CRC Report No. 656

Biodiesel Blend Low-Temperature Performance Validation

CRC Project: DP-2a-07-2

June 2010

COORDINATING RESEARCH COUNCIL, INC.
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Prepared by the

CRC Diesel Performance Group

June 2010

CRC Performance Committee
of the
Coordinating Research Council, Inc.

Executive Summary

The study described in this report is Phase 2 of CRC Project DP-2a-07; the results of Phase 1 are reported in CRC Report No. 650. The original study objective was to validate that the cold soak filtration test (CSFT) is able to identify biodiesel that, in blends up to B20, shows precipitate formation and causes fuel filter plugging at temperatures above the cloud point (CP). Four B100 materials were tested as B5 and B20 blends in three Class 8 trucks, each thought to represent approximately 30% of the North American Class 8 truck market based on engine OEM market size. Three of the B100 exhibited an average CSFT <200 seconds, while the fourth had CSFT >720 seconds. For each fuel/truck combination the low-temperature operability limit was bracketed and the results used to calculate an estimated minimum operating temperature (EMOT). The original study showed that high CSFT B100 can cause low-temperature operability problems at temperatures at and above CP for B20 blends. For B5 blends vehicle operability on the test was not affected above CP, although high fuel filter pressure drop was observed.

The purpose of the Phase 2 study was to provide a more complete understanding by testing an additional high CSFT B100. A second objective was to test blends made from biodiesel having a CSFT between 200 seconds and 360 seconds. The cold soak filterability requirement in the ASTM D6751 specification for B100 blend stock requires that all B100 meet a 360 second CSFT maximum, and that biodiesel to be used in blends with CP less than -12°C have a CSFT of less than 200 seconds. While the original study showed good performance for B100 with CSFT less than 200 seconds, it did not include B100 with CSFT in the 200 second to 360 second intermediate range.

To achieve these objectives we acquired two B100 samples, B100E with average CSFT of 320 seconds and B100F with average CSFT of 683 seconds. Testing was conducted using the same base diesel fuels as in the original study. B5 blends were prepared from a No. 2 diesel fuel having a CP of -28.6°C and B20 blends were prepared from a 50/50 (by volume) blend of this No. 2 diesel and a No. 1 diesel, having a blend CP of -37.5°C. Three Class 8 trucks, nearly identical to those tested in Phase 1, were obtained and tested using methods identical to those employed in Phase 1.

For B100E with intermediate CSFT value, between 200 seconds and 360 seconds, the B20 blend caused failure to operate at CP in one truck. The CP of this fuel was -23.2°C, below the -12°C lower limit in D6751 for fuels produced from B100 having CSFT time in this range. The fact that one vehicle failed to operate, provides support for the 200 second CSFT requirement for blending of fuels that require a CP below -12°C. At the B5 blend level the EMOT was at CP for two of the trucks, confirming this conclusion. For B100 F that failed the CSFT requirement, failure to operate at CP was observed for the B20 blend in two trucks, including truck A2 which had an EMOT significantly above CP. At the B5 level EMOT was about 1°C below CP, however high fuel filter pressure drop was observed in passing tests suggesting that failure would occur under even slightly more severe conditions. These results confirmed the conclusion of the Phase 1 study that high CSFT material can cause fuel filter plugging at and above CP.

As observed in Phase 1 CFPP tended to predict an operability limit at lower temperature than CP and in many cases lower than the EMOT, and so is not protective of the most severe vehicles. This is also consistent with previous observations for conventional diesel fuel. LTFT was protective of all vehicles but was very conservative in some cases. Overall the study results confirmed what was learned in Phase 1, and provided support for the cold soak filterability requirements as currently stated in the ASTM D6751 specification.

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Jeff Jetter	Honda
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David Forester	Power Service Products
Ken Mitchell	Shell Canada

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Acronyms and Abbreviations

ASTM	ASTM International, at standards setting organization
AWCD	All-weather chassis dynamometer
Bxx	Biodiesel blend containing xx volume percent biodiesel
CFPP	Cold filter plugging point
CP	Cloud point
CRC	Coordinating Research Council
CSFT	Cold soak filtration time
DDC	Detroit Diesel Corporation
EMOT	Estimated minimum operability temperature
FAME	Fatty acid methyl ester
HD	Heavy-duty
IOR	Imperial Oil Research
kph	kilometer per hour
LD	Light-duty
LTFT	Low-temperature flow test\
OEM	Original equipment manufacturer
rpm	revolutions per minute
USDOE	United States Department of Energy

1. Introduction

Diesel fuels must perform under a range of weather conditions, and so petroleum-derived diesel is formulated to have a lower CP during winter months with significantly lower CP fuels required in northern tier states and colder areas. Tenth percentile minimum ambient air temperatures are shown in an appendix to the ASTM D975 Standard Specification for Diesel Fuel Oils[1] and are used to estimate low-temperature operability requirements. This is most commonly done by ensuring that fuel CP is below the tenth percentile minimum ambient air temperature. Note that for petroleum-derived diesel fuels flow improver additives can allow operability at temperatures as much as 10°C below CP.

Biodiesel blend operability may be complicated by the observation that some biodiesel blendstock can form precipitates in blends at temperatures above CP. Phase 1 of this study showed that the CSFT could identify biodiesel that forms these precipitates.[2] Four B100 materials were tested as B5 and B20 blends in three Class 8 trucks, each believed to represent approximately 30% of the North American Class 8 truck market. Three of the B100 exhibited an average CSFT <200 seconds, while the fourth had CSFT >720 seconds. For each fuel/truck combination the low-temperature operability limit was bracketed and the results used to calculate an estimated minimum operating temperature. The original study showed that high CSFT B100 can cause low-temperature operability problems at temperatures above CP for B20 blends. For B5 blends vehicle operability on the test was not affected above CP, although high fuel filter pressure drop was observed. Consequently, ASTM added a cold soak filterability requirement to the D6751 specification for B100.

The purpose of the Phase 2 study was to provide a more complete understanding by first testing an additional high CSFT B100, blended at the 5% level, to confirm that vehicle operability above CP is not affected, at least under the conditions of the chassis dynamometer test. A second objective was to test B20 made from biodiesel having a CSFT between 200 seconds and 360 seconds. The cold soak filterability requirement in the ASTM D6751 specification for B100 requires that all B100 meet a 360 second CSFT maximum, and that biodiesel to be used in blends with CP<-12°C have a CSFT <200 seconds. While the original study showed good performance for B100 with CSFT <200 seconds, it did not test B100 with CSFT in the intermediate range. Some industry stakeholders questioned the need for the 200 second limit.

The methods used in Phases 1 and 2 are identical. Therefore, this report does not include background information on low-temperature operability of diesel fuels, nor does it include all details on study methodology. The reader is referred to CRC Report 650 for this information.

[1] ASTM D975 Standard Specification for Diesel Fuel Oils. Copyright © ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, United States.

[2] CRC Report 650: Biodiesel Blend Low Temperature Performance Validation, CRC Project DP-20-07, June 2008. www.crcao.org.

2. Approach

The testing program general concept is as follows:

- Four fuels were tested in 3 HD vehicles. Fuels include B5 and B20 blends from two biodiesels. One of the B100 failed the cold soak filtration requirement, and the second had a cold soak filtration time between 200 seconds and 360 seconds.
- Biodiesel was characterized for quality by multiple labs. Base fuel and blends were characterized for CP, CFPP, LTFT and other low temperature operability parameters by multiple labs.
- Vehicles were cooled to test temperature (initial test temperature was the CP) overnight then started and driven on an all-weather dynamometer. In subsequent tests, temperatures were adjusted to try to define an operability limit.
- Testing protocol was identical to that used in the Phase 1 study, and very close to that used in previous studies.[3,4]

Test Vehicles

Three test vehicle types were selected based on engine OEM market share, as shown in Table 1. These engines are believed to be representative of those with the largest market share for North American Class 8 trucks as the manufacturers each have roughly 30% market share. The designations A2, C2, and D2 are to indicate that these trucks are similar (same engine manufacturer) to Trucks A, C, and D in Phase 1. In Phase 1 Truck B was a spare truck, essentially identical to Truck A, that was kept available in case of vehicle malfunction. A spare truck was not used for Phase 2.

Table 1. Class 8 trucks procured for this program.

Test Vehicle	Model Year	Engine
Freightliner	2003	Detroit Diesel Series 60
International	2004	Caterpillar C-12
International	2005	Cummins ISM

Fuel System and Fuel Filter Configurations

Three different engines were chosen representing three different fuel system configurations to maximize the understanding of their influence on the test results. Fuel systems and fuel filter configurations are, of course, critical to the operability limit determination. The three trucks were selected to correspond as closely as possible to the three trucks used in the Phase 1 program. The manufacturers of the engines were

[3] CRC Report No. 649. Evaluation of Low Temperature Operability Performance of Light-Duty Diesel Vehicles for North America - Vehicle Test Report. CRC Project No. DP-2-04-1 and Evaluation of Low Temperature Operability for Light-Duty Diesel Vehicles for North America - Data Analysis Report. CRC Project No. DP-2-04-2. November 2007. www.crcao.org.

[4] Chandler, J.E. "Comparison of All Weather Chassis Dynamometer Low-Temperature Operability Limits for Heavy and Light Duty Trucks with Standard Laboratory Test Methods" *SAE Technical. Paper No.* 962197 (1996).

consulted and their recommendations were followed. Two test vehicle types had the primary fuel filter housing located outside of the engine compartment and behind the cab (Truck A2 and C2). The third vehicle type (Truck D2) had the primary filter housing within the engine compartment. All primary filters ran at negative gauge pressure. Only one engine, Truck C2, had a secondary filter, normally run at positive gauge pressure. For Trucks A2 and C2 the return fuel from the engine passed through the filter housing to warm up the incoming fuel before being returned to the fuel tank. For Truck D2, an electric heater was part of the fuel filter to warm up the incoming fuel. The heater drew approximately 230 W of power, as compared to the 50 W of power the heater in Truck D in the Phase 1 program.

Table 2. Fuel filter configuration and micron size.

Truck	**Test Vehicle**	**Mounting Location**	**Inlet fuel heated at filter by**	**Primary Filter Micron size**	**Secondary Filter Micron size**
A2	International	External, behind cab	Return fuel	7	N/A
C2	International	External, behind cab	Return fuel	10	4
D2	Freightliner	Engine compartment	Electric heater	7	N/A

The fuel systems of the vehicles are shown in schematic drawings (Figures 1 – 3) indicating the locations of pressure and temperature sensors.

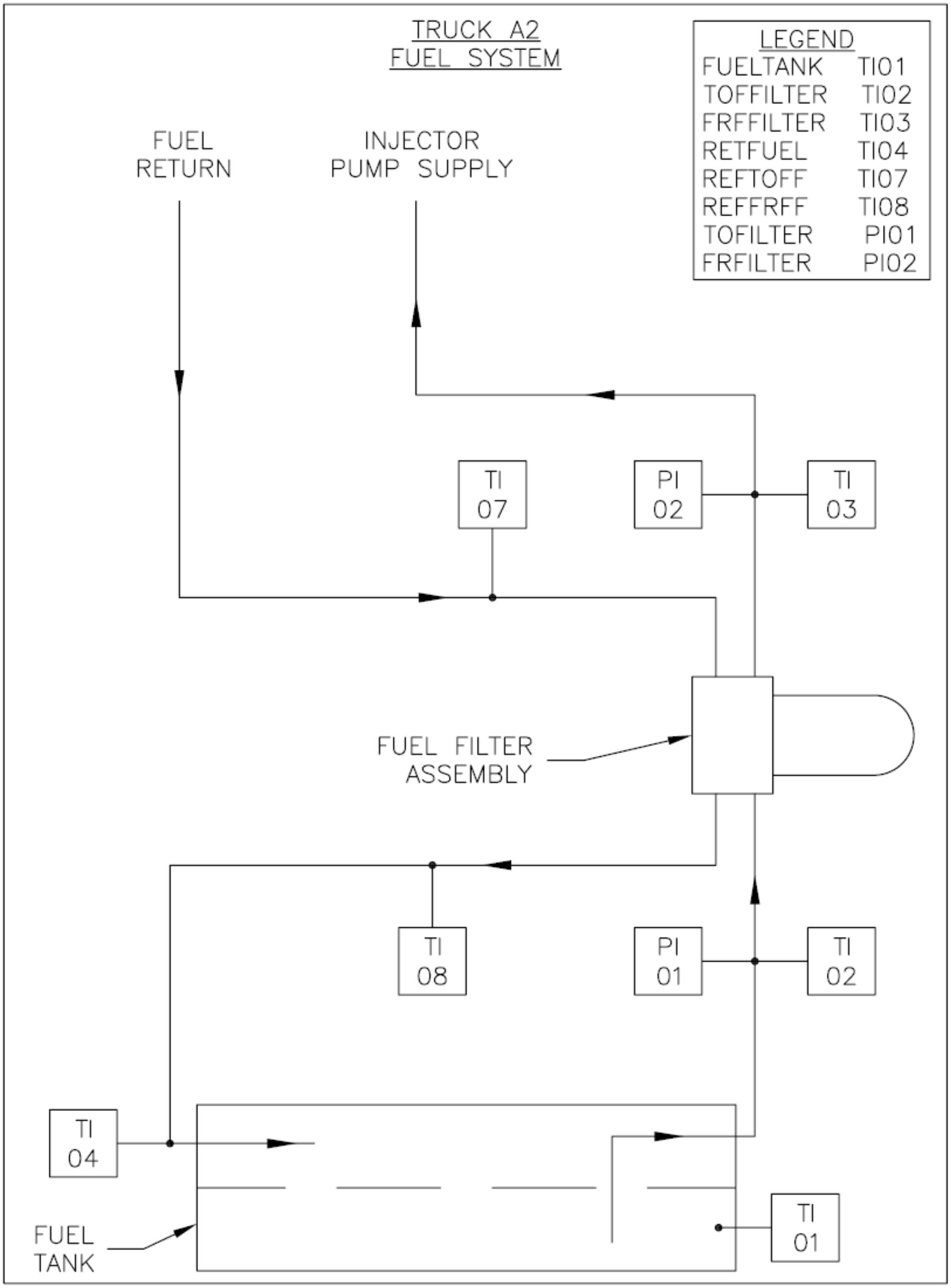

Figure 1. Vehicle fuel system diagram for Truck A2.

