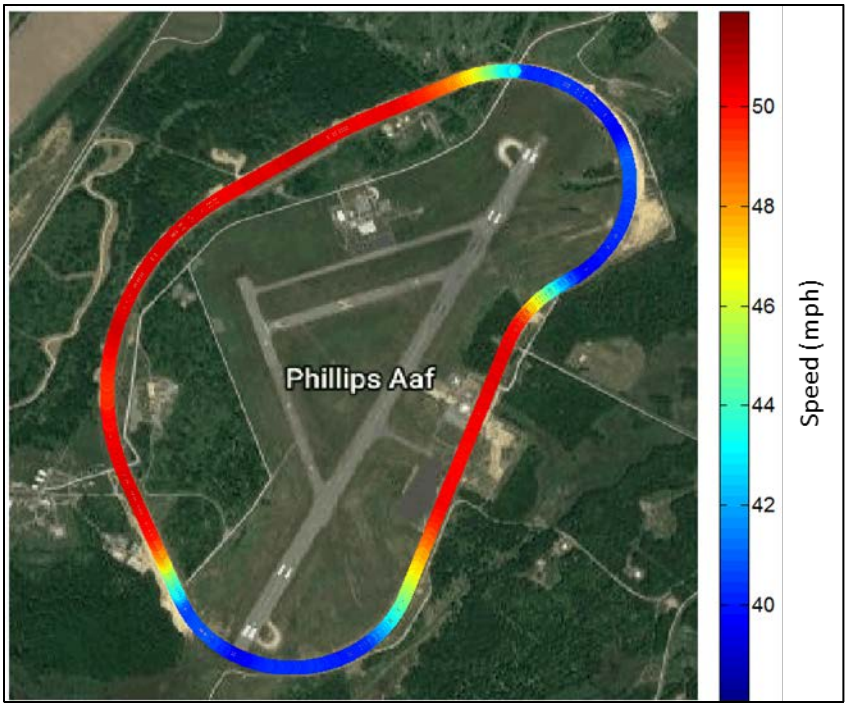


Figure 5. ATEF speed profile (mph)

© Google Maps

ATEF (9/21/2016) - Morning

	Truck T12 (A3)		Truck T13 (A5)	
Lap	Baseline	Test	Baseline	Test
1	Warm-Up		Warm-Up	
2	Baseline		Baseline	
3		35/45 Man		35/45 Man
4		35/45 Man		35/45 Man
5		35/45 Man		35/45 Man
6		35/45 Man		35/45 Man
7		35/45 Man		35/45 Man
8	Base Gravel		Base Gravel	
9	Base Gravel		Base Gravel	
10	Base Gravel		Base Gravel	
11	Base Gravel		Base Gravel	
12	Base Gravel		Base Gravel	
13	Base Gravel			Smart Grav
14	Base Gravel			Smart Grav
15	Base Gravel			Smart Grav
16	Base Gravel			Smart Grav
17	Base Gravel			Smart Grav

ATEF (9/21/2016) - Afternoon

	Truck T12 (A3)		Truck T13 (A5)	
Lap	Baseline	Test	Baseline	Test
1	Warm-Up		Warm-Up	
2	Base Gravel		Base Gravel	
3	Base Gravel		Base Gravel	
4	Base Gravel		Base Gravel	
5	Base Gravel		Base Gravel	
6		Smart Grav	Base Gravel	
7		Smart Grav	Base Gravel	
8		Smart Grav	Base Gravel	
9		Smart Grav	Base Gravel	
10		Smart Grav	Base Gravel	

Figure 6. ATEF test matrix (9/21/2016)

The third day of testing at ATEF included a condition that was not in the original test matrix, economy mode. Truck T12 (M915A3) was equipped with a transmission control pad button labeled as “MODE,” shown in the upper right-hand side of the pad in Figure 7. Enabling this feature allowed the transmission to shift into the final top gear, sixth (0.67:1). Otherwise, the transmission would remain in fifth gear (0.76:1) even at higher speeds. This feature was not on truck T13 (M915A5), which naturally used all six gears by default.

Figure 7. Allison transmission control pad (left) and transmission (right)
Photo by Allison Transmission

Because economy mode was not part of the original test plan, it was considered lower priority, and a full control vehicle style test was not performed. However, the team felt it would still be valuable to benchmark the effect while the other vehicle repeated the 35/45-mph manual condition to double-check the previous day's data. This was followed by urban testing, which was performed on the same track with three theoretical stop signs, and a target speed of 25 mph. Figure 8 shows a map of the course and the locations of the three theoretical stop signs. Due to the reduced speed, the urban test conditions took approximately twice as long, and therefore, only three laps were completed for each condition. The schedule for day three is shown in Figure 9. All testing was performed on the paved course.

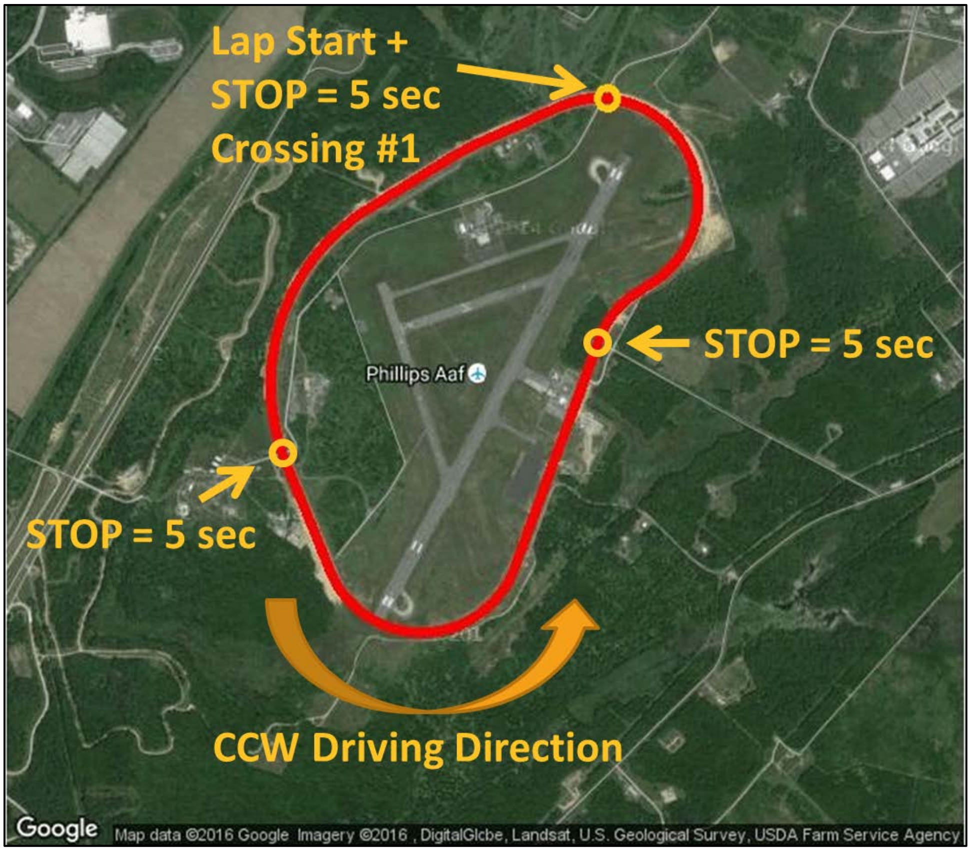


Figure 8. ATEF map, urban
© *Google Maps*

ATEF (9/22/2016)

	Truck T12 (A3)		Truck T13 (A5)	
Lap	Baseline	Test	Baseline	Test
0	Warm-Up		Warm-Up	
1	Baseline		Baseline	
2	Baseline		Baseline	
3	Baseline		Baseline	
4	Baseline		Baseline	
5	Baseline		Baseline	
6		Economy		35/45 Man
7		Economy		35/45 Man
8		Economy		35/45 Man
9		Economy		35/45 Man
10		Economy		35/45 Man
11	Urban Base			Urb Smart
12	Urban Base			Urb Smart
13	Urban Base			Urb Smart
14		Urb Smart	Urban Base	
15		Urb Smart	Urban Base	
16		Urb Smart	Urban Base	

Figure 9. ATEF test matrix (9/22/2016)

Churchville Test Area (CTA)

The CTA spans over 250 acres with 11 miles of interconnecting roads and test courses. It has a number of hilly cross-country courses with steep grades as well as controlled surfaces including mud, dust, and gravel. Test Course C, used for this testing, was wetted ahead of testing for dust control. The course is roughly 2.4 miles round trip, with a turnaround loop on either end. Figure 10 shows a map of the course, the four stop locations, and the geofence area used to split the laps. Unlike ATEF, at CTA the vehicles came to a complete stop between laps.

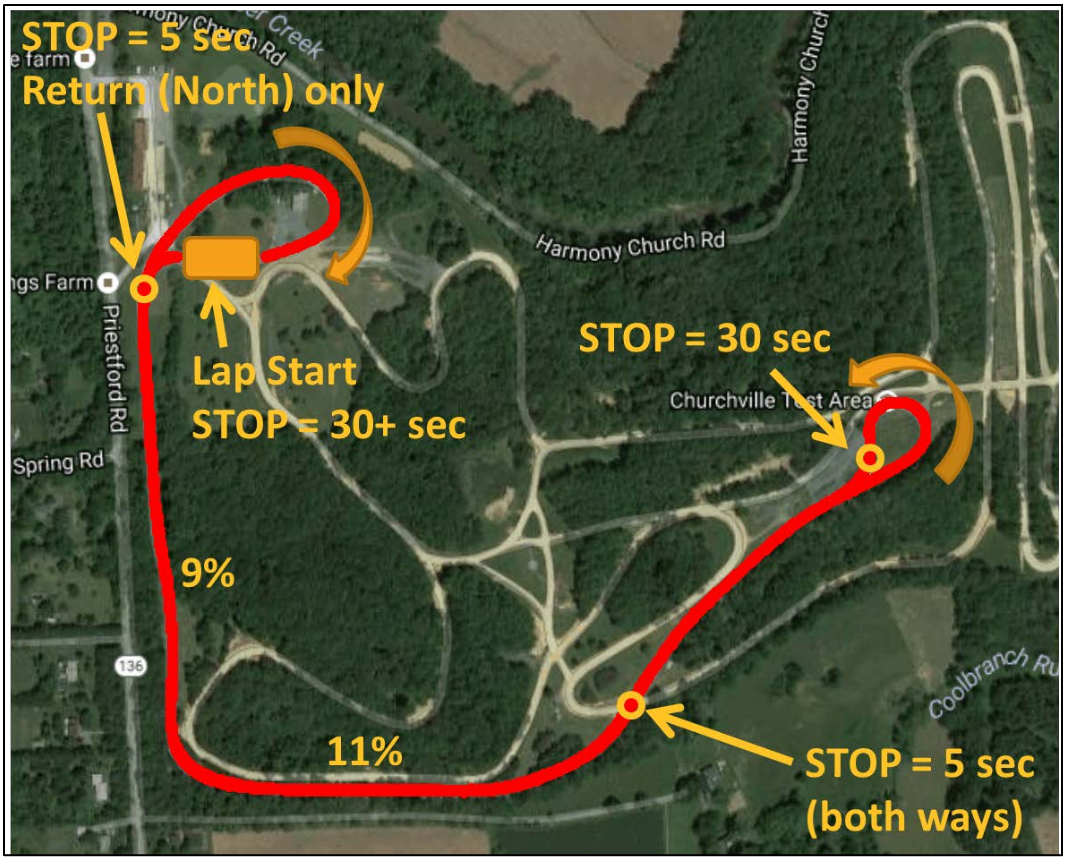


Figure 10. CTA map, Course C
© *Google Maps*

The test schedule for CTA Course C is shown in Figure 11. Example speed, fueling, and road grade traces are shown in Figure 12 for the baseline condition. Grade was calculated from the Garmin GPS using the velocity component data (east, north and up). The trace data show a large portion of the fueling is driven by uphill grade events on this test course.

