TP 14110E

SIMPLIFIED FUEL ADDITIVE TEST PHASE IV: TEST PROTOCOL

PREPARED FOR

TRANSPORTATION DEVELOPMENT CENTRE
TRANSPORT CANADA

BY

ENGINE SYSTEMS DEVELOPMENT CENTRE

MAY 2003

TP 14110 E

SIMPLIFIED FUEL ADDITIVE TEST PHASE IV: TEST PROTOCOL

BY

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ENGINE SYSTEMS DEVELOPMENT CENTRE

MAY 2003

Since some of the accepted measures in the industry are imperial, metric measures are not always used in this report.

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Un sommaire français se trouve avant la table des matières.

Transport Canada Transports Canada

PUBLICATION DATA FORM

1. Transport Canada Publication No.
TP 14110E

2. Project No.
5102-03

3. Recipient's Catalogue No.

4. Title and Subtitle
Simplified Fuel Additive Test Phase IV: Test Protocol

5. Publication Date
May 2003

6. Performing Organization Document No.

7. Author(s)
Fan Su, Malcolm L. Payne, Manuel Vasquez, and Aref Taghizadeh

8. Transport Canada File No.
2450-DP700/4

9. Performing Organization Name and Address
Engine Systems Development Centre
155 Montreal-Toronto Highway
Lachine, Quebec
Canada H8S 1B4

10. PWGSC File No.
MTB-1-00766

11. PWGSC or Transport Canada Contract No.
T8200-011511/001/MTB

12. Sponsoring Agency Name and Address
Transportation Development Centre (TDC)
800 René Lévesque Blvd. West
Suite 600
Montreal, Quebec
H3B 1X9

13. Type of Publication and Period Covered
Final

14. Project Officer
R. Nishizaki

15. Supplementary Notes (Funding programs, titles of related publications, etc.)
Co-sponsored by the Program of Energy Research and Development (PERD) of Natural Resources Canada (NRCan)

16. Abstract

The methodology and the development of the Simplified Fuel Additive Test (SFAT) protocol as a lower cost alternative to AAR RP-503 are described in this report on Phase IV, the final part of the project, which validates work completed in the earlier phases.

Repeated runs on two products (a fuel additive and a fuel system add-on device), which were evaluated in Phase III, were carried out. Chemical analysis of baseline and treated fuel, showing the same results of Phase III, revealed no significant effects of the products on fuel chemical properties. Engine brake-specific fuel consumption (BSFC) and emissions changes detected for the products appear to be consistent with that of Phase III. The 1.66% improvement on engine BSFC (average of Phase III and Phase IV results) and non-significant changes detected on emissions were similar to those reported earlier by other investigators for the same fuel additive.

Based on the Phase IV results, the SFAT procedure was finalized and is presented in this report. The procedure proves to be efficient, accurate and cost-effective for evaluation of fuel additives and engine fuel system add-on devices.

17. Key Words
Single-Cylinder Research Engine, SCRE, locomotive, diesel engine, emissions, performance-enhancing device, PEP, fuel additive, chemical analysis, fuel and lube oil analysis

18. Distribution Statement
Limited number of copies available from the Transportation Development Centre

19. Security Classification (of this publication)
Unclassified

20. Security Classification (of this page)
Unclassified

21. Declassification (date)
—

22. No. of Pages
xiv, 18, apps

23. Price
Shipping/ Handling

Transports Canada Transport Canada

FORMULE DE DONNÉES POUR PUBLICATION

1. N° de la publication de Transports Canada
TP 14110E

2. N° de l'étude
5102-03

3. N° de catalogue du destinataire

4. Titre et sous-titre
Simplified Fuel Additive Test Phase IV: Test Protocol

5. Date de la publication
Mai 2003

6. N° de document de l'organisme exécutant

7. Auteur(s)
Fan Su, Malcolm L. Payne, Manuel Vasquez et Aref Taghizadeh

8. N° de dossier - Transports Canada
2450-DP700/4

9. Nom et adresse de l'organisme exécutant
Centre de développement de systèmes moteurs inc.
155, autoroute Montréal-Toronto
Lachine, Québec
Canada H8S 1B4

10. N° de dossier - TPSGC
MTB-1-00766

11. N° de contrat - TPSGC ou Transports Canada
T8200-011511/001/MTB

12. Nom et adresse de l'organisme parrain
Centre de développement des transports (CDT)
800, boul. René-Lévesque Ouest
Bureau 600
Montréal (Québec)
H3B 1X9

13. Genre de publication et période visée
Final

14. Agent de projet
R. Nishizaki

15. Remarques additionnelles (programmes de financement, titres de publications connexes, etc.)
Projet coparrainé par le Programme de recherche et développement énergétiques (PRDE) de Ressources naturelles Canada (RNCan)

16. Résumé

Le présent rapport rend compte de la quatrième et dernière phase du projet, qui a consisté à valider les tâches exécutées au cours des phases antérieures. Il rappelle également les travaux qui ont mené à la mise au point du protocole SFAT (pour *Simplified Fuel Additive Test*) en tant que solution de rechange économique à la norme PR 503 de l'AAR.