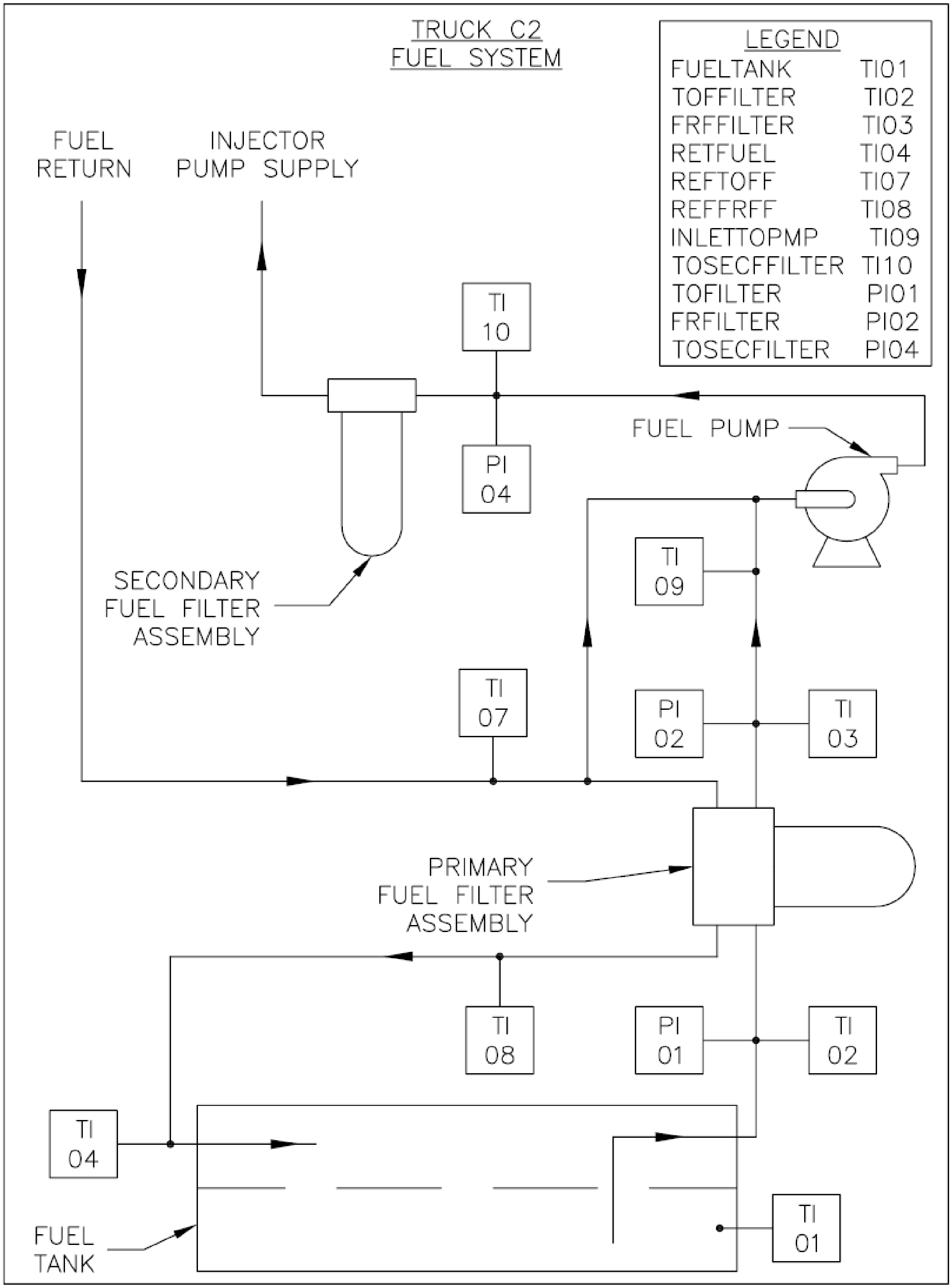

Figure 2. Vehicle fuel system diagram for Truck C2.

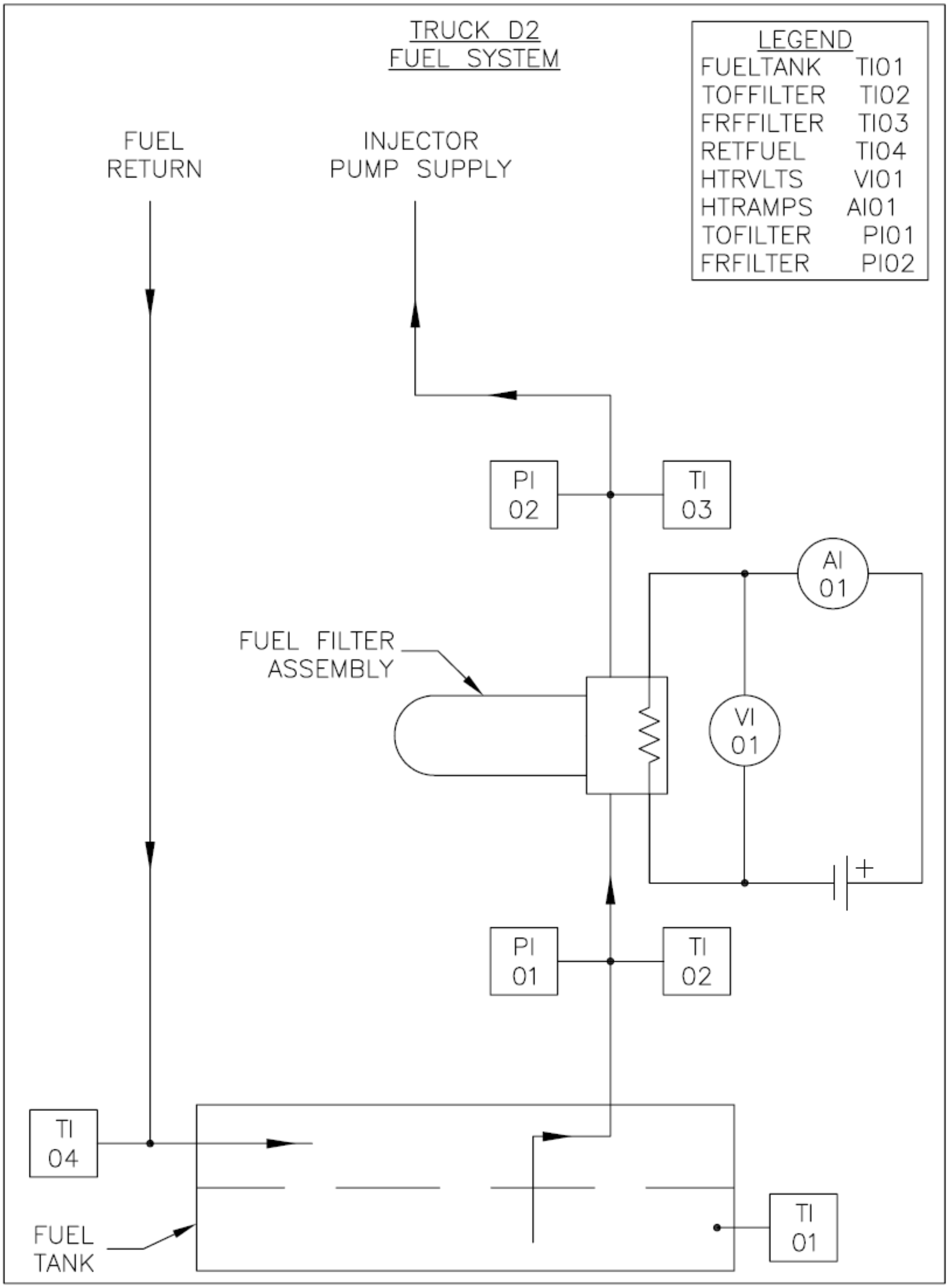

Figure 3. Vehicle fuel system diagram for Truck D2.

Test Vehicle Preparation

Sensors were installed on each test vehicle to measure and record temperatures, pressures, and engine speed. The vehicle speed, wind speed, and tractive force were measured by facility sensors. Following are the key parameters:

- Temperatures: ambient, fuel tank, fuel before and after filter, fuel return, engine oil, and coolant.
- Pressure: before and after fuel filter, after secondary filter (if equipped).
- Speed: engine speed (rpm), vehicle speed (kph), wind speed (kph).
- Force: tractive force.
- Voltage and current to fuel filter heater in the case of DDC Series 60 engine.

The engine oil in each vehicle was replaced with SAE 0W40 multi-grade oil.

An engine block heater was standard equipment in all of the test vehicles, as was an ether starting-aid system.

Test Fuels

Two test fuels were procured representing an Arctic winter diesel and a regional winter diesel. These are referred to as No. 1 diesel and No. 2 diesel, respectively. The No. 2 diesel was used for making B5 blends. To obtain fuels with a realistically low CP, the B20 blends were prepared from a 50/50 (volume) blend of the No. 1 and No. 2 diesel fuels. Two B100 fuels were shipped to IOR for blending. One was a canola derived B100, identified as E, and the other was a soy based B100, identified as S. By mixing 80% of E and 20% of S, a third B100 was created and identified as F. Table 3 describes each of the test fuels with the volume percentage of their blending components.

Table 3. Test fuels for low-temperature operability limit study, volume percent.

Fuel Code		% #1D	% #2D	% E	% F
TF #12	B5E		95	5	
TF #13	B20F	40	40		20
TF #14	B5F		95		5
TF #15	B20E	40	40	20	

Test Procedures

The test procedure used was an established protocol using a simplified drive cycle but simulating typical cold temperature operations of heavy-duty diesel trucks.

To prepare the test trucks, one of the two fuel tanks was disconnected from each fuel system. At the start of each test fuel, the previous fuel was drained from the tank and the test fuel flushed into the tank using a double flush procedure. A volume of 200 L of fuel (approximately half of the tank) was used at the start of each test. The trucks were then placed inside the test facility the night before the test to be conditioned, or "soaked", to the test temperature. A minimum of 12 hours and usually over 14 hours of soaking occurred before tests began. Normally, the air temperature of the facility was set to about 2 °C below the target test temperature to allow the fuel tank to reach the test temperature within a reasonable time. The air temperature of the test facility was then set to the test temperature before the start of the test. During the overnight soak period, a one-liter sample of the test fuel in a glass bottle was also placed in the facility so that the appearance of the test fuel at the test temperature could be observed, and a photo taken for the record.

The engine block heaters were plugged in during the overnight soak. Both the ether injection starting aid system and warm batteries were used to maximize engine starting probability. Once the engine was started, it was left at the idle condition for 10 minutes before accelerating at a modest rate to 80 km/hr (kph). The truck was then maintained at 80 kph for one hour to complete the drive cycle. The loading of the chassis dynamometer was set to simulate 36,400 kg (~80,000 lb) gross vehicle weight of a Class-8 heavy-duty diesel truck.

The operability of the test fuel blend was assessed based on four sequential requirements: (i) starting the engine; (ii) maintaining idle condition for 10 minutes; (iii) accelerating to 80 kph; and (iv) maintaining a steady speed of 80 kph for one hour. Any test where these four requirements were not met was regarded as a failure of the vehicle to operate on that fuel at the test temperature.