CTA - C Course (9/23/2016)

	Truck T12 (A3)		Truck T13 (A5)	
Lap	Baseline	Test	Baseline	Test
1	Warm-Up		Warm-Up	
2	Warm-Up		Warm-Up	
3	Warm-Up		Warm-Up	
4	Baseline		Baseline	
5	Baseline		Baseline	
6	Baseline		Baseline	
7		Smart	Baseline	
8		Smart	Baseline	
9		Smart	Baseline	
10	Baseline			Smart
11	Baseline			Smart
12	Baseline			Smart
13		AMAS		AMAS
14		AMAS		AMAS
15		AMAS		AMAS

Figure 11. CTA – C course test matrix (9/23/2016)

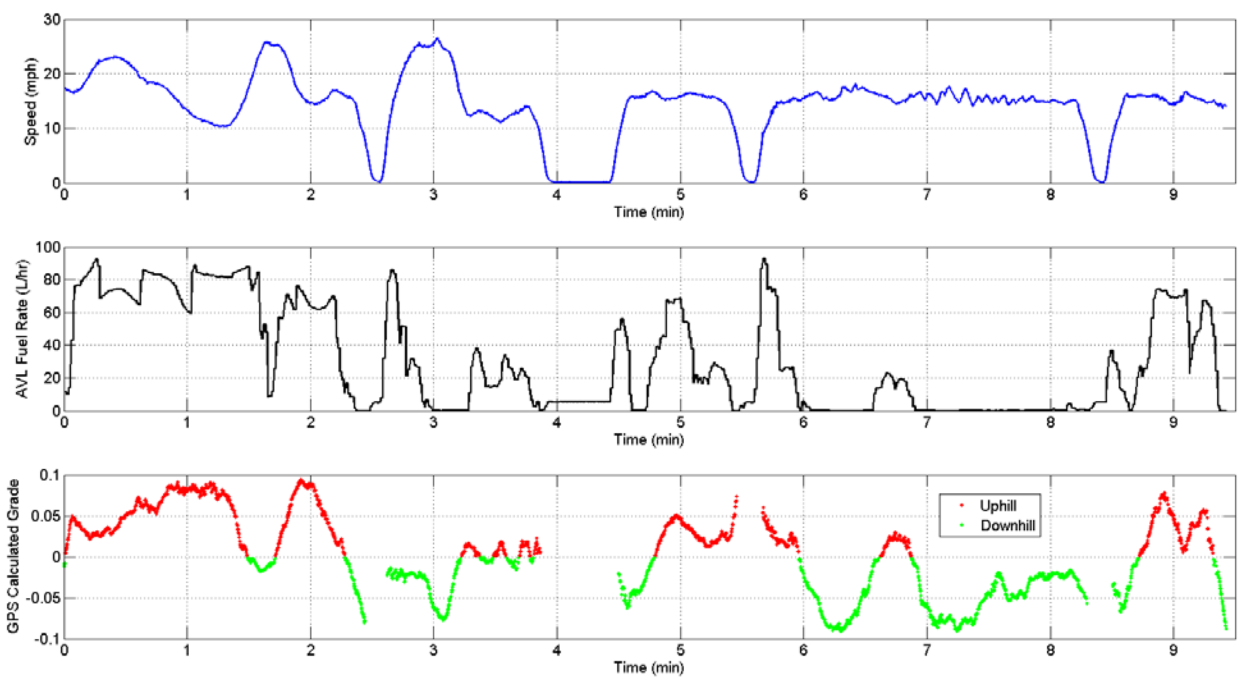


Figure 12. Speed, fueling, and grade traces

Munson Test Area (MTA)

The MTA maintains a number of specific surfaces and obstacles for vehicle testing. For the fuel economy testing performed here, sections of the paved course, improved gravel, and the 15% grade slope were used. As at the ATEF, the vehicles ran all laps for each condition sequentially, entering each lap at speed. The geo-marker for lap start was used to splice the data for individual laps. Figure 13 shows a map of the course, lap start, and clockwise direction of travel for all laps.

Figure 13. MTA map, fuel consumption course
© *Google Maps*

The test schedule for MTA is shown in Figure 14. The morning and afternoon test schedules are exactly the same. The AVL fuel flow meter was not properly configured on truck T13 (M915A5) during the morning tests so the tests were repeated in the afternoon by both vehicles. All testing at MTA was performed in manual / baseline mode at three different target speeds for comparison with previous benchmark testing.

MTA - (10/4/2016) AM

Lap	Truck T12 (A3)	Truck T13 (A5)
1	Warm-Up	Warm-Up
2	10 mph	10 mph
3	10 mph	10 mph
4	10 mph	10 mph
5	10 mph	10 mph
6	10 mph	10 mph
7	15 mph	15 mph
8	15 mph	15 mph
9	15 mph	15 mph
10	15 mph	15 mph
11	15 mph	15 mph
12	20 mph	20 mph
13	20 mph	20 mph
14	20 mph	20 mph
15	20 mph	20 mph
16	20 mph	20 mph

MTA - (10/4/2016) PM

Lap	Truck T12 (A3)	Truck T13 (A5)
1	Warm-Up	Warm-Up
2	10 mph	10 mph
3	10 mph	10 mph
4	10 mph	10 mph
5	10 mph	10 mph
6	10 mph	10 mph
7	15 mph	15 mph
8	15 mph	15 mph
9	15 mph	15 mph
10	15 mph	15 mph
11	15 mph	15 mph
12	20 mph	20 mph
13	20 mph	20 mph
14	20 mph	20 mph
15	20 mph	20 mph
16	20 mph	20 mph

Figure 14. MTA fuel course test matrix (10/4/2016)

Perryman Test Area (PTA)

PTA Course 1 is a roughly 5-mile-long cross-country loop. Laps were again run sequentially using the lap start geo-marker to parse individual laps. Figure 15 shows a map of the course, lap start, and counterclockwise direction of travel for all laps.

Figure 15. PTA map, Course 1
© Google Maps

The test schedule for PTA is shown in Figure 16. Just like MTA, all testing was performed in manual / baseline mode for comparison with previous benchmark testing.

PTA - (10/12/2016)

Lap	Truck T12 (A3)	Truck T13 (A5)
1	Warm-Up	Warm-Up
2	Course 1	Course 1
3	Course 1	Course 1
4	Course 1	Course 1

Figure 16. PTA test matrix (10/12/2016)

Results

Fuel consumption was calculated for each valid test lap using both the high-accuracy AVL KMA mobile unit and the integrated CAN-reported fuel rate from the engine for comparison. Various other lap statistics were also calculated to ensure run-to-run repeatability. These statistics included lap, time, distance, average speed, fuel use, average fuel density, average coolant temperature, average oil temperature, average transmission temperature, median engine speed, and total engine work. The raw fuel consumption numbers from the control and test vehicle for each lap were then entered into the SAE J1321-supplied data analysis worksheet to compute fuel saved and fuel economy improvement with corresponding 95% confidence intervals. An example is shown in Figure 17 for truck T12 (M915A3) comparing Smart cruise to the manual / baseline condition on ATEF-paved, using the CAN-reported fuel values.

SAE 1321 Data Analysis - Fuel Economy Improvement Testing

Baseline Segment				Test Segment			
Gallons or Lbs				Gallons or Lbs			
Run	Test	Control	T/C	Run	Test	Control	T/C
1	0.99	1.14	0.8687	1	0.83	1.08	0.7683
2	0.97	1.09	0.8887	2	0.83	1.09	0.7602
3	0.98	1.11	0.8810	3	0.83	1.09	0.7581
4	0.97	1.07	0.9102	4	0.82	1.12	0.7366
5	0.95	1.08	0.8842	5	0.82	1.08	0.7633
6				6			
7				7			
8				8			
9				9			
10				10			
11				11			
12				12			
13				13			
14				14			
15				15			

Test Result	Nominal		Confidence Interval
Fuel Saved	**14.58%**	**±**	**2.26%**
Improvement	**17.07%**	**±**	**2.65%**

Summary Stats	Baseline	Test
Mean T/C	0.8866	0.7573
Number of Data Points	5	5
Standard Deviations	0.0151	0.0122
Variances	0.0002292	0.0001490
Difference in Means	0.1293	

F-Test for Equal Variances	
Baseline T/C Variance	0.00023
Test T/C Variance	0.00015
F test stat (test/baseline)	0.65007
F low	0.10412
F high	9.60453
Are Variances Equal ?	yes

T-Test with Equal Variances (2-tailed)	
Pooled St dev	0.01375
t-crit	2.306
t-stat	14.863
Is Fuel Economy Improved ?	yes
P-value	0.0000
lower CI bound	0.109203
upper CI bound	0.149313

T-Test with Unequal Variances (2-tailed)	
df (nu)	7.656
t-crit	2.324
t-stat	14.863
Is Fuel Economy Improved ?	yes
P-value	0.0000
lower CI bound	0.109045
upper CI bound	0.149471

Figure 17. SAE J1321-supplied worksheet example

A high-level overview of the various test courses, target speeds, and modes of operation tested is shown in Table 3. All the SAE J1321 worksheet comparison results are summarized in Table 4. Red values indicate the fuel consumption got worse or increased, a gray background indicates data are not available, and gray text indicates the data were valid but the solution was not statically significant and therefore neither a benefit nor a disadvantage can be claimed. The major component of the reference to test case comparison has been highlighted in yellow for ease of identification. Note that the example in Figure 17 corresponds to the third row of Table 4.