Deux produits (un additif pour carburants et un dispositif d'optimisation pour système d'alimentation) évalués au cours de la phase III ont été soumis à des essais répétés. L'analyse chimique d'un carburant de référence et d'un carburant traité a donné les mêmes résultats qu'à la phase III et n'a donc révélé aucun effet significatif des produits sur les propriétés chimiques des carburants. En effet, dans le cas des deux carburants analysés, la fluctuation de la puissance au frein et du niveau des émissions polluantes est comparable à celle observée au cours de la phase III. Par ailleurs, l'amélioration de 1,66 % de la puissance au frein (moyenne des résultats de la phase III et de la phase IV) et l'absence d'effet significatif sur les émissions polluantes corroborent les résultats d'études faites par d'autres sur le même additif pour carburant.

Les chercheurs se sont fondés sur les résultats de la phase IV pour mettre au point la version définitive du protocole SFAT, exposé dans le présent rapport. Ce protocole se révèle efficace, précis et économique pour l'évaluation d'additifs pour carburants et de dispositifs d'optimisation pour système d'alimentation.

17. Mots clés
Moteur de recherche monocylindre, locomotive, moteur diesel, émissions, optimiseur de rendement, additif pour carburants, analyse chimique, analyse de carburants et d'huiles lubrifiantes

18. Diffusion
Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.

19. Classification de sécurité (de cette publication)
Non classifiée

20. Classification de sécurité (de cette page)
Non classifiée

21. Déclassification (date)
—

22. Nombre de pages
xiv, 18, ann.

23. Prix
Port et manutention

ACKNOWLEDGEMENTS

This work was supported in part by the Transportation Development Centre of Transport Canada.

Acknowledgements are also made to the following persons (alphabetical order) for their valuable suggestions and comments:

R. Ballantyne – RAC
R. Becker – VIA Rail
R. Cataldi – AAR
G. Gutoski – Fairbanks Morse
S.G. Fritz – Southwest Research Institute
C. McClung – Caterpillar
D. Mullins – CP Rail
B. Neil – Fairbanks Morse
R.S. Nishizaki – Transportation Development Centre, Transport Canada
M. Quinn – Caterpillar
G. Taylor – Instrumental Solutions, Inc.

EXECUTIVE SUMMARY

The Simplified Fuel Additive Test (SFAT) project was initiated in 1998. The objective of this work was to develop a method for the evaluation of fuel additives, performance-enhancing devices, and lubricating oil additives at a reduced cost and time relative to the current test procedure, AAR RP-503. The development process consisted of the following phases.

Phase I: Feasibility of SFAT protocol (TP 13215E)
Phase II: SFAT procedure development and methodology (TP 13494E)
Phase III: Testing and verification (TP 13823E)
Phase IV: Test procedure validation, data reduction and finalization of protocol

Phase I results indicated that a single-cylinder medium-speed diesel engine would not only be technically feasible but also economically feasible in conducting evaluation tests because of special design features and mechanical simplicity. From these results, a preliminary test methodology was proposed in Phase II based on a literature survey and other researchers' work on both the single-cylinder engine and multi-cylinder engine. To verify the test procedure, eight candidate engine performance enhancing products (PEPs), including three add-on devices, three fuel additives and two lube oil additives, were tested in Phase III. The work completed in Phase III suggested that 75 hours of engine tests (engine operating at full load) would be sufficient to detect fuel additive (or add-on device) effects on engine fuel economy, emissions and deposits. The testing system was also proved to be effective in determining a minimum of 1 percent change in the brake specific fuel consumption and a minimum 5 percent (on average) in exhaust emissions. In addition, the data obtained for a fuel additive appear to be very similar to those reported earlier by other investigators. However, no experimental evidence has come from studies of the same test sequence as being suitable for the evaluation of oil additives.

The test procedure was validated and fine-tuned in Phase IV by conducting repeated tests on a fuel additive and a fuel system add-on device, which were tested in Phase III. Consistent evaluation results confirmed the reliability of conducting tests using the Single-Cylinder Research Engine (SCRE) facility.

Further investigations on test results revealed that some issues, such as identical engine components, information about a candidate, etc., are critical for accurately evaluating a product. They are the sources of errors that might mask effects of the product. It was also observed that the test sequence was not appropriate for oil system add-on devices because of dynamic changes of oil properties affecting engine performance and emissions.

On the basis of tests and the analysis of results, the final test procedure for fuel additives and fuel system add-on devices was derived. It is a two-step test procedure: chemical analysis and SCRE tests. The engine tests will be a minimum of 75 hours (engine operating at full load), including 20 hours of baseline testing, 35 hours of preconditioning testing and 20 hours of product performance testing. Following these tests, a baseline check-up test shall be performed to determine whether the same baseline can be obtained as before the test. Testing at additional engine operating modes is also recommended. The developed SFAT test procedure is cost-effective and efficient in evaluating a product.

SOMMAIRE

Le projet Essai simplifié d'additifs pour carburants (SFAT, pour *Simplified Fuel Additive Test*) a débuté en 1998. L'objectif de cette étude était de mettre au point une méthode pour évaluer les additifs pour carburants, les optimiseurs de rendement et les additifs pour huiles lubrifiantes, qui serait à la fois plus économique et moins longue à appliquer que le protocole d'essai actuel, soit celui de la PR 503 de l'AAR. Les travaux se sont déroulés en quatre phases successives :

Phase I : Faisabilité d'un protocole simplifié d'évaluation des additifs pour carburants (TP 13215E)
Phase II : Développement du protocole (TP 13494E)
Phase III : Essais et vérification (TP 13823E)
Phase IV : Validation du protocole d'essai, réduction des données et mise au point définitive du protocole