3. Fuel and Blend Component Characterization Results

Base Diesel Characterization

Bench low-temperature operability test results for the No. 1 diesel, No. 2 diesel and their 50/50 blend are shown in
Table 4 (taken from the Phase 1 report). The 95% confidence interval is reported for the No. 2 diesel CP because this fuel was actually tested in the vehicles. Precision is in line with expectations for this measurement. Neither the No. 1 diesel, nor the 50/50 blend of the two, were tested in the vehicles. The 50/50 blend was used as the petroleum diesel fraction of the B20 blends.

B100 Characterization

The measured properties of B100E and F are shown in Table 5 and 6, respectively. One laboratory performed the full set of D6751 tests. Critical tests were repeated by several other test labs. Both B100's met D6751 requirements, with the exception of cold soak filterability for B100F, as discussed below. FAME speciation for both B100 is reported in Appendix I.

The CSFT was performed by several different laboratories on samples retained at the IOR Sarnia lab after vehicle testing. The test method described in Annex A1 of ASTM D6751-08 was employed. Some difficulty was encountered in obtaining consistent CSFT results. Not all test labs properly performed the initial 40°C/3 hr thermal treatment. Test results where thermal pretreatment that was not exactly as specified in the D6751 Annex method were rejected. Also, recent work has shown a difference in filtration times between filters from different manufacturers. Only tests using Whatman GF/F filters were included. Note that ASTM has developed an improved test method for cold soak filterability, D7501, and that more carefully defines thermal pretreatment and requires the use of Whatman GF/F filters. A table with the resulting dataset is shown in Appendix I.

Even with the restrictions noted above, there were still outliers. To reject outliers in an unbiased manner the high and low values obtained for each B100 were also rejected. The resulting dataset is shown in Figure 4, which indicates that overall consistent results can be obtained with careful attention to exactly how the tests are conducted. Notably, one outlier remains for B100E, but in the absence of a reason to reject this number, it was retained in the dataset.

Table 4. Bench low temperature operability test results (ºC) for No. 1 and No. 2 diesel fuels and the 50/50 (volume) blend.

Lab	CP				CFPP		LTFT		
	Method	No. 2	No. 1	50/50 No.2/No.1	Method	No. 2	Method	No. 2	50/50 No.2/No.1
A	D2500	-30	-50						
B	D2500	-29	-50	-36	D6371	-32			
C	D5773	-29.4	-48.1						
D	D5773	-27.4	-47.9				D4539	-27	
G	D5772	-26.5	-41.7		D6371	-25			
I	D5773	-29	-52	-39			D4539	-27	-35
	Average	**-28.6**	**-48.3**	**-37.5**		**-28.5**		**-27.0**	**-35**
	St. Dev.	1.32							
	95% conf	1.06							

Table 5. Characterization and properties of B100E.

Lab:	Method	B	C	E	F	G	**Average**
Cloud Point, ºC	various	-2.5	-1.3	-1	-2	-3	-2.0
Cold Filter Plugging Point, ºC	D6371	-6.5	-6	-7		--	-6.5
Flash Point, ºC	D93				>150	170.6	>150
Acid Value, mg KOH/g	D664				0.08	0.06	0.07
Water and Sediment , vol%	D2709				<0.005	0.01	<0.01
Dissolved Water, ppm	various				670	604	637
Kinematic viscosity at 40°C, mm^2/s	D445					4.534	4.534
Copper strip corrosion	D130					1a	1a
Distillation (AET T90), °C	D1160					354	354
Carbon residue, wt%	D4530					0.0067	0.0067
Oxidation Stability, hr	EN14112			18.6	18.7	>12	>12
Sulfur, ppm	various					2.7	2.7
Sulfated Ash, wt%	D874					<0.001	<0.001
Phosphorus, ppm	D4951					<5	<5
Na+K, ppm	EN14538					<2	<2
Ca+Mg, ppm	EN14538					<0.5	<0.5
Particulate Contamination, mg/L	D7321					4.3	4.3
Free glycerin, wt%	D6584	0.002		0.001	<0.001	<0.005	<0.005
Total glycerin, wt%	D6584	0.143		0.151	0.151	0.182	0.157
Monoglyceride, wt%	D6584			0.508	0.505	0.591	0.535

Table 6. Characterization and properties of B100F.

Lab:	Method	B	C	E	F	G	**Average**
Cloud Point, ºC	various	-2.9	-2	-1	-1	-3	-2.0
Cold Filter Plugging Point, ºC	D6371	-7.9	-8	-6			-7.3
Flash Point, ºC	D93				>150	165	>150
Acid Value, mg KOH/g	D664				0.1	0.07	0.09
Water and Sediment , vol%	D2709				<0.005	0.01	<0.01
Dissolved Water, ppm	various				530	687	609
Kinematic viscosity at 40°C, mm^2/s	D445					4.403	4.403
Copper strip corrosion	D130					1a	1a
Distillation (AET T90), °C	D1160					354	354
Carbon residue, wt%	D4530					0.0067	0.0067
Oxidation Stability, hr	EN14112			13	12.2	>12	>12
Sulfur, ppm	various					2.3	2.3
Sulfated Ash, wt%	D874					<0.001	<0.001
Phosphorus, ppm	D4951					<5	<5
Na+K, ppm	EN14538					<2	<2
Ca+Mg, ppm	EN14538					<0.6	<0.6
Particulate Contamination, mg/L	D7321					9.2	9.2
Free glycerin, wt%	D6584	0.001		0.001	<0.001	<0.005	<0.005
Total glycerin, wt%	D6584	0.136		0.150	0.149	0.181	0.154
Monoglycerides, wt%	D6584			0.511	0.495	0.589	0.532

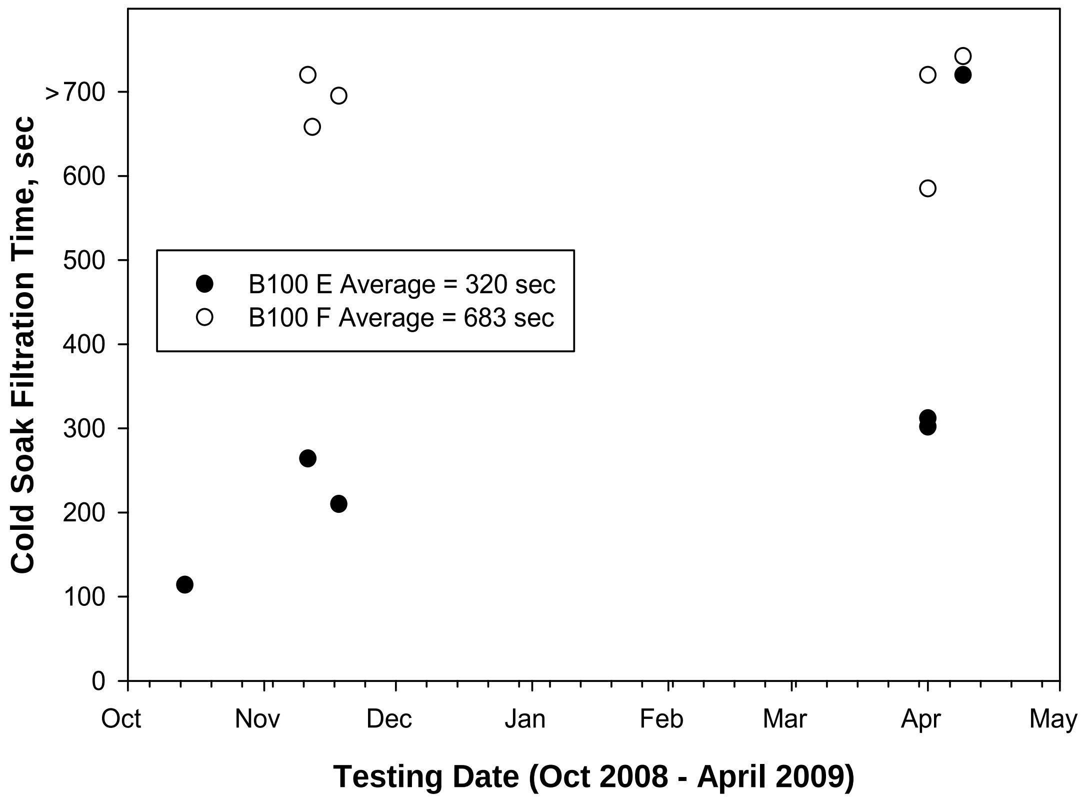

Figure 4. Cold soak filtration time results for B100 samples.

B5 Blends

B5 blends were prepared from each B100 by blending with the No. 2 diesel fuel. CP and other low temperature operability test results are shown in Table 7. CP is compared with CFPP and LTFT in Figure 5, which also includes data for test fuels from the Phase 1 study. The B5 results are those clustered between CP of -23°C and -25.3°C; thus, as expected for a diesel with a cloud point in this temperature range addition of 5% biodiesel causes a 3°C to 5°C increase in CP. CFPP tends to be a degree or more below CP, while LTFT is equal to or slightly above CP. This is in line with expectations as the LTFT test was developed to predict performance with the most challenging vehicle fuel systems. Additional characterization results for the B5 blends are shown in Appendix II.

B20 Blends

B20 blends were prepared from each B100 by blending with a 50/50 (volume) blend of the No. 1 and No. 2 diesel fuel. Results for CP, CFPP, and LTFT are shown in Table 8. Recall that the CP of the 50/50 No. 1/No. 2 diesel blend was -37.5°C. Addition of 20% biodiesel causes an increase of CP by 12 to 15°C, as expected for a diesel fuel with a cloud point in this temperature range. Figure 5 also shows a comparison of CP with CFPP and LTFT results for the B20 blends. For the two Phase 2 fuels LTFT is slightly above CP. Note that in the Phase 1 study we observed that TF#5, which was prepared from B100A having a high CSFT, had an average LTFT of -1.5°C while CP was -17.9°C. B100F, the high CSFT B100 used this Phase 2 work, does not produce a similarly high LTFT. Average CSFT for B100A was well over 720 seconds, with some measured values over 900 seconds. The high LTFT of blends from B100A, combined with the long CSFT, suggest significantly higher concentrations of the precipitating impurities in this sample than in the two B100 tested in Phase 2. Additional characterization results for B20 blends are reported in Appendix II.

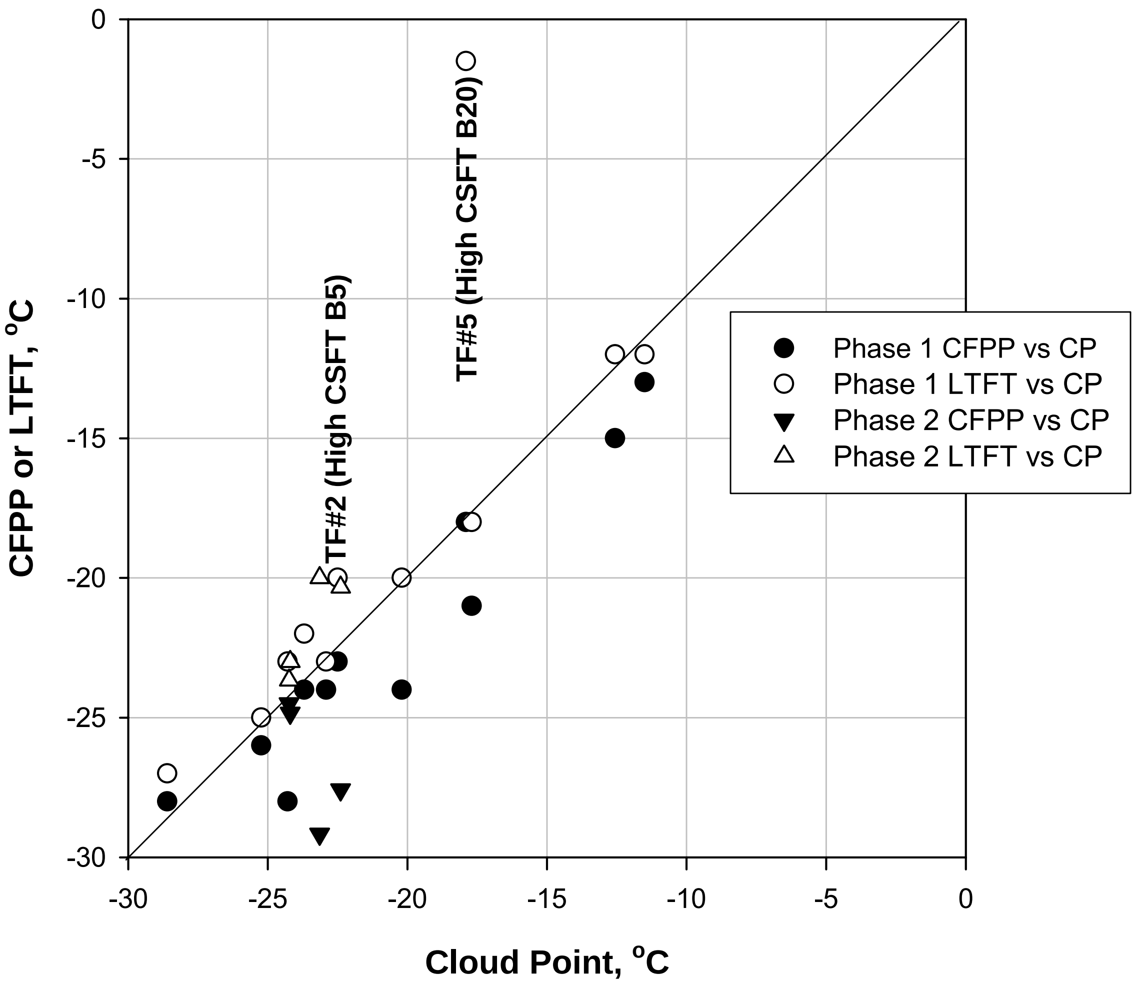

Figure 5. Comparison of CP with CFPP and LTFT for B5 and B20 blends.