Table 3. ATC Test Course Overview

Course	Lap Dist. (mi)	Speeds (mph)	Modes
ATEF Paved	4.5	50 straights, 40 turns	Manual, AMAS, Smart
ATEF Paved	4.5	50 straights, 40 turns	Economy (T12 only)
ATEF Paved	4.5	45 straights, 35 turns	Manual
ATEF Gravel	4.5	50 straights, 40 turns	Manual, Smart
ATEF Paved (Urban)	4.5	25 with three stops	Manual, Smart
Churchville C	2.4	25 with four stops	Manual, AMAS, Smart
Munson Fuel Course (15% Grade)	1.5	10, 15, 20	Manual
Perryman Course 1	5.0	30	Manual

Table 4. SAE J1321 Results Summary

			Fuel Saved		FE (mpg) Improvement	
			CAN Based	AVL Based	CAN Based	AVL Based
Truck	Reference	Test Case	Nominal ± CI	Nominal ± CI	Nominal ± CI	Nominal ± CI
T12 (A3)	40/50 Manual Paved	40/50 AMAS Paved	-4.3% ± 3.7%	N/A	-4.2% ± 3.5%	N/A
T13 (A5)	40/50 Manual Paved	40/50 AMAS Paved	-2.9% ± 2.4%	-2.7% ± 2.2%	-2.8% ± 2.3%	-2.6% ± 2.1%
T12 (A3)	40/50 Manual Paved	Smart Cruise Paved	14.6% ± 2.3%	N/A	17.1% ± 2.6%	N/A
T13 (A5)	40/50 Manual Paved	Smart Cruise Paved	13.8% ± 3.0%	12.9% ± 4.3%	16.0% ± 3.4%	14.9% ± 4.9%
T12 (A3)	40/50 Manual Paved	35/45 Manual Paved	12.1% ± 2.7%	11.5% ± 2.8%	13.8% ± 3.0%	12.9% ± 3.2%
T13 (A5)	40/50 Manual Paved	35/45 Manual Paved	10.9% ± 2.6%	8.3% ± 2.1%	12.2% ± 2.9%	9.1% ± 2.2%
T12 (A3)	40/50 Manual Paved	40/50 Manual Gravel	-39.4% ± 4.1%	-36.8% ± 2.4%	-28.3% ± 2.9%	-26.9% ± 1.7%
T13 (A5)	40/50 Manual Paved	40/50 Manual Gravel	-50.1% ± 3.1%	-48.8% ± 4.0%	-33.4% ± 2.1%	-32.8% ± 2.7%
T12 (A3)	40/50 Manual Gravel	Smart Cruise Gravel	4.3% ± 3.0%	3.3% ± 2.8%	4.5% ± 3.1%	3.4% ± 2.9%
T13 (A5)	40/50 Manual Gravel	Smart Cruise Gravel	8.3% ± 2.6%	4.8% ± 4.6%	9.1% ± 2.8%	5.1% ± 4.9%
T12 (A3)	Urban Manual Paved	Urban Smart Paved	-4.0% ± 2.3%	-1.4% ± 2.6%	-3.8% ± 2.2%	-1.4% ± 2.6%
T13 (A5)	Urban Manual Paved	Urban Smart Paved	0.1% ± 3.1%	0.7% ± 1.4%	0.1% ± 3.1%	0.7% ± 1.4%
T12 (A3)	40/50 Manual Paved	40/50 Economy Paved	7.7% ± 1.6%	7.3% ± 1.4%	8.3% ± 1.7%	7.9% ± 1.5%
T12 (A3)	CTA-C Manual	CTA-C Smart	-19.0% ± 3.0%	-20.0% ± 2.9%	-15.9% ± 2.5%	-16.7% ± 2.4%
T13 (A5)	CTA-C Manual	CTA-C Smart	-15.0% ± 4.6%	-13.8% ± 3.8%	-13.1% ± 4.0%	-12.1% ± 3.3%
T12 (A3)	CTA-C Manual	CTA-C AMAS	-13.8% ± 2.6%	-17.9% ± 2.5%	-12.1% ± 2.3%	-15.2% ± 2.1%
T13 (A5)	CTA-C Manual	CTA-C AMAS	-10.5% ± 19.9%	-13.3% ± 17.7%	-9.5% ± 18.0%	-11.7% ± 15.6%

CI = 95% confidence interval

The MTA and PTA test runs were not intended for a fuel consumption improvement calculation, but rather to benchmark the fuel economy in manual mode for comparison against legacy testing. Table 5 shows summary statistics for each unique test condition and vehicle. Each row represents an average of all valid runs at that condition. Fuel economy was calculated using the AVL KMA mobile fuel flow results.

Table 5. Averages for Each Test Condition

	Truck	Lap Time (sec)	Lap Distance (mi)	Average Speed (mph)	Total Fuel CAN (gallons)	Total Fuel AVL (gallons)	Fuel Density (kg/L)	Coolant Temp (°C)	Engine Oil Temp (°C)	Trans Oil Temp (°C)	Engine Speed (rpm)	Engine Work (kWh)	Fuel Economy (g/kWh)	Fuel Economy (mpg)
Baseline	T12 (A3)	355	4.53	45.9	0.96	1.03	0.82	87	89	91	1,491	15.1	213	4.38
Economy	T12 (A3)	354	4.53	46.1	0.89	0.96	0.82	87	88	91	1,381	14.3	209	4.71
Baseline	T13 (A5)	354	4.53	46.0	1.09	1.09	0.82	80	81	93	1,512	15.6	217	4.16
AMAS Cruise	T12 (A3)	354	4.53	46.0	1.00		0.82	87	89	91	1,468	16.1		4.55
AMAS Cruise	T13 (A5)	350	4.53	46.6	1.08	1.09	0.82	80	81	92	1,472	16.2	209	4.15
Smart Cruise	T12 (A3)	398	4.53	41.0	0.83		0.82	87	88	90	1,318	13.8		5.48
Smart Cruise	T13 (A5)	398	4.52	40.9	0.92	0.94	0.82	80	80	91	1,431	13.1	220	4.84
35/45 Manual	T12 (A3)	398	4.53	41.0	0.85	0.92	0.83	86	88	90	1,339	13.3	217	4.91
35/45 Manual	T13 (A5)	398	4.53	40.9	0.99	1.01	0.82	80	81	91	1,443	13.9	226	4.49
Baseline Gravel	T12 (A3)	362	4.57	45.5	1.31	1.39	0.82	91	92	94	1,509	22.0	196	3.29
Baseline Gravel	T13 (A5)	364	4.57	45.2	1.56	1.56	0.82	83	85	96	1,531	23.0	210	2.93
Smart Cruise Gravel	T12 (A3)	411	4.57	40.0	1.19	1.29	0.81	91	93	95	1,390	20.0	198	3.54
Smart Cruise Gravel	T13 (A5)	402	4.57	40.9	1.45	1.50	0.82	82	84	92	1,423	21.4	217	3.05
Urban Baseline	T12 (A3)	705	4.53	23.1	0.91	1.05	0.82	90	91	94	1,512	13.0	252	4.30
Urban Baseline	T13 (A5)	700	4.53	23.3	1.03	1.04	0.82	81	83	96	1,148	14.1	227	4.37
Urban Smart Cruise	T12 (A3)	687	4.53	23.7	0.95	1.07	0.82	89	91	93	1,417	13.9	238	4.24
Urban Smart Cruise	T13 (A5)	697	4.53	23.4	1.02	1.03	0.82	81	82	95	1,170	14.1	225	4.40
CTA – C Baseline	T12 (A3)	565	2.23	14.2	1.14	1.23	0.82	92	94	98	1,355	18.3	210	1.80
CTA – C Baseline	T13 (A5)	561	2.24	14.3	1.34	1.34	0.82	88	90	99	1,388	19.2	218	1.67
CTA – C Smart	T12 (A3)	740	2.22	10.8	1.34	1.46	0.82	93	95	100	1,274	21.5	211	1.52
CTA – C Smart	T13 (A5)	750	2.22	10.7	1.56	1.57	0.82	91	94	102	1,284	23.4	207	1.42
CTA – C AMAS	T12 (A3)	609	2.22	13.1	1.30	1.44	0.81	93	95	100	1,352	21.5	207	1.54
CTA – C AMAS	T13 (A5)	601	2.23	13.4	1.49	1.53	0.81	91	95	102	1,380	22.8	206	1.47
MTA – 10 mph	T12 (A3)	528	1.52	10.4	0.57	0.61	0.82	92	92	98	1,043	8.3	228	2.50
MTA – 10 mph	T13 (A5)	545	1.53	10.1	0.69	0.67	0.82	86	87	99	1,099	9.6	217	2.23
MTA – 15 mph	T12 (A3)	366	1.52	15.0	0.48	0.54	0.82	92	93	96	1,398	7.4	226	2.82
MTA – 15 mph	T13 (A5)	372	1.52	14.8	0.60	0.61	0.82	85	89	95	1,469	8.3	227	2.50
MTA – 20 mph	T12 (A3)	281	1.52	19.5	0.45	0.50	0.82	92	93	97	1,391	7.1	217	3.05
MTA – 20 mph	T13 (A5)	284	1.52	19.3	0.63	0.64	0.82	85	87	99	1,507	9.1	217	2.41
PTA – Course 1	T12 (A3)	622	4.98	28.8	1.47	1.59	0.83	90	91	95	1,370	23.2	215	3.13
PTA – Course 1	T13 (A5)	621	4.97	28.8	1.79	1.80	0.83	85	87	96	1,387	25.6	220	2.76

A subset of these results is also shown graphically in Figure 18. The plot on the left shows the relationship between fuel economy and total fuel use grouped by test area. Truck T13 (A5) generally had higher fuel use and lower fuel economy due to its lower gearing and higher test weight. The plot on the right shows the relatively tight relationship between the total mass of fuel used and the total CAN-reported engine work. The slope of the fit curve represents the average brake specific fuel consumption across all test conditions, ~ 212 g/kWh. This is equivalent to roughly 39.4% thermal efficiency, assuming diesel has a lower net heating value of 43 MJ/kg. Looking at specific test cases in the table shows that conditions with higher than average brake specific fuel consumption include low-speed, light-load conditions such as ATEF – Urban. Test cases with the lowest brake specific fuel consumption and highest efficiency include high-load conditions such as ATEF – Gravel.