Les résultats de la phase I ont confirmé qu'il est faisable techniquement et avantageux économiquement de se servir d'un moteur de recherche monocylindre dérivé d'un moteur diesel à vitesse moyenne en tant qu'outil d'évaluation, en raison des caractéristiques de conception particulières de ce moteur et de sa simplicité sur le plan mécanique. Une fois établie la faisabilité du projet, les chercheurs ont mis au point, au cours de la phase II, un protocole préliminaire fondé sur les résultats d'une recherche documentaire et sur des données concernant les moteurs monocylindres et les moteurs multi-cylindres issues des travaux d'autres chercheurs. La phase III a consisté à vérifier ce protocole sur huit produits candidats, soit trois dispositifs d'optimisation du rendement, trois additifs pour carburants et deux additifs pour huiles lubrifiantes. Les résultats obtenus donnent à penser qu'il suffit de 75 heures d'essai sur moteur (moteur fonctionnant à plein régime) pour détecter les effets d'un additif pour carburants (ou d'un dispositif d'optimisation) sur la consommation de carburant, les émissions polluantes et les dépôts. Le protocole s'est en outre révélé efficace à détecter une fluctuation d'au moins 1 p. 100 de la puissance au frein et d'au moins 5 p. 100 (en moyenne) des émissions d'échappement. De plus, les données recueillies concernant un additif pour carburants ressemblent beaucoup à celles déjà publiées par d'autres chercheurs. Toutefois, l'étude n'a pas permis de conclure au bien-fondé de la séquence d'essais pour l'évaluation d'additifs pour huiles lubrifiantes.

Le protocole d'essai a été validé et mis au point dans sa forme définitive au cours de la phase IV. Des essais répétés ont été effectués sur un additif pour carburants et un dispositif d'optimisation pour système d'alimentation déjà évalués au cours de la phase III. Des résultats cohérents ont confirmé la fiabilité des essais menés à l'aide du moteur de recherche monocylindre.

Une analyse approfondie des résultats d'essais a révélé que certains critères (organes de moteur identiques, information sur un produit candidat, etc.) sont essentiels pour évaluer avec précision un produit. Autrement, des erreurs peuvent être induites, qui risquent de masquer les effets du produit. Il a également été observé que la séquence d'essais ne convient pas à l'évaluation des dispositifs d'optimisation pour système de lubrification, à cause de la fluctuation dynamique des propriétés des huiles, qui se répercute sur le rendement du moteur et sur les émissions.

Au terme des essais et de l’analyse des résultats, les chercheurs ont mis au point le protocole définitif pour l’essai des additifs pour carburants et dispositifs d’optimisation pour système d’alimentation. Il s’agit d’un protocole en deux étapes qui comprend une analyse chimique suivie d’essais sur un moteur monocylindre. Les essais sur moteur doivent durer au moins 75 heures (le moteur fonctionnant à plein régime), soit 20 heures de marche avec le carburant de référence, 35 heures de rodage et 20 heures d’essai de performance du produit. Le protocole prévoit en outre, après cette séquence d’essais, un dernier essai de marche avec le carburant de référence, qui sert à déterminer si les conditions de référence sont identiques avant et après les essais. Des essais à d’autres régimes moteur sont également recommandés. En définitive, le protocole d’essai résultant de ces travaux s’avère à la fois économique et efficace pour l’évaluation d’un produit.

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GLOSSARY

AAR	Association of American Railroads
ASTM	American Society for Testing and Materials
BSFC	Brake-Specific Fuel Consumption
CA	Crank Angle
CFR	Code of Federal Register (U.S.)
CO_2	Carbon dioxide
CO	Carbon monoxide
CP	Canadian Pacific
DIN	Deutsche Industrie Norm
ECOM	ECOM America, Ltd.
EMD	Electro-Motive Division of General Motors Corp.
EPA	Environmental Protection Agency (U.S.)
ESDC	Engine Systems Development Centre, Inc.
IMEP	Indicated Mean Effective Pressure
NO_x	Oxides of nitrogen
PEP	Performance-Enhancing Product
RAC	Railway Association of Canada
RP	Recommended Practice
SAE	Society of Automotive Engineers
SCRE	Single-Cylinder Research Engine
SFAT	Simplified Fuel Additive Test
SD	Standard Deviation
STP	Standard Test Practice
SwRI	Southwest Research Institute

1 INTRODUCTION

Operating cost reduction through fuel economy is a major challenge in the railway transportation sector. Such a reduction can be realized via approved aftermarket performance-enhancing products (PEPs). Certification of these products requires performance and emissions tests in accordance with Association of American Railroads (AAR) Recommended Practice test procedure AAR RP-503 (adopted in 1980 and revised in 1994). This procedure consists of four stages and is designed to compare the effects of fuel oil additives on fuel chemical properties, engine wear and deposits, as well as engine performance characteristics. Currently, the only organization that can carry out the AAR RP-503 test is the Southwest Research Institute (SwRI). Each test requires more than 1000 hours for completion, with a high price tag attached to it. The existing test is lengthy and expensive, preventing small businesses from entering the market. The need for an alternative procedure that could provide similar results and include emissions tests at a lower cost and reduced time resulted in the development of a Simplified Fuel Additive Test (SFAT) protocol.