Table 7. Cloud point, CFPP, and LTFT results for B5 blends (°C).
[a]Lowest pass temperature

Lab	**Cloud point**	**TF#12**	**TF#14**	**CFPP**	**TF#12**	**TF#14**	**LTFT[a]**	**TF#12**	**TF#14**
	Method	**B5E**	**B5F**	Method	**B5E**	**B5F**	Method	**B5E**	**B5F**
C	**D5773**	-25.2	-25	D6371	-25	-29	D4539	-23	-23
D	**D5772**	-21	-21.2	D6371	-21	-27	D4539	-24	-24
E	**D5773**	-25	-24	D6371	-24	-31			
G	**D2500**	-25	-24	D6371	-31	-26			
H	**D5773**	-22	-24	D6371	-24	-26	D4539	-22	-24
I	**D2500**	-25.6	-25.9	D6371	-24	-26.5			
J	**D5773**	-25	-25						
K	**D5771**	-24.5	-24.5						
Average		**-24.2**	**-24.2**		**-25**	**-28**		**-23**	**-24**
Standard Dev		1.69	1.38		3.31	2.01		1.00	0.58
95% conf.		1.11	0.90		2.65	1.61		1.13	0.65

Table 8. Cloud point, CFPP, and LTFT results for B20 blends (°C).

Lab	**Cloud point**	**TF#13**	**TF#15**	**CFPP**	**TF#13**	**TF#15**	**LTFT**[a]	**TF#13**	**TF#15**
	Method	**B20F**	**B20E**	Method	**B20F**	**B20E**	Method	**B20F**	**B20E**
C	**D5773**	-23.6	-24.5	D6371	-29	-32	D4539	-22	-22
D	**D2500**	-19.7	-20.5	D6371	-27	-30	D4539	-18	-16
E	**D5771**	-23	-23	D6371	-31	-33			
G	**D5773**	-25	-26	D6371	-26	-27			
H	**D5773**	-21	-22	D6371	-26	-27	D4539	-21	-22
I	**D2500**	-22.2	-23.3	D6371	-26.5	-26			
J	**D5772**	-23	-24						
K	**D5773**	-22	-22.5						
Average		**-22.4**	**-23.2**		**-28**	**-29**		**-20**	**-20**
Standard Dev		1.62	1.67		2.01	2.93		2.08	3.46
95% conf.		1.06	1.09		1.61	2.34		2.36	3.92

[a]Lowest pass temperature

4. Vehicle Low-Temperature Operability Results

A listing of all vehicle tests performed in Phase 2 along with the basic results (test temperature, maximum fuel filter pressure drop, and pass/fail rating) is shown in Table 9. For a test to be rated as failing, at some point in the test the vehicle failed to operate by:

- Not starting
- Not completing the 10minute idle
- Not accelerating to 80 kph
- Not being able to maintain 80 kph for the required time.

Table 9. Basic vehicle testing results.

Test Date	Run No.	Vehicle	Fuel	Test Temperature, °C	Maximum Primary Filter ΔP, kPa	Rating
2008-09-08	1	Truck D2	TF #12	-25	-19.5	P
	2	Truck C2	TF #12	-25	-95.6	F
	3	Truck A2	TF #12	-25	-88.4	F
2008-09-09	4	Truck D2	TF #12	-26	-84.4	F
	5	Truck C2	TF #12	-23	-52.1	P
2008-09-16	6	Truck A2	TF #12	-23	-13.2	P
	7	Truck C2	TF #13	-24	-96.1	F
	8	Truck D2	TF #13	-24	-71.3	P
2008-09-17	9	Truck D2	TF #13	-26	-79.6	F
	10	Truck C2	TF #13	-22	-95.7	F
	11	Truck A2	TF #13	-22	-93.2	F
2008-09-18	12	Truck A2	TF #13	-20	-30.0	P
	13	Truck C2	TF #14	-24	-45.6	P
	14	Truck D2	TF #14	-24	-11.8	P
2008-09-19	15	Truck A2	TF #14	-24	-53.7	P
	16	Truck D2	TF #14	-26	-51.8	F
	17	Truck C2	TF #14	-26	-96.6	F
2008-09-22	18	Truck A2	TF #14	-26	-88.7	F
	19	Truck C2	TF #15	-23	-97.1	F
	20	Truck D2	TF #15	-23	-89.2	P

Operability Results for Each Truck

Figures 6 – 8 show operability results for each truck, including results from the Phase 1 study. Results for Truck A2 indicate 3 failing tests in Phase 2, for a total of 15 failing tests in the overall test program. There were also 3 passing tests in Phase 2, for a total of 13 passing tests in the overall program. Operability limit was bracketed for 3 of the 4 Phase 2 test fuels (TF#15 was not tested in this truck). Thus, overall operability limit was bracketed for 12 of the 15 test fuels. Test fuel #13 caused the truck to fail to operate very near CP. Notably this fuel was a B20 produced from B100F, having a high CSFT value.

Results for Truck C2 are shown in Figure 7. For Phase 2 there were 5 failing tests, for a total of 16 failing tests in the overall program. There were 2 passing tests, for a total of 17 passing tests in the overall program. Operability limit was bracketed for 2 of the Phase 2 fuels, and for 12 of the 15 fuels in the overall program. For the fuels where operability was not bracketed, failure to operate was observed at or very near to CP.

Results for Truck D2 are shown in Figure 8. There were 3 failing tests in Phase 2, for a total of 10 failing tests. There were 4 Phase 2 passing tests, for a total of 22 passing tests. Operability limit was bracketed for 3 of the 4 Phase 2 test fuels and 10 of the 15 overall program fuels. For fuels where operability was not bracketed, operability at or below CP was demonstrated. Because of the electrical heating of the primary fuel filter and a higher fuel return rate, this truck was the least challenging from a low-temperature operability standpoint and could tolerate high fuel filter pressure drop without an operability failure, in contrast to the other trucks.

Primary fuel filter pressure traces for each truck are shown in Figures 9 - 11; truck speed traces are found in Appendix III. Failing tests were those where the pressure trace does not extend to 70 minutes. B100F, the high CSFT material, was used in test fuels #13 (B20) and #14 (B5). The pressure traces show significant fuel filter pressure drop for both of these fuels in Trucks A2 and C2, even for passing tests. B100E, with intermediate CSFT, also shows significant fuel filter pressure drop in many of the passing tests.

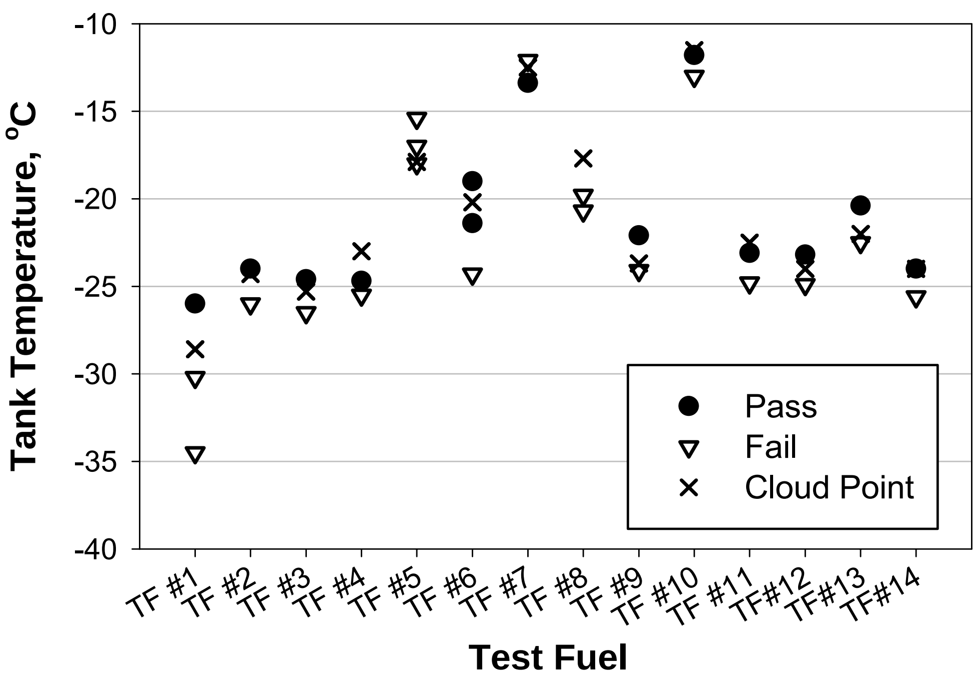

Figure 6. Operability test results for Trucks A and A2.

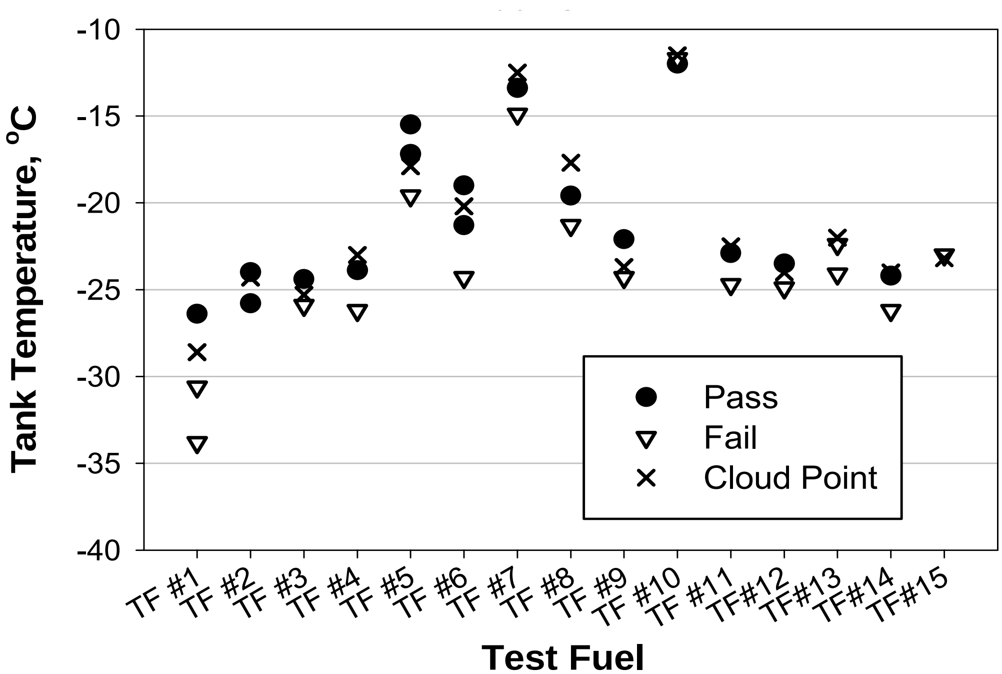

Figure 7. Operability test results for Trucks C and C2.