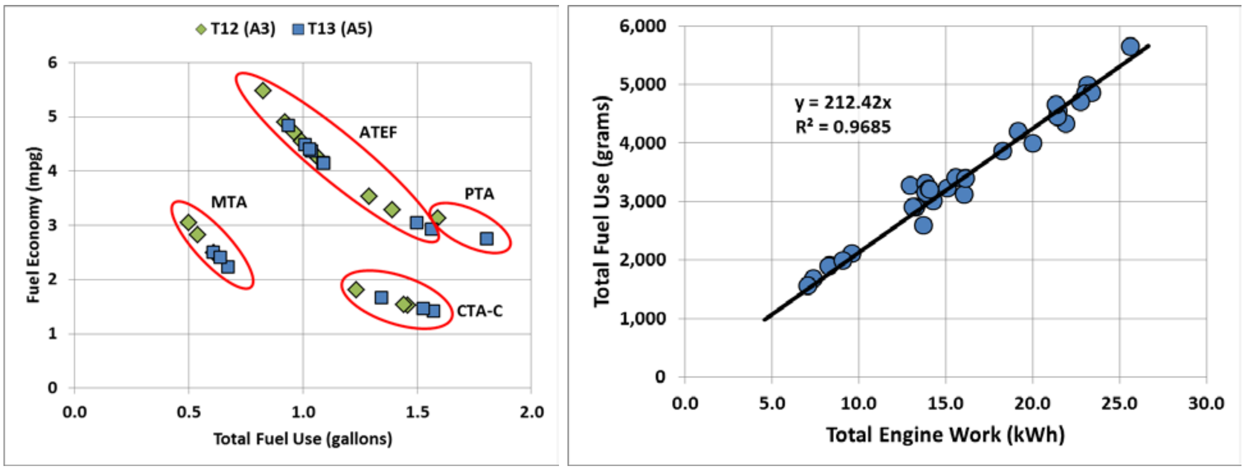


Figure 18. Fuel use trends

A graphical comparison of the fuel savings from the various modes of operation is shown in Figure 19. The AMAS Cruise mode did not demonstrate a benefit over manual drivers under any conditions. The Smart Cruise system showed promising results on ATEF, but requires further refinement for hilly conditions such as CTA Course C.

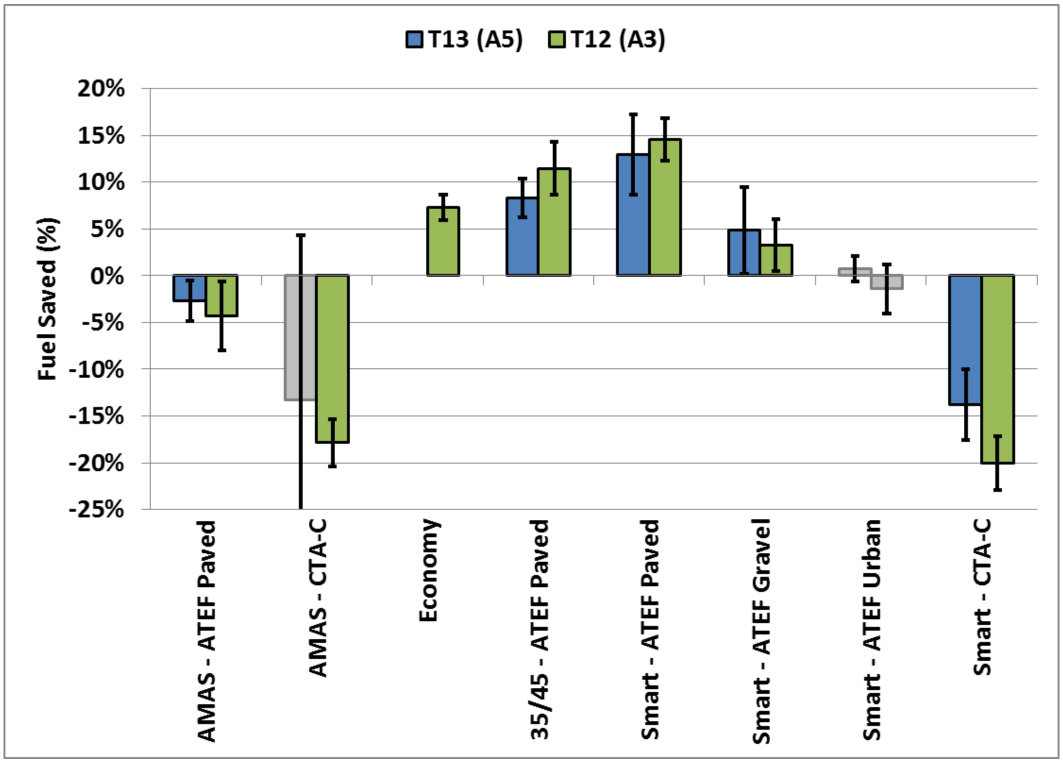


Figure 19. Fuel savings from various modes of operation

Additional Analysis

Beyond the bulk lap statistics presented in the previous section, a wealth of time series 10-Hz data was collected and made available to the group. These data can be used to dive into specific test cases and identify areas for improvement. Although not the focus of this report, a sampling of the possible data products that can be derived from this data is presented below. The left graph in Figure 20 shows all points of operation for truck T13 (M915A5) from all test runs combined with the J1939 broadcast torque curve in red. The right graph in Figure 20 is a smoothed surface fit of engine fuel rate. Such a map could be used as a lookup to better estimate fuel consumption under various operating conditions when trying to make a model-based decision on where to operate the vehicle. Figure 21 shows a simple example of how laying data on top of a course map can help better understand what is going on in certain sections. This example clearly shows the aggressive fueling to accelerate the vehicle out of the turns and upshift as the vehicle reaches speed. The lack of fueling and downshift going into the turns are also shown.

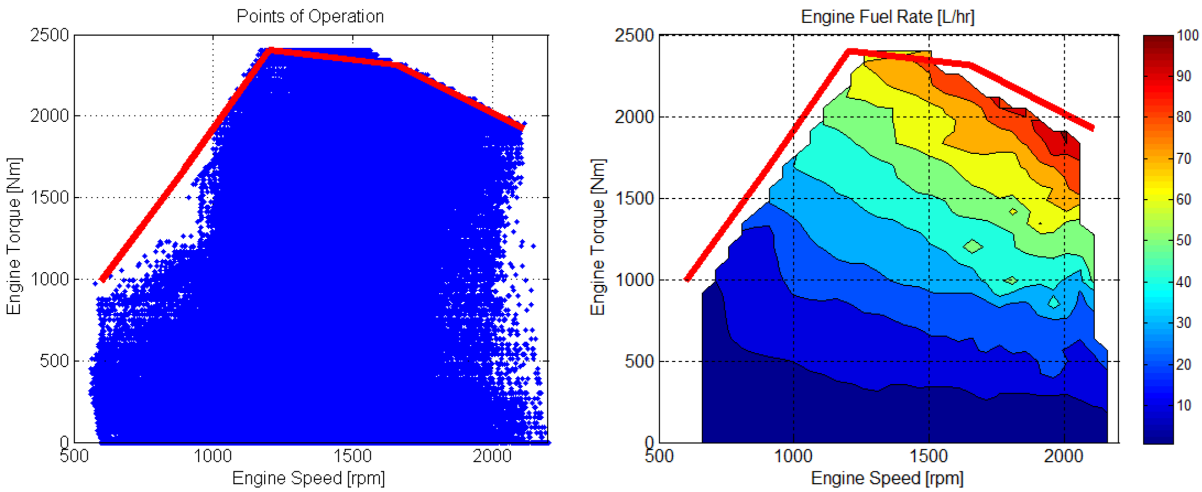


Figure 20. Engine map operation and fueling

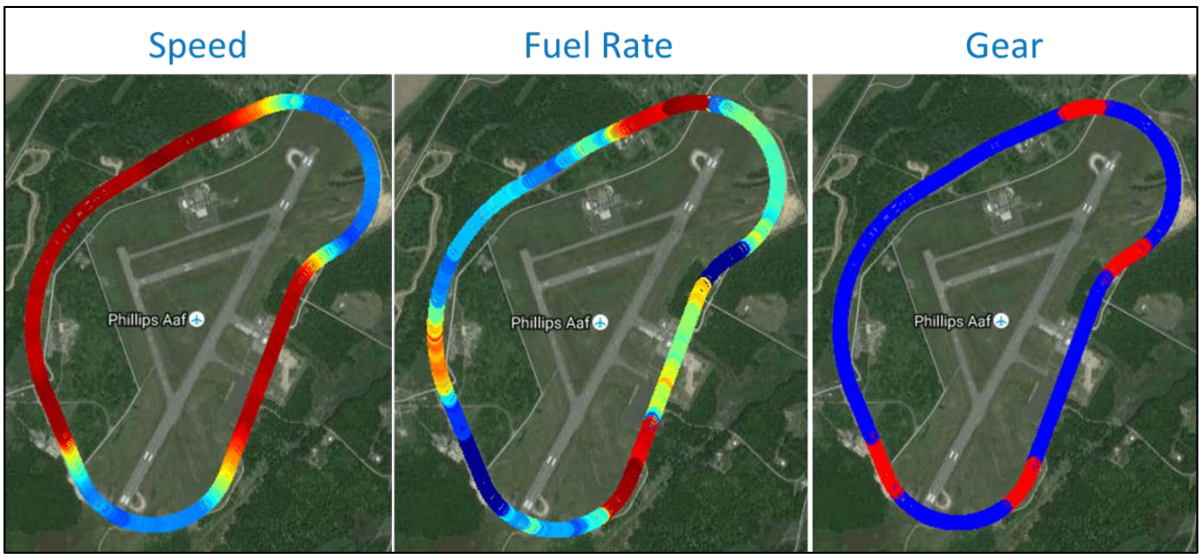


Figure 21. Data visualization over course map

Figure 22 shows engine speed versus vehicle speed, color-coded by engine fuel rate for the two vehicles. Note that truck T12 (M915A3) never enters the red color band as this vehicle has a lower horsepower rating than T13 (M915A5). The different gearing and wheel sizes between the two vehicles are also apparent. Truck T13 (M915A5) reaches 50 mph in fourth gear at ~2,200 rpm, whereas T12 (M915A3) is much closer to ~2,000 rpm when it reaches 50 mph.