The SFAT project aims to develop a protocol that can be used to properly evaluate the claimed benefits of PEPs (such as fuel additives and engine add-on devices) at a lower cost and reduced time. The project began in 1998 and was divided into four phases:

Phase I: Feasibility of SFAT protocol
Phase II: SFAT procedure development and methodology
Phase III: Testing and verification
Phase IV: Test procedure validation, data reduction and finalization of protocol

The preliminary feasibility study [1] showed that utilization of a single-cylinder research engine derived from a medium-speed diesel engine would be more economical and less complex. Additionally, it would be more representative of modern locomotive diesel engines for performance evaluation of fuel additives, oil additives, and add-on devices.

During the second stage of this project, an attempt was made to put together a methodology that would apply a universal test sequence to wide range of after-market engine PEPs. Therefore, a tentative test methodology and procedure was proposed based on a literature survey in Phase II of the project [2].

Initial experimental work was conducted on eight selected PEPs (three add-on devices, three fuel additives and two oil additives) to verify the preliminary test procedure in Phase III [3]. Based on the experimental results, a test procedure was derived for fuel additives and fuel system add-on devices. The experimental data seemed to indicate that a single test sequence could not be applied to both fuel and oil additives. Therefore, it was decided that the established method would be applied only to fuel additives and add-on devices, and that a separate method should be developed for oil additive evaluation.

This report consists of the final SFAT test protocol derived from the work performed during the four phases of the project and discusses the validity and repeatability of the results and the limitations imposed by the test parameters.

2 SFAT PROJECT OVERVIEW

2.1 Phase I – Feasibility Study [1]

The focus of this phase was to determine the feasibility of replacing the AAR RP-503 protocol for testing diesel fuel oil additives with a new procedure, using the Single-Cylinder Research Engine (SCRE-251) as the laboratory test engine that tests for both engine performance and emissions compliance.

A literature search was conducted to obtain relevant information relating to PEPs and test procedures. The EPA regulations were reviewed and required testing equipment was determined. The review of documentation concerning the design of SCRE-251 revealed that this engine was designed to simulate multi-cylinder medium-speed diesel engines with major cost and time advantages. In addition, there exists the flexibility to configure the SCRE-251 to simulate the performance conditions representative of current high IMEP multi-cylinder diesel engines.

It was concluded that a test protocol could be established using SCRE-251 to evaluate the performance of fuel/oil additives and add-on devices in place of AAR RP-503 at reduced cost and time, while determining the emissions trend exhibited by the PEPs.

2.2 Phase II – Procedure Development and Methodology [2]

The information obtained in Phase I was used to establish a tentative test methodology for SCRE-251. The test procedure was based on the review of existing test protocols, which included AAR RP-503, SAE J304, SAE J1423, DIN 51361, ASTM STP 509A Part I, and the U.S. Army guide for evaluating aftermarket fuel and lubricant additives. The facility was upgraded and the test engine was configured accordingly to conform to the required parameters.

The developed test sequence included a questionnaire to be completed by the PEP manufacturer, a preliminary chemical analysis baseline engine test and emissions measurements, preconditioning, and performance engine test and emissions analysis.

The test cell upgrades allow low-speed and high-speed data acquisitions and emissions measurements under various loads and speeds using PC-based software for data collection and data processing. Required materials, including fuel, lubricant and candidate additives, were acquired and stored for the engine test that would precede this phase of the project.

2.3 Phase III – Testing and Verification [3]

The validity of the tentative test procedure that was developed in Phase II was verified in this phase. The eight selected aftermarket products were tested on the SCRE-251 to verify the suitability of the procedure. Upon completion of this phase it was determined that a test sequence consisting of 20 hours of baseline testing, 35 hours of preconditioning testing, and 20 hours of performance testing would be sufficient for performance and emissions evaluations of fuel additives and add-on devices. It was also noted that this procedure would not be applicable to oil additives.

According to the gathered experimental results, the oil additives would require a longer preconditioning period (approximately 200 hours). Inclusion of oil additives into the test procedure would have extended the time required for the test, while not offering any benefit to the manufacturers of the fuel additives and add-on devices. For this reason it was concluded that a separate test procedure should be developed for oil additives to fully investigate their effects on engine performance and exhaust emissions.

Further investigations on test results of an oil system add-on device enabled us to suggest that a separate test procedure would be more suitable for the evaluation of oil system add-on devices. The device tested in this phase is claimed to remove the volatile fraction of the lube oil and thereby improve the combustion process. Though fuel economy and emissions changes could be observed after a preconditioning time similar to the fuel additive evaluation tests, dynamic changes of oil properties with higher engine oil consumption rate (0.8 to 0.9% of fuel consumption) might require more hours of testing and more detections, such as the effects of oil refilling on test results and the effects of oil soot concentrations on engine deposits, to fully understand the device.

2.4 Phase IV – Validation and Finalization

The current phase of the project was undertaken to verify the repeatability and reproducibility of the test results under the test sequence established in Phase III. The outcome of the work is discussed in the following sections.

3 PHASE IV RESULTS AND DISCUSSIONS

Repeated runs on PEP-1A and PEP-2B, which were tested in Phase III, were carried out to validate the developed test procedure. Results and discussions are provided in this section.

3.1 Chemical Analysis Results

Chemical and physical parameters of the baseline and treated fuel were determined before engine tests to verify the effects of a product on limiting fuel specification requirements. Test results (Table 1) showed changes on some parameters, such as carbon residue and heating values; however, they are considered to be either minimal or within test-to-test repeatability. The treated fuel properties were within fuel limiting specifications and were acceptable for engine tests.