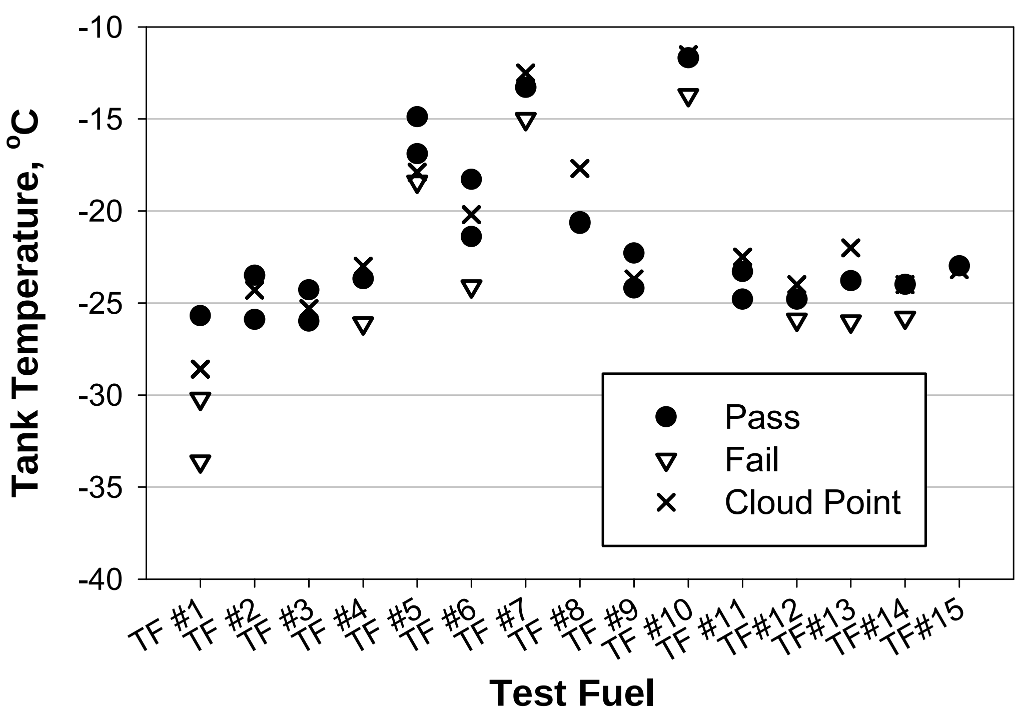

Figure 8. Operability test results for Trucks D and D2.

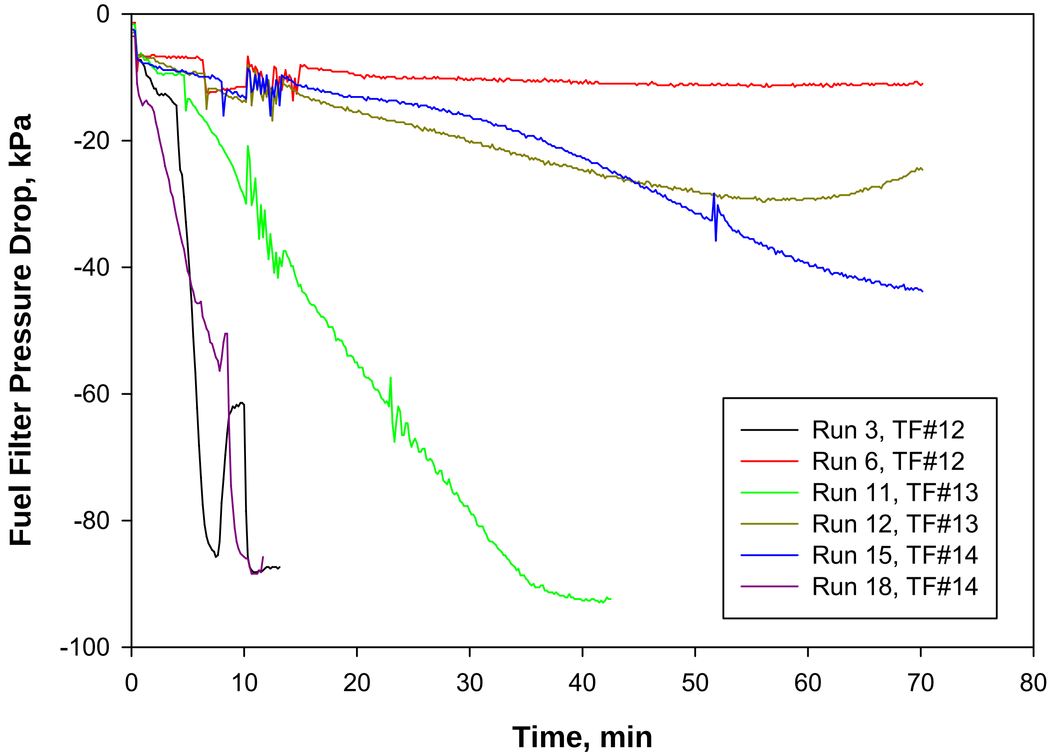

Figure 9. Primary fuel filter pressure drop for tests run on Truck A2.

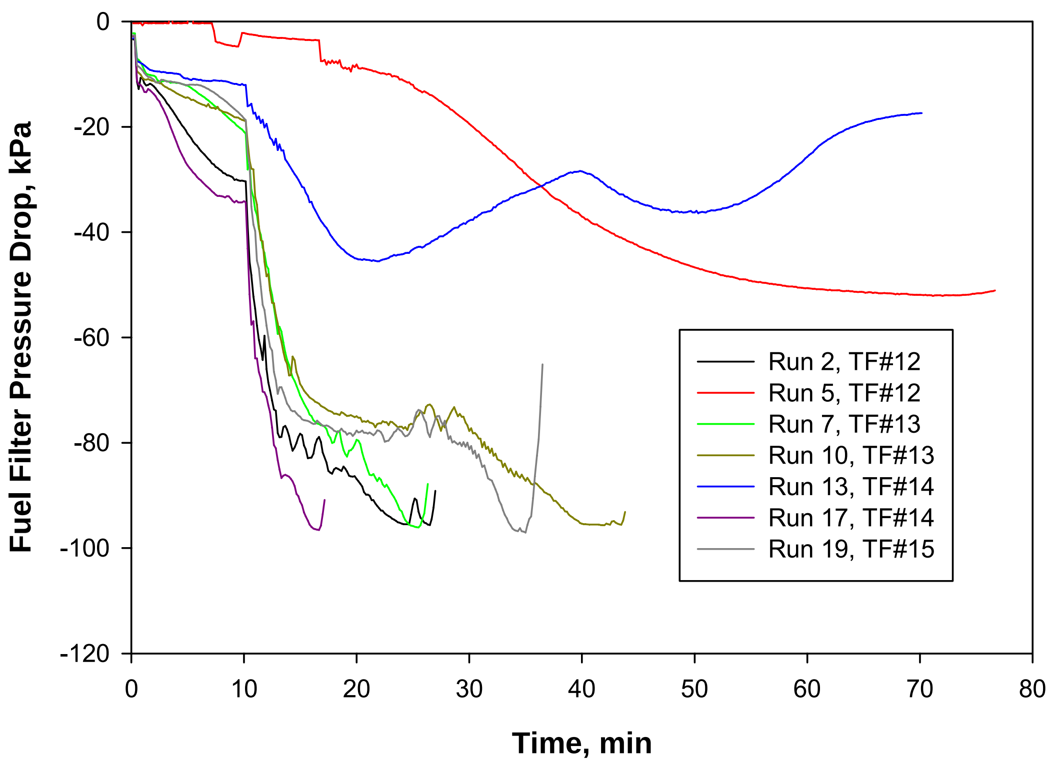

Figure 10. Primary fuel filter pressure drop for tests run on Truck C2.

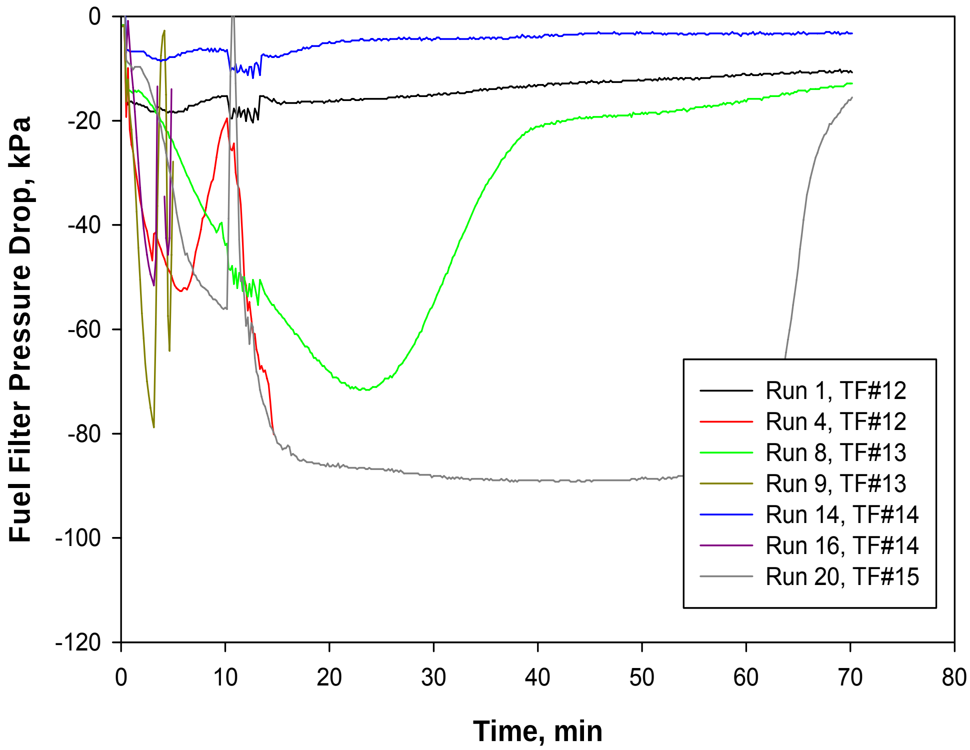

Figure 11. Primary fuel filter pressure drop for tests run in Truck D2.

Operability Results for Each Fuel

B5 Blends

Low temperature operability results for test fuels #12 and #14 are shown in Figures 12 and 13, respectively; along with photographs of the fuel at the various test temperatures. Both fuels were notably cloudy at and above CP, with increased degree of clouding as the temperature was decreased. Test fuel #12, made from B100E having intermediate CSFT, gave trouble free operation in Truck A2 with no increase in fuel filter pressure drop at -23°C. When tested at a slightly lower temperature in Truck C2, the fuel also passed; however, a significant increase in fuel filter pressure drop was observed (see filter pressure drop plots in previous section of this report). Overall it appeared that this fuel was able to operate at least down to CP in all three vehicles under the conditions of this test, but only in one vehicle (D2) below CP. Under more severe real world conditions with longer cooling times and mixing of the vehicle fuel tank, it is possible that this fuel could cause operability issues at or near CP, based on the increase in filter pressure drop observed in one test vehicle.

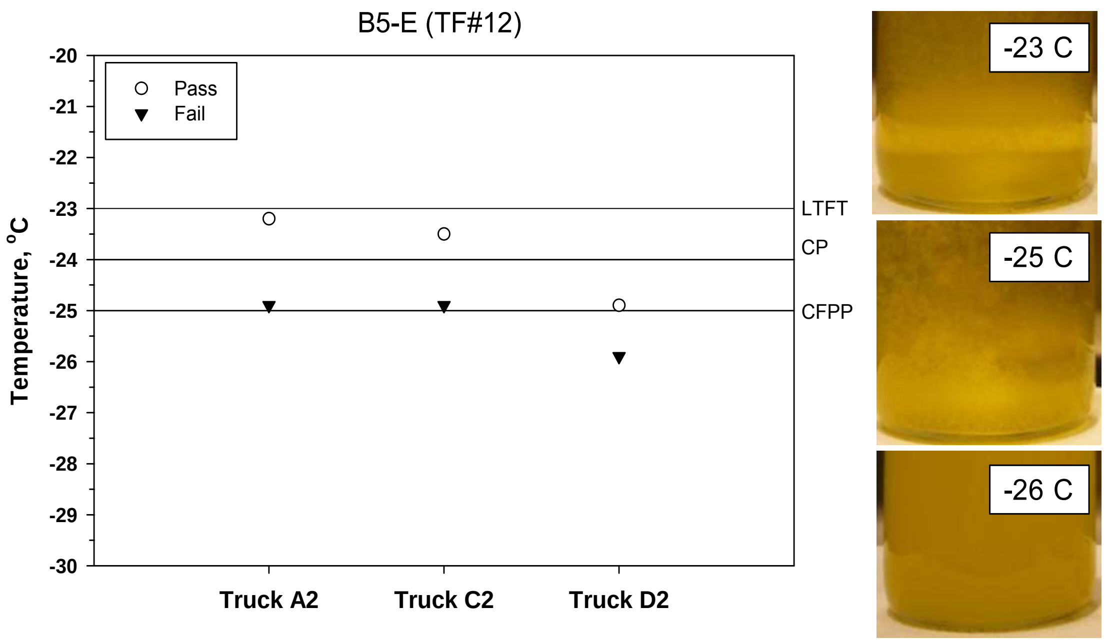

Figure 12. Vehicle operability results for TF#12.

Test fuel #14, made from B100F which failed the CSFT requirement, gave trouble free operation in all three trucks at CP. However, fuel filter pressure drop increased continuously in the passing test conducted in Truck A2 and stayed high during the passing test in Truck C2. Thus, this fuel may also be expected to cause operability issues under more severe real world conditions.