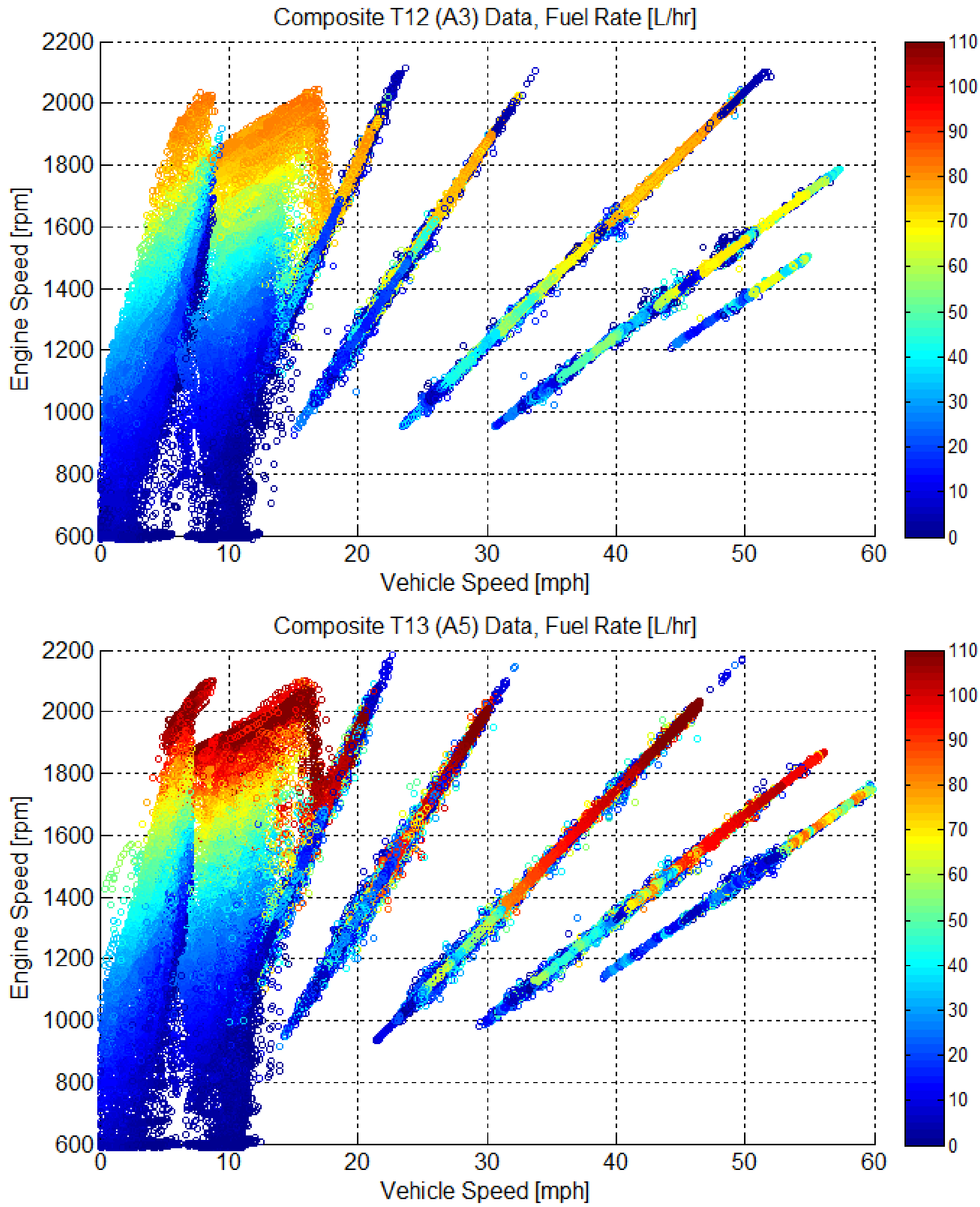


Figure 22. Engine speed versus vehicle speed

Conclusion

The data acquisition system assembled for this testing gathered J1939-legislated CAN data, environmental data from an on-board weather station, position and velocity data from a GLONASS-enabled GPS, high-accuracy fuel flow data from an AVL KMA mobile fuel flow meter, as well as data from additional temperature and pressure sensors installed on the vehicle. All data were recorded by Vector GL2000 data loggers.

Testing results have benchmarked the performance of T12 and T13 over various courses at ATC. The AMAS Cruise control system did not show a benefit over a manual driver for any of the conditions tested. The Smart Cruise system demonstrated fuel savings exceeding the economy mode function, manual driving, and the project target on ATEF–Paved. However, there is still room for improvement from the Smart system on courses with additional obstacles, especially the large hills at CTA-C. The collected data provide deeper insight into the behavior of these vehicles under various test conditions and will allow the models (and on-vehicle efficiency-improving implementation) to be refined before the next round of testing.

Appendix A. Required Signal List

	Signal
Vehicle and Engine Data	Accelerator Pedal Position
	Engine Percent Load At Current Speed (%)
	Engine Speed
	Engine Torque
	Engine Total Average Fuel Economy
	Engine Exhaust Gas Temperature (C)
	Engine Coolant Temperature (C)
	Engine Turbocharger Boost Pressure (kPa)
	Fan Drive State (bit)
	Fan Speed (rpm)
	Nominal Friction - Percent Torque (%)
	Total Vehicle Distance
	Engine Speed At Point 2 (Engine Configuration) (rpm)
	Engine Speed At Point 3 (Engine Configuration) (rpm)
	Engine Speed At Point 4 (Engine Configuration) (rpm)
	Engine Speed At Point 5 (Engine Configuration) (rpm)
	Engine Speed At High Idle Point 6 (Engine Configuration)(rpm)
	Calculated speed of the transmission output shaft.
	Engine Percent Torque At Point 2 (Engine Configuration) (%)
	Engine Percent Torque At Point 3 (Engine Configuration) (%)
	Engine Percent Torque At Point 4 (Engine Configuration) (%)
	Engine Percent Torque At Point 5 (Engine Configuration) (%)
	Engine Reference Torque (Engine Configuration) (Nm)
	Engine Intercooler Temperature (C)
	Engine Fuel Temperature 1 (C)
	Engine Oil Temperature 1 (C)
	Engine Oil Pressure (kPa)
	Engine PTO Enable Switch (bit)
	Wheel-Based Vehicle Speed (kph)
	Cruise Control States
	Cruise Control Active (bit)
	Cruise Control Enable Switch (bit)
	Cruise Control Accelerate Switch (bit)
	Engine Fuel Rate (l/h)
	Engine Instantaneous Fuel Economy (km/L)
	Engine Average Fuel Economy (km/L)
	Engine Air Inlet Temperature (C)
	Engine Air Inlet Pressure (kPa)
	Radiator In-Out
	CAC In-Out
	High Resolution Total Vehicle Distance (m)

	Signal
Transmission Data	Transmission Torque Converter Lockup Disable Request
	Transmission Input Shaft Speed (rpm)
	Transmission Output Shaft Speed (rpm)
	Transmission Torque Converter Lockup Engaged
	Transmission Current Gear (gear value)
	Transmission Selected Gear (gear value)
	Transmission Actual Gear Ratio
	Transmission Oil Temperature
Brake Data	Brake Pedal Position
	Brake Switch
	Brake Application Pressure
	Brake Primary Pressure
	Brake Secondary Pressure
Environmental Data	Compass Bearing
	Altitude
	Latitude
	Longitude
	Barometric Pressure (kPa)
	Ambient Air Temperature (C)
	Grade / Yaw
	Wind speed / direction
	Time Stamp (from the GPS Antenna/Weather Station)
Battery	Alternator Current
	Battery Potential / Power Input 1

Appendix B. Actual Recorded Signal List with Units

MATLAB Name	Units
AMB__AmbientAirTemp	[deg C]
AMB__EngAirIntakeTemp	[deg C]
AUXIO7__BPSL_FRONT_DRIVER	
AUXIO7__BPSL_FRONT_PASSENGER	
AUXIO7__BPSL_MID_DRIVER	
AUXIO7__BPSL_MID_PASSENGER	
AUXIO7__BPSL_REAR_PASSENGER	
AVL_AK1__Density	[kg/l]
AVL_AK1__Frequency	[Hz]
AVL_AK1__Fuel_Temp1	[C]
AVL_AK1__Fuel_Temp2	[C]
AVL_AK2__Flow_Mass	[kg/h]
AVL_AK2__Flow_Vol	[l/h]
Airmar__Altitude	[m]
Airmar__Atmospheric_Pressure	[Pa]
Airmar__COG_True	[deg]
Airmar__Date	[days]
Airmar__Humidity	[%]
Airmar__Latitude	[deg]
Airmar__Longitude	[deg]
Airmar__Mag_Variation	[deg]
Airmar__Num_Sats	
Airmar__Rate_of_Turn	[deg/s]
Airmar__SOG	[m/s]
Airmar__Temperature	[K]
Airmar__Time	[sec]
Airmar__Wind_Direction_Apparent	[deg]
Airmar__Wind_Speed_Apparent	[m/s]
CCVS__CruiseCtrlAccelerateSwitch	
CCVS__CruiseCtrlActive	
CCVS__CruiseCtrlCoastSwitch	
CCVS__CruiseCtrlEnableSwitch	
CCVS__CruiseCtrlResumeSwitch	
CCVS__CruiseCtrlSetSpeed	[km/h]
CCVS__CruiseCtrlSetSwitch	
CCVS__CruiseCtrlStates	
CCVS__PTOGovernorState	
CCVS__ParkingBrakeSwitch	
CCVS__WheelBasedVehicleSpeed	[km/h]
DD__FuelLevel1	[%]
Digital__DI_0	
EBC1__ABSFullyOperational	
EBC1__ABSOffroadSwitch	
EBC1__ABS_EBSAmberWarningSignal	
EBC1__ASRBrakeCtrlActive	
EBC1__ASREngCtrlActive	
EBC1__ASROffroadSwitch	
EBC1__ATC_ASRInformationSignal	
EBC1__AntiLockBrakingActive	
EBC1__EBSBrakeSwitch	
EBC1__TrailerABSStatus	
EBC1__TrctrMntdTrailerABSWarningSignal	
EBC2__FrontAxleSpeed	[km/h]
EBC2__RelativeSpeedFrontAxleLeftWheel	[km/h]
EBC2__RelativeSpeedFrontAxleRightWheel	[km/h]
EBC2__RelativeSpeedRearAxle1LeftWheel	[km/h]
EBC2__RelativeSpeedRearAxle1RightWheel	[km/h]
EBC2__RelativeSpeedRearAxle2LeftWheel	[km/h]
EBC2__RelativeSpeedRearAxle2RightWheel	[km/h]
EBC5__BrakeTempWarning	
EBC5__FoundationBrakeUse	
EBC5__HaltBrakeMode	