Table 1: Baseline and product-treated fuel properties

Fuel Property		ASTM	PEP-1A		PEP-1B	
			Baseline	Treated Fuel	Baseline	Treated Fuel
Density @ 15°C (kg/L)		D1298	0.834	0.832	0.835	0.833
Flash point (°C)		D56	52	54	N/A	N/A
Cloud point (°C)		D2500	-21	-24	-23	-22
Pour point (°C)		D97	-33	-33	-36	-30
Viscosity @ 40°C		D445	2.2	2.2	2.1	2.1
Distillation	- Initial boiling point	D86	163	163	164	159
	- 10% recovered (°C)		185	184	190	188
	- 50% recovered (°C)		249	252	244	238
	- 90% recovered (°C)		323	320	309	300
	- Final boiling point		362	355	N/A	N/A
	- Loss (%)		1.0	1.0	N/A	N/A
	- Recovered (%)		N/A	N/A	N/A	N/A
Ash (%)		D482	< 0.001	< 0.001	< 0.001	< 0.001
Copper strip corrosion		D130	1A	1A	1A	1B
Water & sediment (%, v/v)		D2709	< 0.05	< 0.05	< 0.05	<0.05
Sulfur (%, p/p)		D129	0.04	0.02	0.03	0.03
Heating value (kJ/kg)		D240	44884	45057	45456	45400
Carbon residue (%)		D189	0.019	0.008	0.02	0.03
Particulate contamination		D2276	N/A	N/A	0	0
Cetane index		D976	48.4	49.8	46.5	45.5

Note: N/A- not available

3.2 Engine Test Results

Baseline brake-specific fuel consumption (BSFC) values of both PEP-1A and PEP-2B tests were investigated to determine variations of BSFC measurements. It was found that the repeatability of BSFC measurements was within 1% of mean value.

The engine brake horsepower was maintained during an evaluation run. This enabled the effect of a product on engine performance to be observed through engine fuel consumption changes. Figure 1 (a, b and c) and Figure 2 (a and b) show BSFC results obtained from PEP-1A and PEP-2B runs.

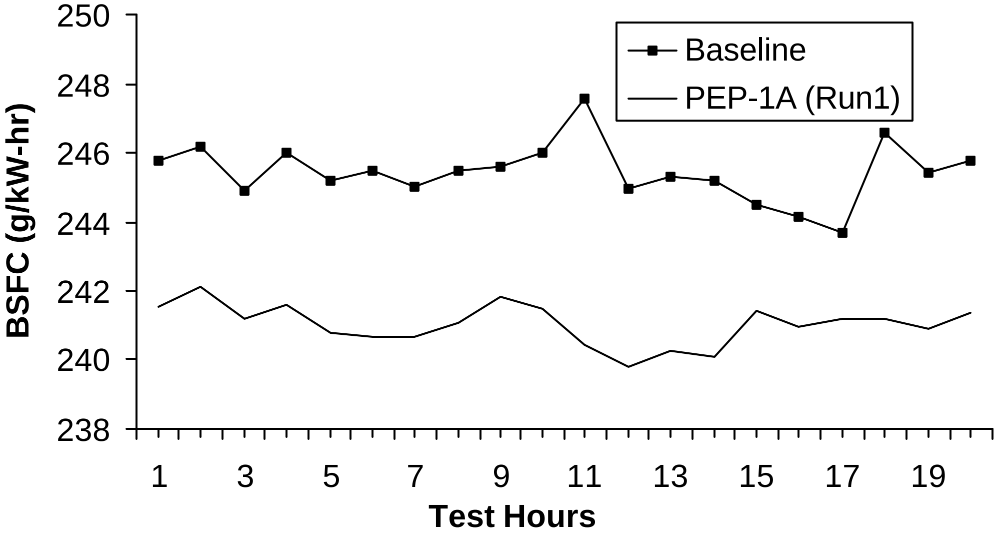


Figure 1a: Comparison of BSFC values (PEP-1A Run1)

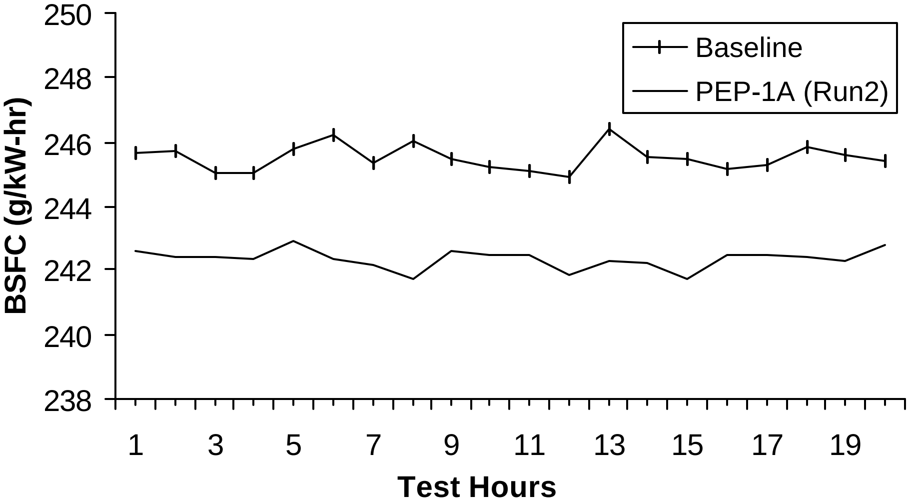


Figure 1b: Comparison of BSFC values (PEP-1A Run2)