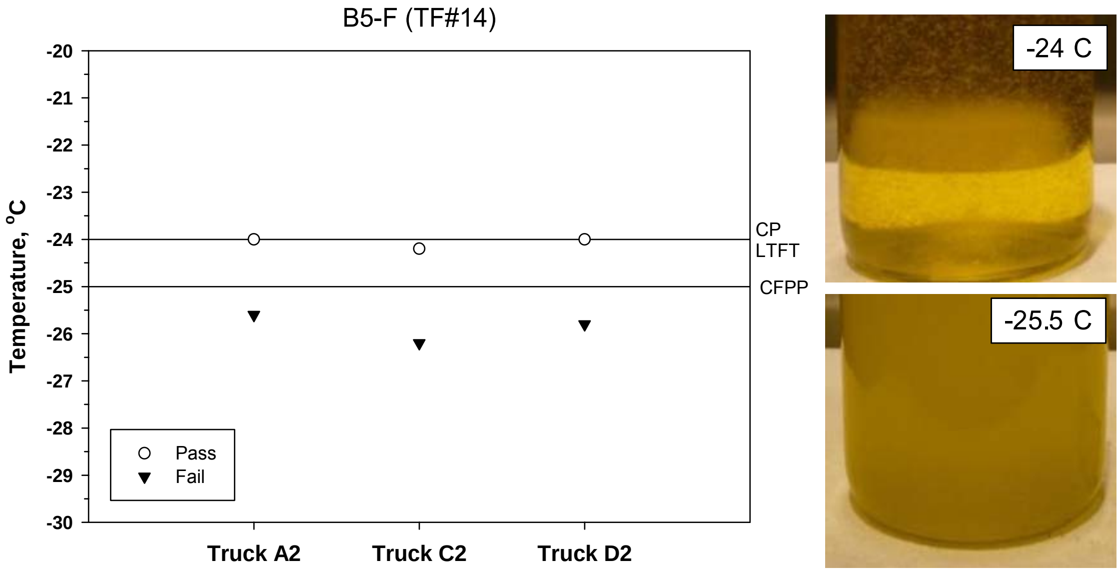

Figure 13. Vehicle operability results for TF#14.

B20 Blends

Low temperature operability results for test fuels #13 and #15 are shown in Figures 14 and 15, respectively; along with photographs of the fuel at test temperature. Test fuel #13, produced from B100 F that failed the CSFT requirement, showed significant clouding even 2°C above CP. Clouding increased as the fuel was cooled to lower temperatures. Test fuel #15 was tested only at CP.

Test fuel #13 gave trouble free operation in Truck A2 at 2°C above CP; however fuel filter pressure drop increased significantly during the test. Both trucks A2 and C2 failed to complete the test on this fuel at CP. Truck D2 with electrically heated fuel filter was able to operate significantly below CP. Test fuel #15 caused Truck C2 to fail to operate at CP, but Truck D2 was able to operate at this temperature.

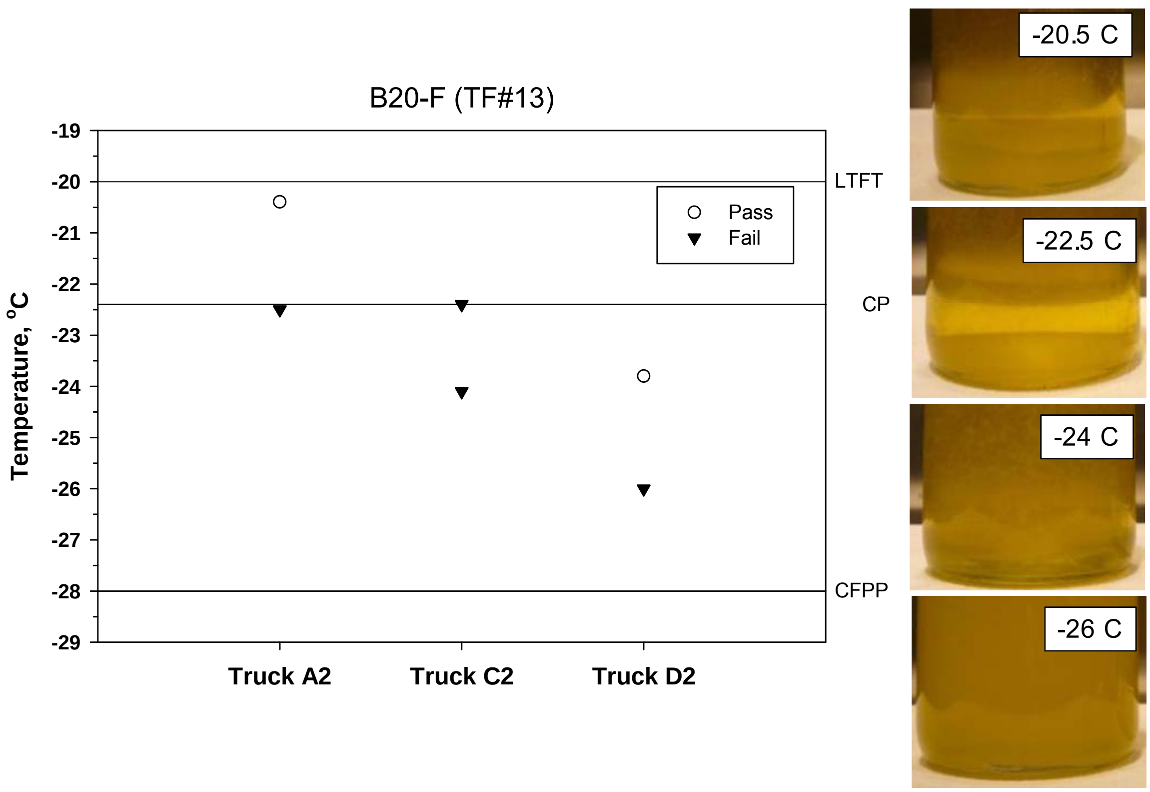

Figure 14. Vehicle operability results for TF#13.

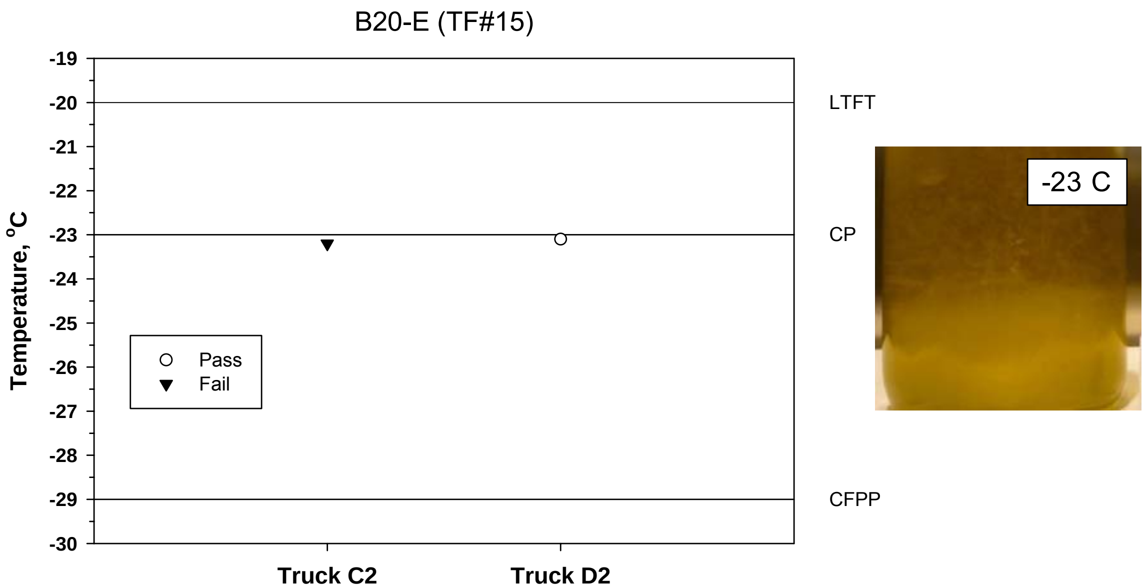

Figure 15. Vehicle operability results for TF#15.

Data Analysis

Based on the data presented in the previous section, it is possible to define an EMOT. To be consistent with previous work, the difference between the lowest pass temperature and the highest fail temperature was calculated and the EMOT was arbitrarily defined to be one-third of the temperature difference above the maximum fail temperature or two-thirds below the lowest passing test. Results of this estimation are shown in Table 10, which includes results from both Phase 1 and Phase 2. In cases where the result is listed as "greater than," no passing test was obtained. In cases where the result is listed as "less than," no failing test was obtained; in general, these results are at temperatures lower than the fuel CP.

Figure 16 shows a comparison of EMOT and CP, and Figure 17 shows an expanded region of this plot to focus in on the Phase 2 fuels. In this and the subsequent figures, the color (white, black, or red) of a symbol indentifies the truck. If the symbol is a circle, then an operability limit was determined. If the symbol is a triangle pointing up, then no passing test was obtained and the operability limit is greater than this value, and similarly for a triangle pointing down. Results in Figure 16 show that CP is an accurate or conservative predictor of EMOT in almost all cases. A regression line suggests that on average CP was conservative by about 1°C over the CP range of these tests. Extrapolation of this line to 0°C indicates a more than 2°C safety margin for CP as a predictor of EMOT at this temperature. However, as the cloud point decreases this safety margin is also reduced, to less than 0.5°C for the lowest CP fuel in the study, the No. 2 diesel fuel containing now biodiesel. An exception to the ability of CP to predict EMOT is TF#5, the B20 blend produced from the high CSFT B100A in Phase 1, which produced failing results at 3°C above CP. Examination of Figure 17 shows that TF#13, a B20 from B100F that fails the cold soak requirement, also has an operability limit above CP. The B5 blend from this B100, TF#14, has operability limits near the regression line in all vehicles. Test fuels from B100 E (TF#12 and TF#15), with intermediate CSFT results, have operability limits at or above CP.

Figure 18 compares EMOT to CFPP and Figure 19 compares EMOT to LTFT. For CFPP many of the EMOT points fall above the parity line, indicating that CFPP tends to over predict EMOT and is not protective of the most severe vehicles. The regression line suggests this is less of an issue for the fuels with EMOT above about -18°C. LTFT was protective of all vehicles but was conservative for TF#5 in Trucks C and D. A regression line (excluding data for TF#5) indicates LTFT is 2°C below EMOT over the entire range of EMOT tested.

Table 10. Estimated minimum operating temperature, °C

	Cloud Point, °C	Truck A or A2	Truck C or C2	Truck D or D2
TF #1	28.6	-28.8	-29.2	-28.7
TF #2	24.3	-25.4	<-25.8	<-25.9
TF #3	25.2	-25.9	-25.4	<-26
TF #4	22.9	-25.2	-25.4	-25.3
TF #5	17.9	>-15.4	-18.8	-17.9
TF #6	20.2	-23.3	-23.3	-23.2
TF #7	12.6	<-13.4	-14.4	-14.4
TF #8	17.7	>-19.8	-20.7	<-20.7
TF #9	23.7	-23.4	-23.6	<-24.2
TF #10	11.5	-12.6	-11.9	-13.0
TF #11	22.5	-24.2	-24.1	<-24.8
TF#12	-24.2	-24.3	-24.5	-25.7
TF#13	-22.4	-21.8	>-22.5	-25.2
TF#14	-24.2	-25.0	-25.4	-25.0
TF#15	-23.2	--	>-23.0	<-23.0