MATLAB Name	Units
EBC5__HillHolderMode	
EBC5__XBRAccelerationLimit	[m/s²]
EBC5__XBRActiveCtrlMode	
EBC5__XBRSystemState	
EC1__EngReferenceTorque	[Nm]
EEC1__ActlEngPrcntTorqueHighResolution	[%]
EEC1__ActualEngPercentTorque	[%]
EEC1__DriversDemandEngPercentTorque	[%]
EEC1__EngSpeed	[rpm]
EEC1__EngStarterMode	
EEC1__EngTorqueMode	
EEC1__SrcAddrssOfCntrllngDvcForEngCtrl	
EEC2__AccelPedalPos1	[%]
EEC2__EngPercentLoadAtCurrentSpeed	[%]
EEC3__EnginesDesiredOperatingSpeed	[rpm]
EEC3__EngnsDsrdOprtngSpdAsymmtryAdjstm	
EEC3__NominalFrictionPercentTorque	[%]
EFL_P1__EngCoolantLevel	[%]
EFL_P1__EngOilPress	[kPa]
ERC1__ActualRetarderPercentTorque	[%]
ERC1__RetarderTorqueMode	
ET1__EngCoolantTemp	[deg C]
ET1__EngFuelTemp1	[deg C]
ET1__EngOilTemp1	[deg C]
ETC1__ProgressiveShiftDisable	
ETC1__TransDrivelineEngaged	
ETC1__TransInputShaftSpeed	[rpm]
ETC1__TransOutputShaftSpeed	[rpm]
ETC1__TransShiftInProcess	
ETC1__TrnsTorqueConverterLockupEngaged	
ETC2__TransActualGearRatio	
ETC2__TransCurrentGear	
ETC2__TransCurrentRange	
ETC2__TransRequestedRange	
ETC2__TransSelectedGear	
ETC7__TransEngCrankEnable	
ETC7__TransMode1Indicator	
ETC7__TransMode2Indicator	
ETC7__TransMode4Indicator	
ETC7__TransRequestedGearFeedback	
ETC7__TransShiftInhibitIndicator	
ETC7__TrnsRqstedRangeDisplayBlankState	
ETC7__TrnsRqstedRangeDisplayFlashState	
ETC8__TransTorqueConverterRatio	
FD__EstPercentFanSpeed	[%]
FD__FanDriveState	
Garmin19x__COG_Mag	[deg]
Garmin19x__COG_True	[deg]
Garmin19x__Elevation	[m]
Garmin19x__Error_H	[m]
Garmin19x__Error_P	[m]
Garmin19x__Error_V	[m]
Garmin19x__Fix_Type	
Garmin19x__Latitude	[deg]
Garmin19x__Longitude	[deg]
Garmin19x__Num_Sats	
Garmin19x__SOG	[km/h]
Garmin19x__UTC_Time	[sec]
Garmin19x__Velocity_East	[m/s]
Garmin19x__Velocity_North	[m/s]
Garmin19x__Velocity_Up	[m/s]
HOURS__EngTotalHoursOfOperation	[hr]

MATLAB Name	Units
HOURS__EngTotalRevolutions	[r]
HRW__FrontAxleLeftWheelSpeed	[km/h]
HRW__FrontAxleRightWheelSpeed	[km/h]
HRW__RearAxleLeftWheelSpeed	[km/h]
HRW__RearAxleRightWheelSpeed	[km/h]
IC1__EngIntakeManifold1Press	[kPa]
LC__CenterStopLightCmd	
LC__LightingDataRqCmd	
LD__BackUpLightAndAlarmHorn	
LD__CenterStopLight	
LD__HighBeamHeadLightData	
LD__LeftStopLight	
LD__LeftTurnSignalLights	
LD__LowBeamHeadLightData	
LD__RightStopLight	
LD__RightTurnSignalLights	
LD__TractorMarkerLight	
LFE__EngAverageFuelEconomy	[km/L]
LFE__EngFuelRate	[L/h]
LFE__EngInstantaneousFuelEconomy	[km/L]
ML__BlackOutBrake_StopLampSelect	
ML__ConvoyDrivingLampSelect	
ML__FrontBlackOutMarkerLampSelect	
ML__OprtrsBlackOutIntensitySelection	[%]
OWW__FrontNonoperatorWasherSwitch	
OWW__FrontNonoperatorWiperSwitch	
OWW__FrontOperatorWasherSwitch	
OWW__FrontOperatorWiperSwitch	
OWW__RearWasherFunction	
OWW__RearWiperSwitch	
PIS__BrakeControlPressure	
PIS__BrakePedalPos	[%]
PIS__EngOverrideCtrlMode	
PIS__EngRequestedTorque_TorqueLimit	[%]
PTO__PowerTakeoffSetSpeed	[rpm]
SHUTDN__EngProtectionSystemConfig	
TC1__RequestedPercentClutchSlip	[%]
TC1__TransRequestedGear	
TC1__TransRequestedLaunchGear	

MATLAB Name	Units
TC1__TrnsShftSlectorDisplayModeSwitch	
TRF1__TransOilLevelCountdownTimer	
TRF1__TransOilLevelHigh_Low	[L]
TRF1__TransOilLevelMeasurementStatus	
TRF1__TransOilTemp	[deg C]
TSC1__EngOverrideCtrlMode	
TSC1__EngRequestedSpeed_SpeedLimit	[rpm]
TSC1__EngRequestedTorqueHighResolution	[%]
TSC1__EngRequestedTorque_TorqueLimit	[%]
TSC1__MessageChecksum	
TSC1__MessageCounter	
TSC1__TSC1CtrlPurpose	
TSC1__TSC1TransRate	
Temp__CAC_In	[C]
Temp__CAC_Out	[C]
Temp__EGT	[C]
Temp__Rad_In	[C]
Temp__Rad_Out	[C]
Time	[s]
VDC1__ROPBrakeCtrlActive	
VDC1__ROPEngCtrlActive	
VDC1__VDCBrakeLightRq	
VDC1__VDCFullyOperational	
VDC1__VDCInformationSignal	
VDC1__YCBrakeCtrlActive	
VDC1__YCEngCtrlActive	
VDC2__LateralAcceleration	[m/s²]
VDC2__LongitudinalAcceleration	[m/s²]
VDC2__SteerWheelAngle	[rad]
VDC2__SteerWheelTurnCounter	[turns]
VDC2__YawRate	[rad/s]
VDHR__HghRsolutionTotalVehicleDistance	[km]
VDHR__HighResolutionTripDistance	[km]
VEP1__BatteryPotential_PowerInput1	[V]
Voltage__AVL	[V]
Voltage__AirPressure	[V]
Voltage__Shunt_mV	[mV]

Appendix C. Bill of Materials

Item #	Description	Supplier	Supplier Part #	Qty
1	**Fuel Flow Meter Assembly**			
2	AVL - KMA Mobile Measurement System (Fuel Flow Meter)	AVL Test Systems		1
3	AVL KMA Mobil Type 150 (Measurement Mod.)		TNMES150.01	1
4	AVL KMA Mobile Density Meter		TNMOBDENS.01	1
5	AVL KMA Mobile Cond. Truck (Mod. Diesel)		TNCOND3024.01	1
6	AVL KMA Mobile Addit. Connection Kit		TNCONEKIT.01	1
7	Packing and Duty		VSVFRE-119NA3	1
8	**Weather Station Assembly**			
9	Airmar 220WX WeatherStation Instrument	iMarine USA	WS-220WX-RH	1
10	Airmar NMEA2000 Communication Cable 6.5 ft		WS2-C02	1
11	Mounting Bracket Fabricated by Primus			
12	**DAQ Unit Assembly**			
13	Vector GL2000 Data Logger (Standard 4x CAN HS)	Vector	28090S	1
14	GL2000 Transfer Request License	Vector	28117	1
15	GL2000 GPS Receiver G-STAR IV	Vector	28100	1
16	VN1610 CAN Network Interface	Vector	7150	1
17	CANcable 2Y	Vector	5075	1
18	Sierra Wireless - AirLink LS300 EV-DO Verizon Modem	Newegg.com	LS300 EV-DO	1
19	CANopen slave module, 8 channel 16-bit voltage input	ICP DAS USA	2017C	1
20	CANopen slave module, 8-channel thermocouple input	ICP DAS USA	2018C	1
21	CANopen slave module, 8-ch counter / digital input	ICP DAS USA	2088C	1
22	Omega signal conditioner for frequency/pulse input	Omega	iDRN-FP	1
23	RS-232 to CAN protocol converter			2
24	Black plastic electronics enclosure	McMaster-Carr	7593K28	2
25	Voltage Regulator - 5V	SparkFun	L7805	2
26	Arduino Pro Mini 328 - 5V/16MHz	SparkFun	DEV-11113	2
27	MAX3232 Transceiver	SparkFun	BOB-11189	2
28	Proto Half-sized Breadboard PCB 3-pack	Adafruit	571	1
29	MCP2515 Serial to CAN Development Board	Amazon	B015W4D9WY	2
30	PVC Junction Box enclosure 12in x 12in x 6in	Home Depot		1
31	DIN 3 Rail (1 meter long)	McMaster-Carr	8961K15	1
32	DIN-Rail mount terminal blocks, standard two circuit	McMaster-Carr	7641K71	10
33	DIN-Rail mount terminal blocks, end covers	McMaster-Carr	7641K72	3
34	DIN-Rail mount terminal blocks, ground block	McMaster-Carr	7641K81	1
35	DIN-Rail mount terminal blocks, fuse block	McMaster-Carr	7641K36	1
36	DIN-Rail mount terminal blocks, end stops	McMaster-Carr	7641K73	2
37	DIN-Rail mount terminal blocks, jumpers	McMaster-Carr	7641K74	4
38	Stranded Copper Wire, 18 gauge, 50ft, Black	McMaster-Carr	8054T15	1
39	Stranded Copper Wire, 18 gauge, 50ft, Red	McMaster-Carr	8054T15	1
40	Stranded Copper Wire, 18 gauge, 50ft, Green	McMaster-Carr	8054T15	1
41	Stranded Copper Wire, 18 gauge, 50ft, Yellow	McMaster-Carr	8054T15	1
42	Communication Cable, 4 wire, 100ft	McMaster-Carr	8280T32	1
43	Communication Cable, 2 wire, 100ft	McMaster-Carr	8280T31	1
44	DB9 connection kit, plug	McMaster-Carr	2146T11	4
45	DB9 connection kit, socket	McMaster-Carr	2146T12	4
46	**Sensors, cables etc.**			
47	Garmin 19x HVS GLONASS enabled GPS (NMEA 0183)	Garmin	010-01010-00	1
48	Alternator Current Shunt, 50mV @ 150 A	Ram Meter Inc.	20M150A50	1
49	Alternator Current Shunt, 50mV @ 500 A	Ram Meter Inc.	21M500A50	1
50	Pipe Fitting, 1/4 NPT Female x Butt-Weld Female	McMaster-Carr	4464K471	5
51	Straight Adapter for 1/8" Tube OD, x 1/4 NPT Male	McMaster-Carr	5272K291	5
52	Type K Thermocouple, 0.125 x 6", ungrounded	Omega	KMQSS-125U-6	5
53	Thermocouple Extension Wire, Type K, 500ft	Omega	EXPP-K-20-500	1
54	Pressure Transducer, 150 psi	Omega	PX309-150G5V	1

Appendix D. Configuration Settings

The configuration settings for the instrumentation and various modules used in the data acquisition system are shown below.