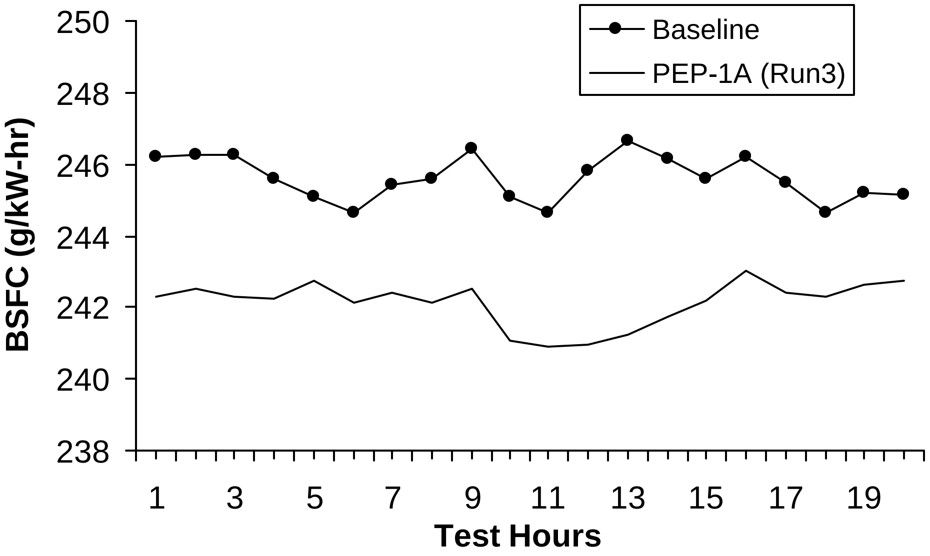


Figure 1c: Comparison of BSFC values (PEP-1A Run3)

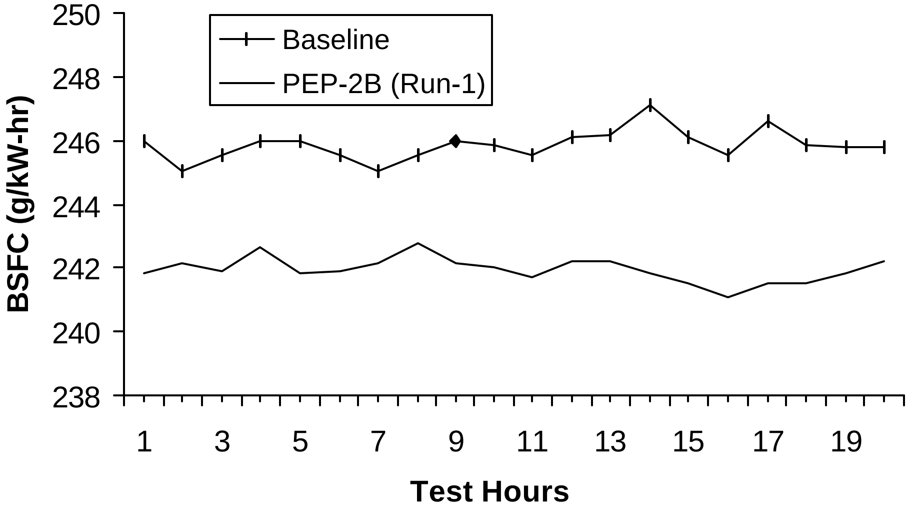


Figure 2a: Comparison of BSFC values (PEP-2B Run1)

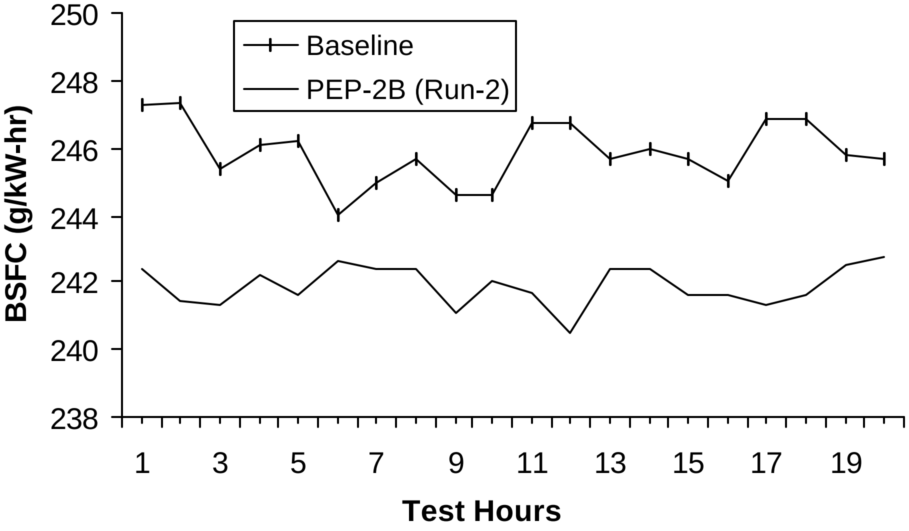


Figure 2b: Comparison of BSFC values (PEP-2B Run2)

Statistical analysis results of BSFC data are shown in Table 2. Similar standard deviations between baseline BSFC data and those of the treated fuel in each of these evaluation runs indicate that the baseline and treated fuel data sets are comparable. The BSFC changes detected from PEP-1A runs were 1.75, 1.30 and 1.43%, respectively. The PEP-2B improved baseline BSFC by up to 1.71%.