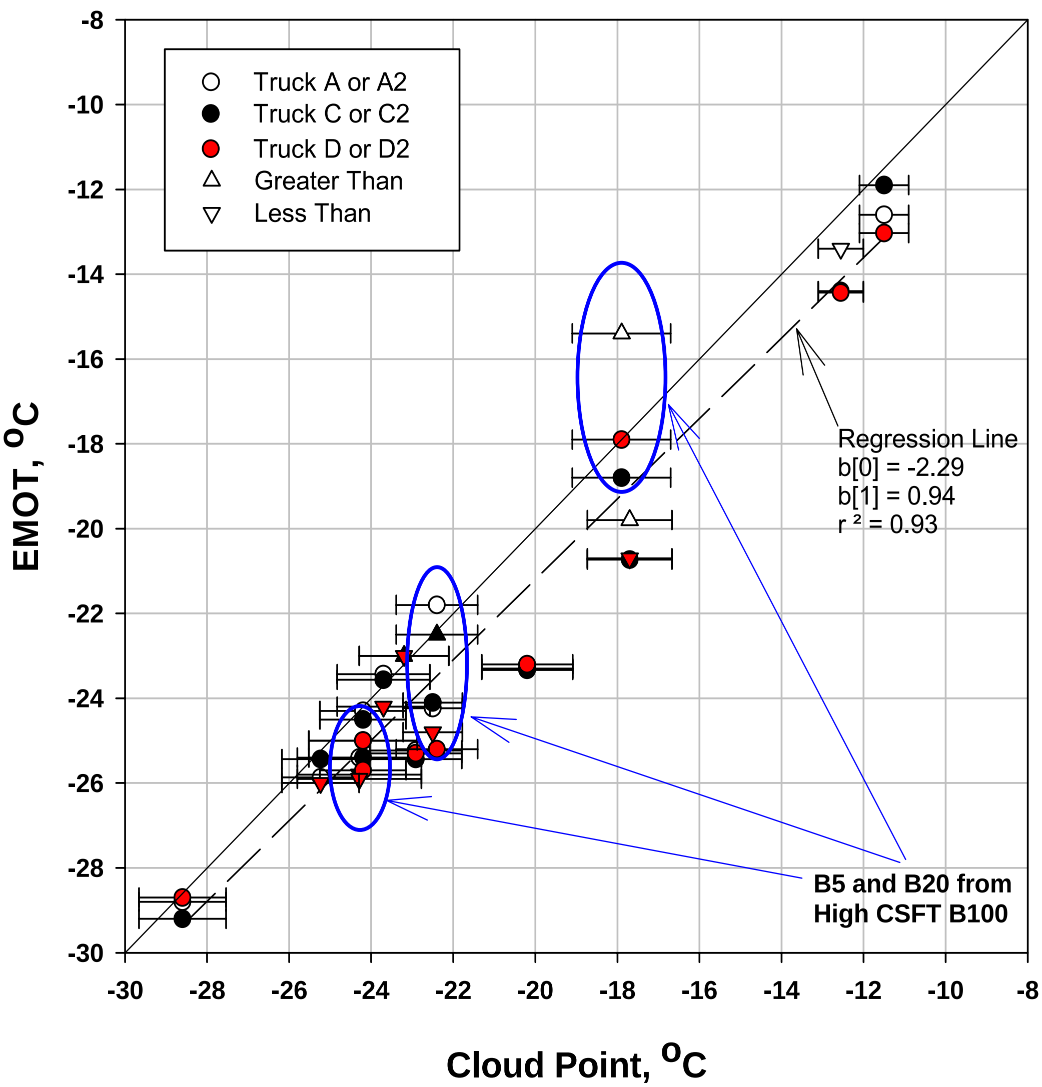

Figure 16. EMOT as a function of CP for all fuels tested (95% confidence interval shown for CP).

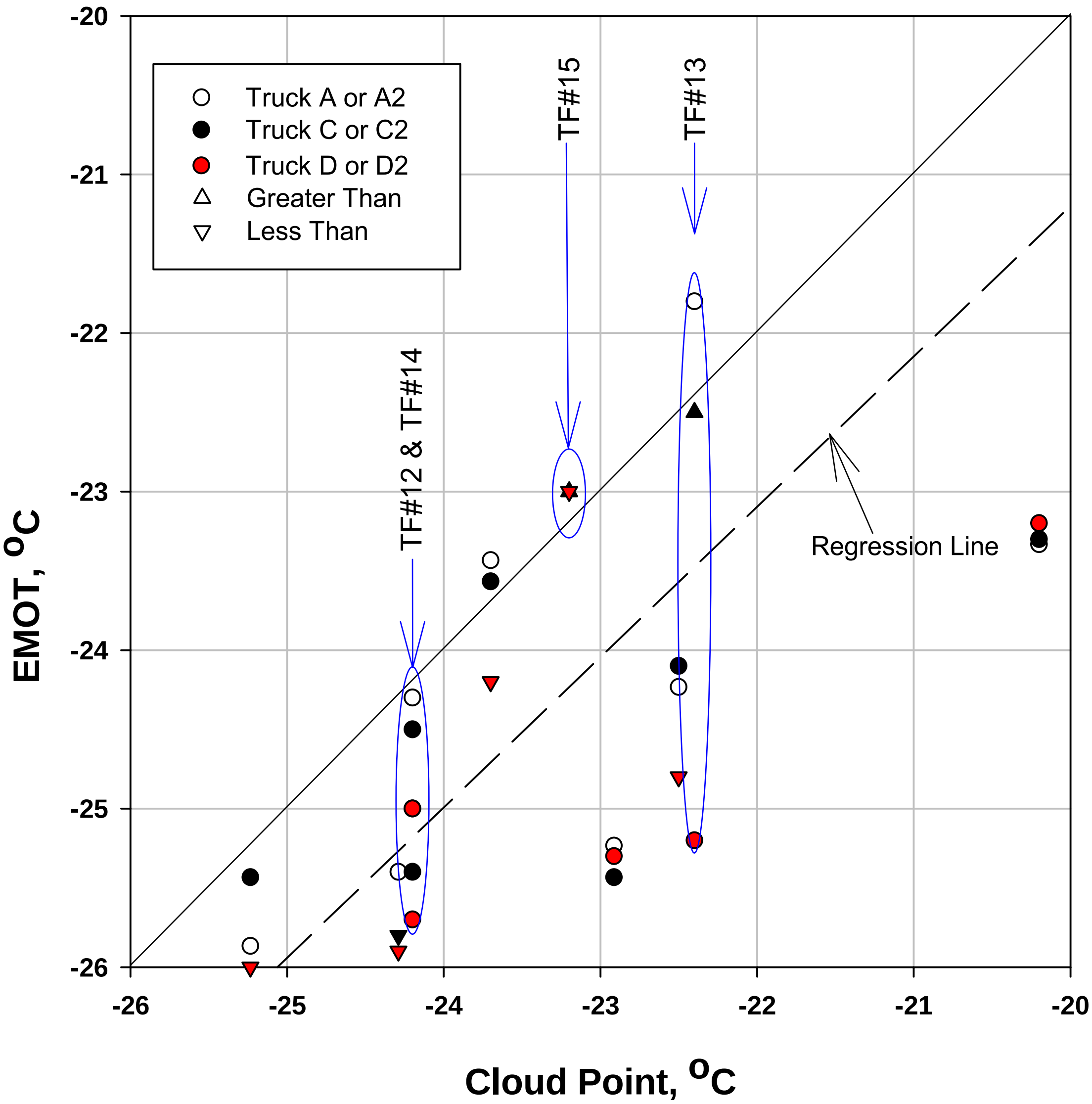

Figure 17. EMOT as a function of CP, expanded to clearly show Phase 2 fuels.

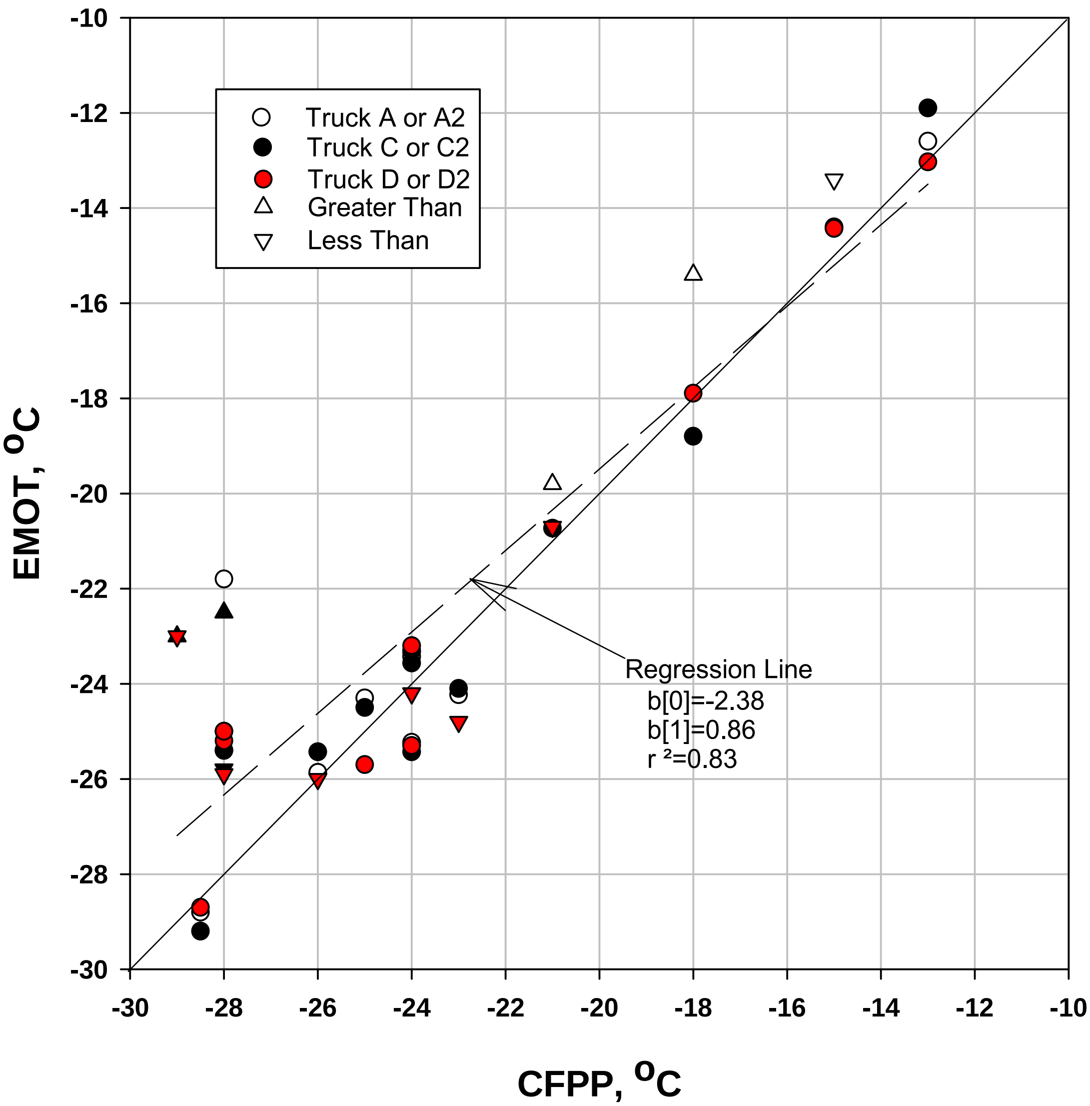

Figure 18. EMOT as a function of CFPP for all fuels tested.

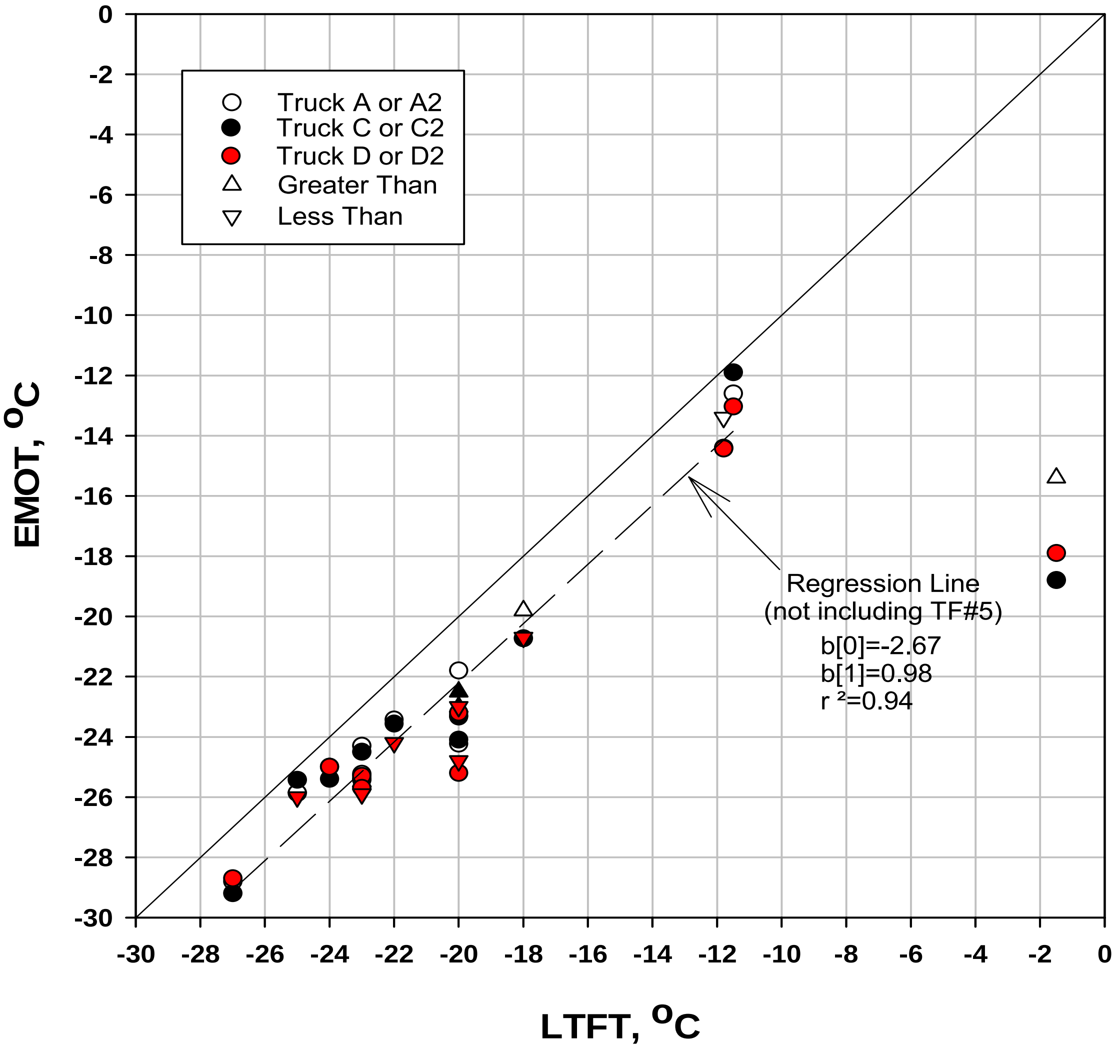

Figure 19. EMOT as a function of LTFT for all fuels tested.