Garmin 19x GPS Configuration

RS-232 Serial Commands

```
$PGRMO,,2*75
$PGRMC,A,,,,,,,,A,8,1,1,,1
$PGRMC1,,1,2,,,,1,W,N
$PGRMC2,5,LOW,GLONASS,ON,GP,PR0,0
$PGRMO,GPGGA,1,1
$PGRMO,GPVTG,1,1
$PGRMO,PGRMV,1,1
$PGRMO,PGRME,1,1
```

Database Messages and Signals

Name	ID	ID-Format	DLC [Byte]
GPGGA_Lat_Lon	0x7A2	CAN Standard	8
GPGGA_UTC_Time	0x7A1	CAN Standard	8
GPVTG_COG_SOG	0x7A3	CAN Standard	8
PGRME_Error	0x7A5	CAN Standard	8
PGRMV_Vel_Dir	0x7A4	CAN Standard	8

Name	Length [Bit]	Byte Order	Value Type	Factor	Offset	Minimum	Maximum	Unit
COG_Mag	16	Intel	Unsigned	0.1	0	0	6553.5	deg
COG_True	16	Intel	Unsigned	0.1	0	0	6553.5	deg
Elevation	20	Intel	Signed	0.1	0	-52428.8	52428.7	m
Error_H	16	Intel	Unsigned	0.01	0	0	655.35	m
Error_P	16	Intel	Unsigned	0.01	0	0	655.35	m
Error_V	16	Intel	Unsigned	0.01	0	0	655.35	m
Fix_Type	4	Intel	Unsigned	1	0	0	15	
Latitude	32	Intel	Signed	1e-006	0	-2147.48	2147.48	deg
Longitude	32	Intel	Signed	1e-006	0	-2147.48	2147.48	deg
Num_Sats	8	Intel	Unsigned	1	0	0	255	
SOG	24	Intel	Unsigned	0.01	0	0	167772	kmph
UTC_Time	32	Intel	Unsigned	0.1	0	0	4.29497e+008	sec
Velocity_East	16	Intel	Signed	0.01	0	-327.68	327.67	mps
Velocity_North	16	Intel	Signed	0.01	0	-327.68	327.67	mps
Velocity_Up	16	Intel	Signed	0.01	0	-327.68	327.67	mps

Airmar 220WX Weather Station

The default CAN configuration was used for the weather station, which included the following output messages.

CAN (NMEA 2000®) Output Message Structure
59392.........ISO Acknowledgement
060928.......ISO Address Claim
126208.......Acknowledge Group Function
126464.......PGN List
126992.......System Time
126996.......Product Information
126998.......Configuration Information
127250.......Vessel Heading
127251.......Rate of Turn
127257.......Attitude
127258.......Magnetic Variation
129025.......Position and Rapid Update
129026.......COG and SOG, Rapid Update
129029.......GNSS Position Data
129033.......Time and Date
129044.......Datum
129538.......GNSS Control Status
129539.......GNSS DOPs
129540.......GNSS Sats in View
130306.......Wind Data
130310.......Environmental Parameters
130311.......Environmental Parameters
130312.......Temperature
130313.......Humidity
130314.......Actual Pressure
130323.......Meteorological Station Data

ICP DAS I/O Modules

The data acquisition system included three types of CANopen I/O modules to translate signals to the CAN. The addresses of the modules were configured with the external DIP switches as follows:

1. Voltage
2. Temperature
3. Counter

Then all three modules were programmed using the following CANopen commands:

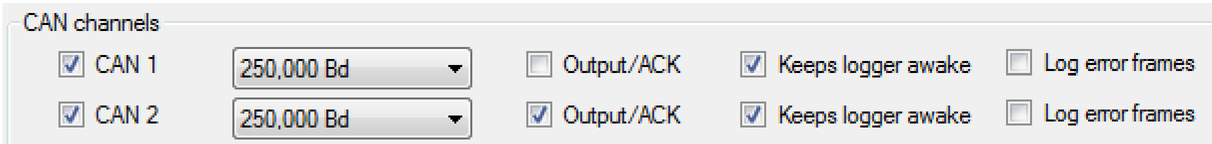
```
601            Tx   d 8 2B 15 10 00 64 00 00 00
601            Tx   d 8 2B 01 18 05 C8 00 00 00
601            Tx   d 8 2B 02 18 05 C8 00 00 00
601            Tx   d 8 2F 04 20 01 0C 00 00 00
601            Tx   d 8 2F 04 20 02 0C 00 00 00
601            Tx   d 8 2F 04 20 03 09 00 00 00
601            Tx   d 8 2F 04 20 04 09 00 00 00
601            Tx   d 8 23 10 10 01 73 61 76 65
```

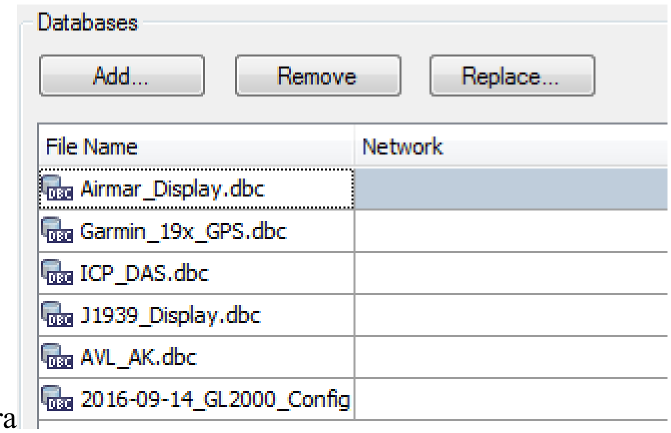
```
602    Tx   d 8 2B 15 10 00 64 00 00 00
602    Tx   d 8 2B 01 18 05 E8 03 00 00
602    Tx   d 8 2B 02 18 05 E8 03 00 00
602    Tx   d 8 2F 04 20 01 0F 00 00 00
602    Tx   d 8 2F 04 20 02 0F 00 00 00
602    Tx   d 8 2F 04 20 03 0F 00 00 00
602    Tx   d 8 2F 04 20 04 0F 00 00 00
602    Tx   d 8 2F 04 20 05 0F 00 00 00
602    Tx   d 8 2F 04 20 06 0F 00 00 00
602    Tx   d 8 2F 04 20 07 0F 00 00 00
602    Tx   d 8 2F 04 20 08 0F 00 00 00
602    Tx   d 8 2F 21 20 01 01 00 00 00
602    Tx   d 8 23 10 10 01 73 61 76 65

603    Tx   d 8 2B 00 18 05 64 00 00 00
603    Tx   d 8 2B 01 18 05 C8 00 00 00
603    Tx   d 8 2B 02 18 05 C8 00 00 00
603    Tx   d 8 23 10 10 01 73 61 76 65
```

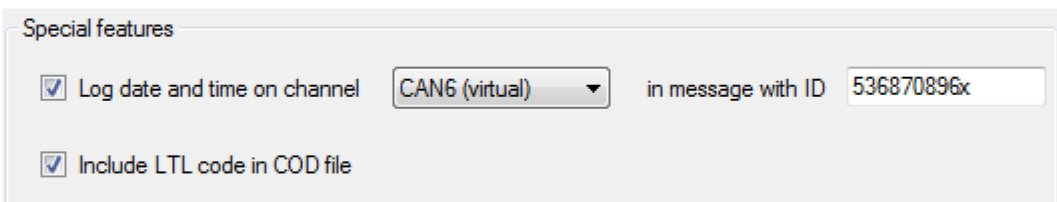
Name	Length [Bit]	Byte Order	Value Type	Factor	Offset	Minimum	Maximum	Unit
AI_ch0	16	Intel	Signed	0.00457764	0	-150	149.995	mV
AI_ch1	16	Intel	Signed	0.00457764	0	-150	149.995	mV
AI_ch2	16	Intel	Signed	0.000152588	0	-5	4.99985	V
AI_ch3	16	Intel	Signed	0.000152588	0	-5	4.99985	V
AI_ch4	16	Intel	Signed	0.000305176	0	-10	9.99969	V
AI_ch5	16	Intel	Signed	0.000305176	0	-10	9.99969	V
AI_ch6	16	Intel	Signed	0.000305176	0	-10	9.99969	V
AI_ch7	16	Intel	Signed	0.000305176	0	-10	9.99969	V
Counter_0	32	Intel	Unsigned	1	0	0	4.29497e+009	
Counter_1	32	Intel	Unsigned	1	0	0	4.29497e+009	
Counter_2	32	Intel	Unsigned	1	0	0	4.29497e+009	
Counter_3	32	Intel	Unsigned	1	0	0	4.29497e+009	
DI_0	1	Intel	Unsigned	1	0	0	1	
DI_1	1	Intel	Unsigned	1	0	0	1	
DI_2	1	Intel	Unsigned	1	0	0	1	
DI_3	1	Intel	Unsigned	1	0	0	1	
DI_4	1	Intel	Unsigned	1	0	0	1	
DI_5	1	Intel	Unsigned	1	0	0	1	
DI_6	1	Intel	Unsigned	1	0	0	1	
DI_7	1	Intel	Unsigned	1	0	0	1	
TC_ch0	16	Intel	Signed	0.0418714	0	-1372.04	1372	°C
TC_ch1	16	Intel	Signed	0.0418714	0	-1372.04	1372	°C
TC_ch2	16	Intel	Signed	0.0418714	0	-1372.04	1372	°C
TC_ch3	16	Intel	Signed	0.0418714	0	-1372.04	1372	°C
TC_ch4	16	Intel	Signed	0.0418714	0	-1372.04	1372	°C
TC_ch5	16	Intel	Signed	0.0418714	0	-1372.04	1372	°C
TC_ch6	16	Intel	Signed	0.0418714	0	-1372.04	1372	°C
TC_ch7	16	Intel	Signed	0.0418714	0	-1372.04	1372	°C