Table 2: BSFC comparison of PEP-1A and PEP-2B tests

Test Run	PEP-1A					PEP-2B				
	Baseline BSFC		Treated BSFC		Changes (%)	Baseline BSFC		Treated BSFC		Changes (%)
	Mean (g/kW-hr)	S.D.	Mean (g/kW-hr)	S.D.		Mean (g/kW-hr)	S.D.	Mean (g/kW-hr)	S.D.	
Run1	245.4	0.8	241.1	0.6	-1.75	246.0	0.5	241.8	0.4	-1.71
Run2	245.5	0.4	242.3	0.3	-1.30	245.9	0.8	241.8	0.6	-1.67
Run3	245.6	0.6	242.1	0.6	-1.43	\	\	\	\	\

Note: Changes (%) = (Treated Mean Value – Baseline Mean Value) /(Baseline Mean Value)

Cylinder pressure recordings of 20 successive engine cycles allowed variation of indicated mean effective pressure (IMEP) measurements to be demonstrated. IMEPs of each combustion cycle were plotted in terms of Relative-IMEP, which is defined as the relative change between an IMEP and the mean value of all the test cycles, versus the test cycle (Figure 3). Approximately 1.0% standard deviation of IMEP measurements is within 1.5% of the transducer manufacturer-specified IMEP stability.

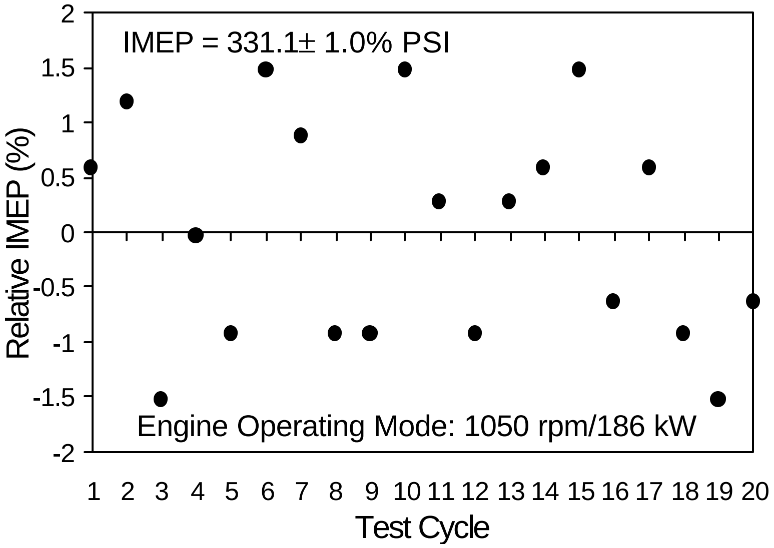


Figure 3: Variation of IMEP measurements

Engine high-speed data are briefly summarized in Table 3. Slight variations observed on the maximum cylinder pressure (Pmax) of each run are attributed to the nature of the combustion process. No obvious changes between the baseline fuel and treated fuel test were detected in the IMEP of an evaluation run, and this finding seems to suggest that fuel consumption improvements of the two products are attributed to augmented combustion processes.

Table 3: Engine combustion analysis results

Product	Test Run	IMEP (psi)	Pmax (psi)	Cumulated Heat Release (kJ)
PEP-1A	Run1 (Baseline)	331	2016	38
	Run1 (Treated)	334	1986	38
	Run2 (Baseline)	328	1989	37
	Run2 (Treated)	330	1980	38
	Run3 (Baseline)	331	2025	37
	Run3 (Treated)	334	2058	38
PEP-2B	Run1 (Baseline)	332	2010	37
	Run1 (Treated)	334	2013	37
	Run2 (Baseline)	333	2058	37
	Run2 (Treated)	334	2025	38

Table 4 shows the emissions results collected during the tests. The PEP-1A reduced baseline CO emissions by 4% on average. NOx increased by 2% on average with application of the device. Similar changes were observed from PEP-2B test results. These changes may not be statistically significant beyond test-to-test repeatability detected during the Phase III test.

Table 4: Comparison of emissions results

Index	CO (g/hp-hr)			NOx (g/hp-hr)			Smoke (BOSCH)		
	AB	AP	Changes (%)	AB	AP	Changes (%)	AB	AP	Changes (%)
PEP-1A (Run1)	3.3	3.1	-6.0	12.2	12.7	4.1	1.35	1.32	-2.2
PEP-1A (Run2)	3.2	3.1	-3.1	12.5	12.6	1.0	1.34	1.32	-1.5
PEP-1A (Run3)	3.2	3.1	-3.1	13.1	13.2	0.8	1.37	1.34	-2.2
PEP-2B (Run1)	3.4	3.2	-5.9	12.4	12.7	2.4	1.34	1.32	-1.5
PEP-2B (Run2)	3.6	3.5	-2.8	12.5	12.6	1.0	1.35	1.33	-1.5
Note: AB – Average of baseline; AP – Average of product; Percentage change = (AP-AB)/AB.									

Carbon deposits on the piston top and valve surfaces (intake and exhaust), and wear conditions on the liner were detected using a bore-scope and engineering judgment. No significant changes between the baseline test and the treated fuel test could be observed.

3.3 Comparison with Phase III Test Results

Test results of Phase IV were compared to that of the Phase III. Engine BSFC improvements were observed in both the Phase III and Phase IV runs for the PEP-1A. These are within 1.46±0.2% (Figure 4).