5. Conclusions

With respect to biodiesel having an intermediate CSFT value, between 200 seconds and 360 seconds, the B20 blend (TF#15) from B100E caused failure to operate at CP in one truck. The CP of this fuel was -23.2°C, well below the -12°C lower limit in D6751 for fuels produced from B100 having CSFT time in this range. The fact that one vehicle failed to operate, provides support for the 200 second CSFT requirement for blending of fuels with CP below -12°C. At the B5 blend (TF#12) level, the EMOT was at CP for two of the trucks (A2 and C2), confirming this conclusion.

For B100F that failed the CSFT requirement, failure to operate at CP was observed for the B20 blend (TF#13) in the two most severe trucks (A2 and C2), and EMOT for truck A2 was significantly above CP. At the B5 level (TF#14) EMOT is about 1°C below CP, however high fuel filter pressure drop was observed in passing tests suggesting that failure would occur under even slightly more severe conditions. These results confirm the conclusion of the Phase 1 study that high CSFT material can cause fuel filter plugging at and above CP.

As observed in Phase 1, CFPP tends to over predict EMOT and is not protective of the most severe vehicles. LTFT was protective of all vehicles but was conservative in some cases.

Overall the study results confirm what was learned in Phase 1, and provide support for the cold soak filterability requirements as currently stated in the ASTM D6751 specification.

Appendix I: Additional B100 Characterization

Table 11. FAME speciation for B100 samples.

		B100 E	B100F
FAME			
Octanoic Acid :	C8:0	0.00	0.00
Decanoic Acid :	C10:0	0.00	0.00
Lauric Acid :	C12:0	0.00	0.00
Myristic Acid :	C14:0	0.00	0.00
Palmitic Acid :	C16:0	4.28	5.88
Palmitoleic Acid :	C16:1	0.00	0.00
Stearic Acid :	C18:0	1.98	2.59
Oleic Acid :	**C18:1**	**58.83**	**53.15**
Linoleic Acid :	C18:2	20.28	26.96
Linolenic Acid :	**C18:3**	**9.33**	**8.18**
Arachidic Acid :	C20:1-3	0.00	0.00
Behenic Acid :	C22:0	0.00	0.00
Erucic Acid :	C22:1	0.00	0.00
Lignoceric Acid :	C24:0	0.00	0.00
Total :		94.71	96.76

Table 12. Cold soak filterability results for Sarnia B100 retains.

Lab	B100 E	B100 F
B	**904**	658
C	114	**720**
D	**87**	**400**
F1	210	695
F2	264	720
A1	312	585
A2	302	720
A3	720	720

Note: high and low values rejected as outliers in bold

Appendix II: Additional Blend Characterization Results

Table 13. Pour point results for B5 and B20 blends (°C).

Lab	**Pour**	**TF#12**	**TF#13**	**TF#14**	**TF#15**
	Method	**B5E**	**B20F**	**B5F**	**B20E**
D		-27	-30	-27	-33
E	D97	-27	-27	-30	-27
I		-33.9	-35.6	-37.2	-38.9
J					
Average					

Appendix III: Truck Speed Traces

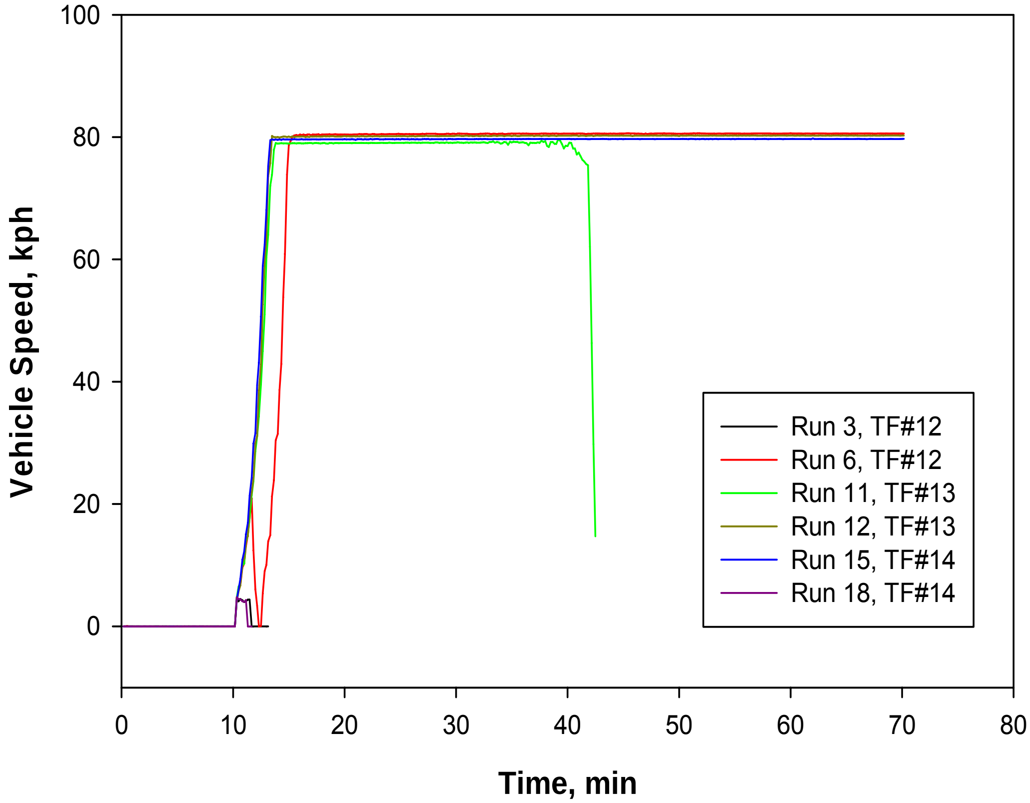

Figure 20. Vehicle speed traces for fuels tested in Truck A2.

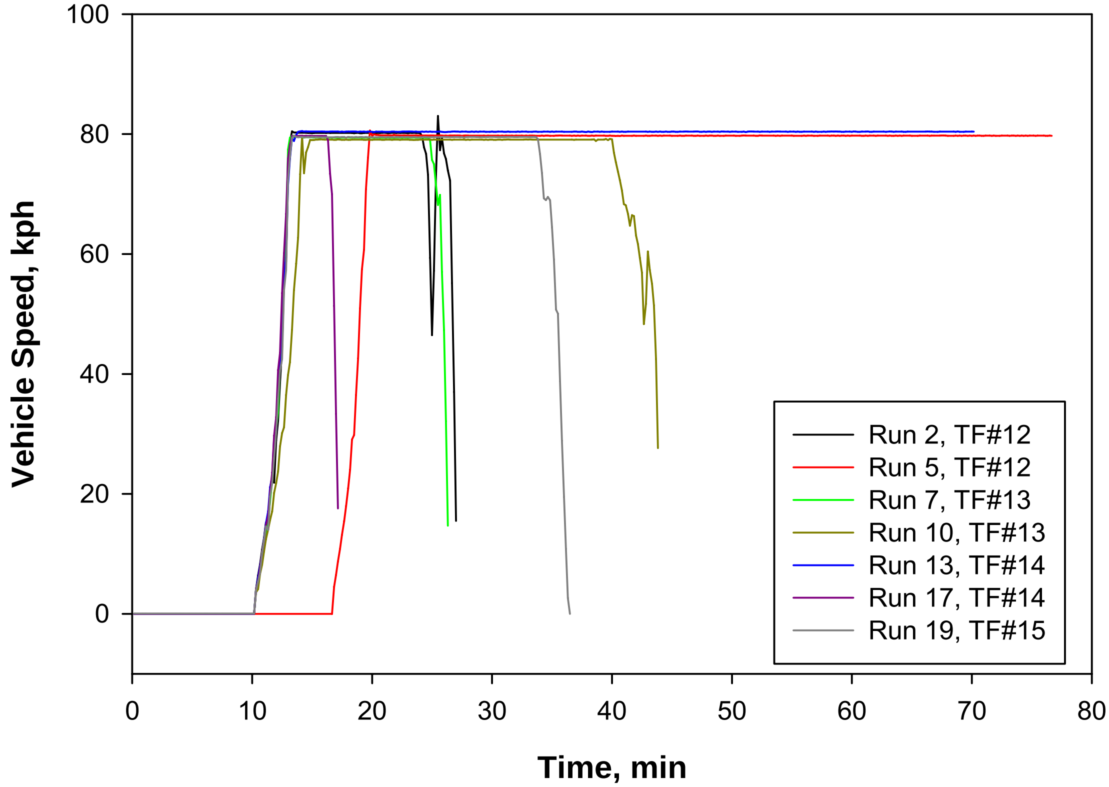

Figure 21. Vehicle speed traces for fuels tested in Truck C2.

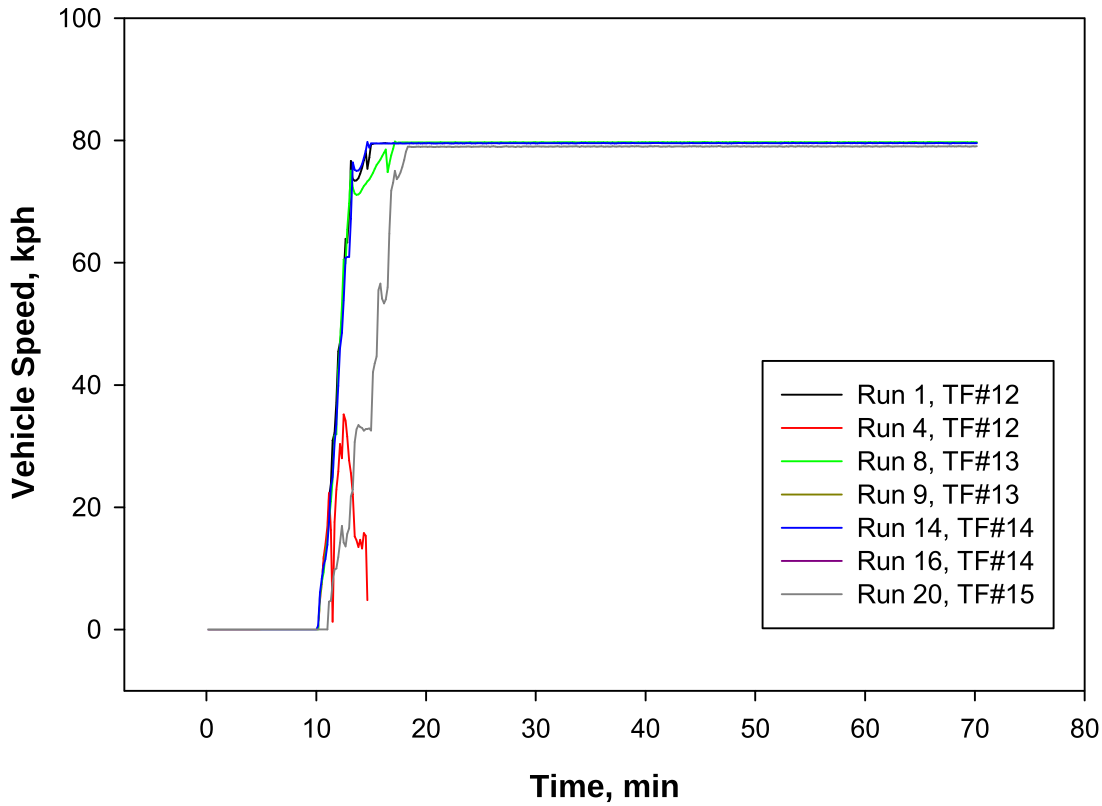

Figure 22. Vehicle speed traces for fuels tested in Truck D2.