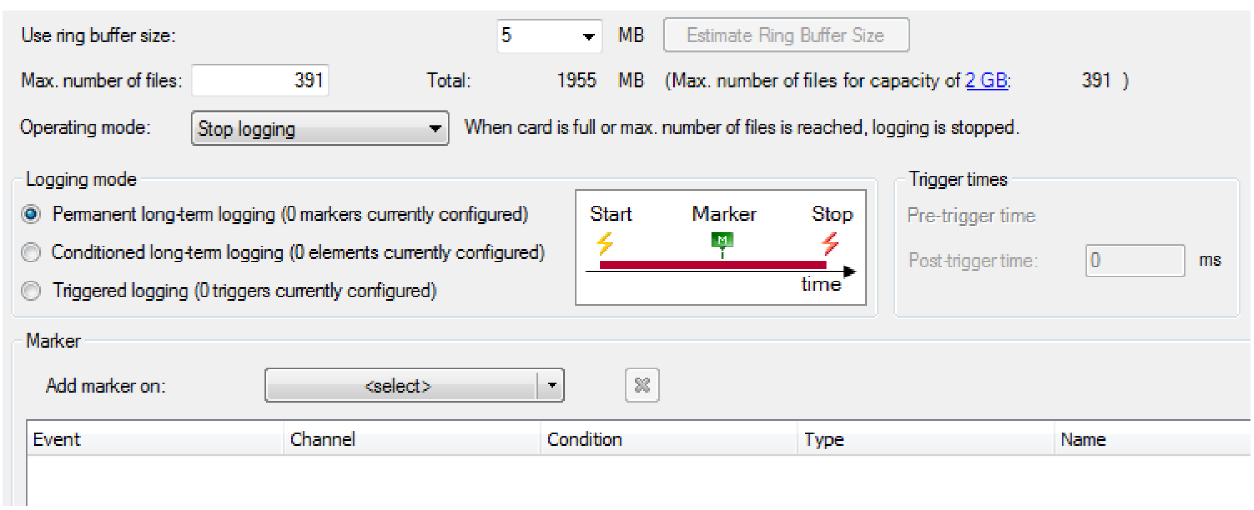
Vector GL2000 Configuration





dara



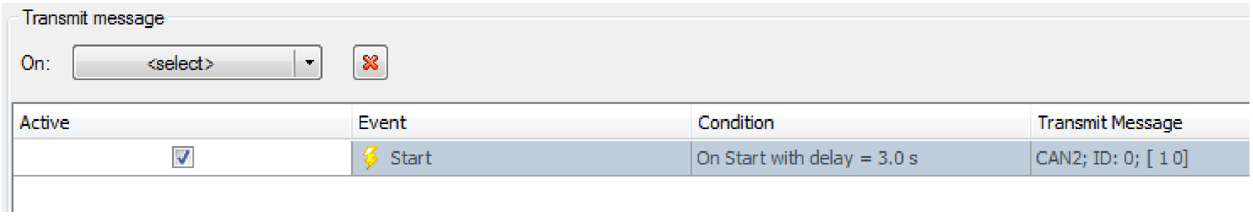


Filters

The order of the filters determines their priority. The last filter has the highest priority.

Add filter: <select>

Active	Action	Rate	Type	Channel	Condition
☑	Pass	all frames	Default	All	
☑	Stop		Symbolic CAN message	CAN2	Datum (ID: 435688483x, DB: Airmar_Display)
☑	Stop		Symbolic CAN message	CAN2	GNSS_DOPs (ID: 435815203x, DB: Airmar_Display)
☑	Stop		Symbolic CAN message	CAN2	GNSS_Sats_in_View (ID: 435815459x, DB: Airmar_Display)
☑	Stop		Symbolic CAN message	CAN2	Meteorological_Station_Data (ID: 436015907x, DB: Airmar_Display)
☑	Stop		CAN channel	CAN1	
☑	Pass	all frames	Symbolic CAN message	CAN1	ACC1 (ID: 285110058x, DB: J1939_Display)
☑	Pass	all frames	Symbolic CAN message	CAN1	AMB (ID: 419362048x, DB: J1939_Display)
☑	Limit	1 frame per 1000 ms	Symbolic CAN message	CAN1	AUXIO1 (ID: 218028327x, DB: J1939_Display)
☑	Limit	1 frame per 1000 ms	Symbolic CAN message	CAN1	AUXIO2 (ID: 413607735x, DB: J1939_Display)
☑	Limit	1 frame per 1000 ms	Symbolic CAN message	CAN1	AUXIO3 (ID: 413542374x, DB: J1939_Display)
☑	Limit	1 frame per 100 ms	Symbolic CAN message	CAN1	AUXIO7 (ID: 412942054x, DB: J1939_Display)
☑	Pass	all frames	Symbolic CAN message	CAN1	CCVS (ID: 419361024x, DB: J1939_Display)
☑	Pass	all frames	Symbolic CAN message	CAN1	DD (ID: 419364070x, DB: J1939_Display)
☑	Pass	all frames	Symbolic CAN message	CAN1	EBC1 (ID: 418382091x, DB: J1939_Display)
☑	Pass	all frames	Symbolic CAN message	CAN1	EBC2 (ID: 419348235x, DB: J1939_Display)
☑	Pass	all frames	Symbolic CAN message	CAN1	EBC5 (ID: 419283979x, DB: J1939_Display)
☑	Pass	all frames	Symbolic CAN message	CAN1	EC1 (ID: 486466304x, DB: J1939_Display)
☑	Limit	1 frame per 50 ms	Symbolic CAN message	CAN1	EEC1 (ID: 217056256x, DB: J1939_Display)
☑	Limit	1 frame per 50 ms	Symbolic CAN message	CAN1	EEC2 (ID: 217056000x, DB: J1939_Display)
☑	Pass	all frames	Symbolic CAN message	CAN1	EEC3 (ID: 419356416x, DB: J1939_Display)
☑	Pass	all frames	Symbolic CAN message	CAN1	EFL_P1 (ID: 419360512x, DB: J1939_Display)
☑	Pass	all frames	Symbolic CAN message	CAN1	ERC1 (ID: 418381839x, DB: J1939_Display)
☑	Pass	all frames	Symbolic CAN message	CAN1	ET1 (ID: 419360256x, DB: J1939_Display)
☑	Limit	1 frame per 50 ms	Symbolic CAN message	CAN1	ETC1 (ID: 217055747x, DB: J1939_Display)
☑	Pass	all frames	Symbolic CAN message	CAN1	ETC2 (ID: 418383107x, DB: J1939_Display)
☑	Pass	all frames	Symbolic CAN message	CAN1	ETC7 (ID: 419318275x, DB: J1939_Display)
☑	Limit	1 frame per 50 ms	Symbolic CAN message	CAN1	ETC8 (ID: 217058307x, DB: J1939_Display)
☑	Pass	all frames	Symbolic CAN message	CAN1	FD (ID: 419347712x, DB: J1939_Display)
☑	Pass	all frames	Symbolic CAN message	CAN1	HOURS (ID: 419357952x, DB: J1939_Display)
☑	Limit	1 frame per 100 ms	Symbolic CAN message	CAN1	HRW (ID: 150892043x, DB: J1939_Display)
☑	Pass	all frames	Symbolic CAN message	CAN1	IC1 (ID: 419362304x, DB: J1939_Display)
☑	Pass	all frames	Symbolic CAN message	CAN1	LC (ID: 217989415x, DB: J1939_Display)
☑	Pass	all frames	Symbolic CAN message	CAN1	LD (ID: 419315767x, DB: J1939_Display)
☑	Pass	all frames	Symbolic CAN message	CAN1	LFE (ID: 419361280x, DB: J1939_Display)
☑	Pass	all frames	Symbolic CAN message	CAN1	LFE (ID: 419361280x, DB: J1939_Display)
☑	Limit	1 frame per 1000 ms	Symbolic CAN message	CAN1	ML (ID: 419318839x, DB: J1939_Display)
☑	Limit	1 frame per 1000 ms	Symbolic CAN message	CAN1	OWW (ID: 419286327x, DB: J1939_Display)
☑	Limit	1 frame per 100 ms	Symbolic CAN message	CAN1	PIS (ID: 218098662x, DB: J1939_Display)
☑	Limit	1 frame per 1000 ms	Symbolic CAN message	CAN1	PTO (ID: 419360768x, DB: J1939_Display)
☑	Pass	all frames	Symbolic CAN message	CAN1	RQST (ID: 418053886x, DB: J1939_Display)
☑	Pass	all frames	Symbolic CAN message	CAN1	SHUTDN (ID: 419357696x, DB: J1939_Display)
☑	Limit	1 frame per 100 ms	Symbolic CAN message	CAN1	TC1 (ID: 201392901x, DB: J1939_Display)
☐	Pass	all frames	Symbolic CAN message	CAN1	TPCM (ID: 485293824x, DB: J1939_Display)
☐	Pass	all frames	Symbolic CAN message	CAN1	TPDT (ID: 485228288x, DB: J1939_Display)
☑	Pass	all frames	Symbolic CAN message	CAN1	TRF1 (ID: 419362819x, DB: J1939_Display)
☑	Pass	all frames	Symbolic CAN message	CAN1	TSC1 (ID: 201385511x, DB: J1939_Display)
☑	Pass	all frames	Symbolic CAN message	CAN1	VDC1 (ID: 419319563x, DB: J1939_Display)
☑	Limit	1 frame per 100 ms	Symbolic CAN message	CAN1	VDC2 (ID: 418384139x, DB: J1939_Display)
☑	Pass	all frames	Symbolic CAN message	CAN1	VDHR (ID: 419348736x, DB: J1939_Display)
☑	Pass	all frames	Symbolic CAN message	CAN1	VEP1 (ID: 419362560x, DB: J1939_Display)


Transmit message
On:
<select>
Active
Event
Condition
Transmit Message
Start
On Start with delay = 3.0 s
CAN2; ID: 0; [1 0]