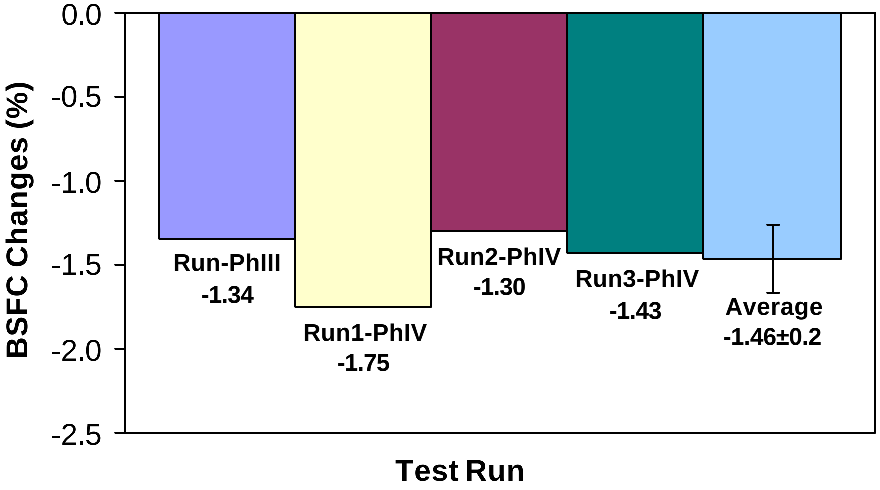


Figure 4: BSFC changes (%) of Phase III and Phase IV test runs for PEP-1A

Figure 5 gives evaluation results of emissions for the PEP-1A. Results of each of these runs show that baseline CO and smoke emissions were reduced with the device. Though an increase in NOx was experienced in the Phase III run and a reduction in NOx was experienced in the Phase IV runs, the percentage changes are within test-to-test repeatability [3] and are considered non-significant.

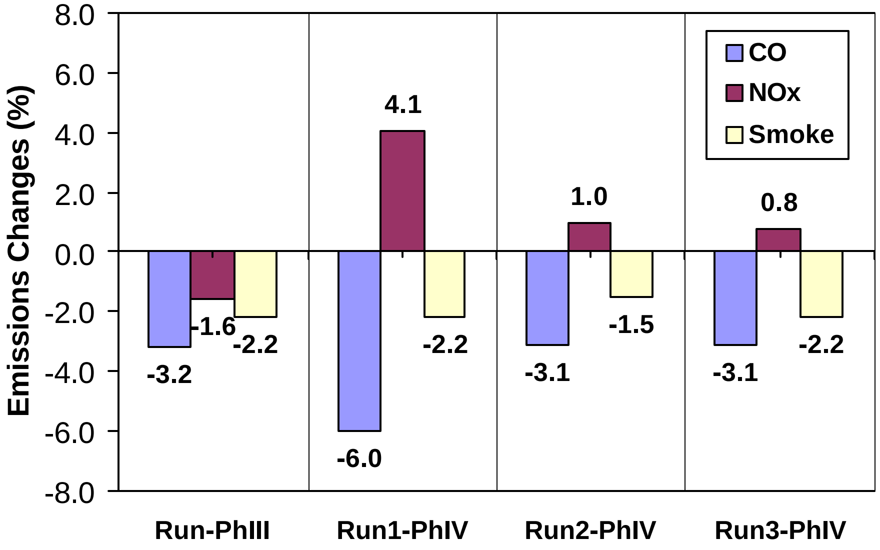


Figure 5: Emissions changes (%) of Phase III and Phase IV test runs for PEP-1A

Figures 6 and 7 present the data provided by runs on the PEP-2B. The PEP-2B improved baseline BSFC by 1.66±0.05%. The results of Phase III agree with those of Phase IV. Emissions results of Phase III (Figure 8) show the same trends as those of Phase IV. Experimental errors are responsible for variations on these percentage changes.

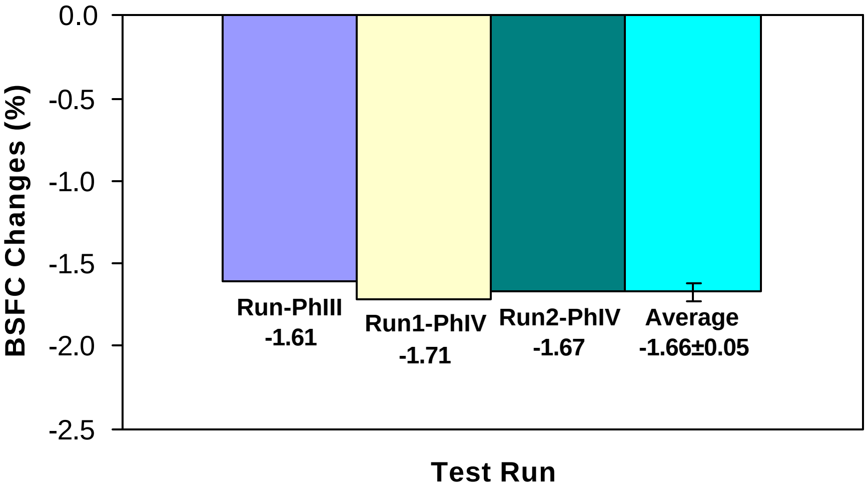


Figure 6: BSFC changes (%) of Phase III and Phase IV test runs for PEP-2B

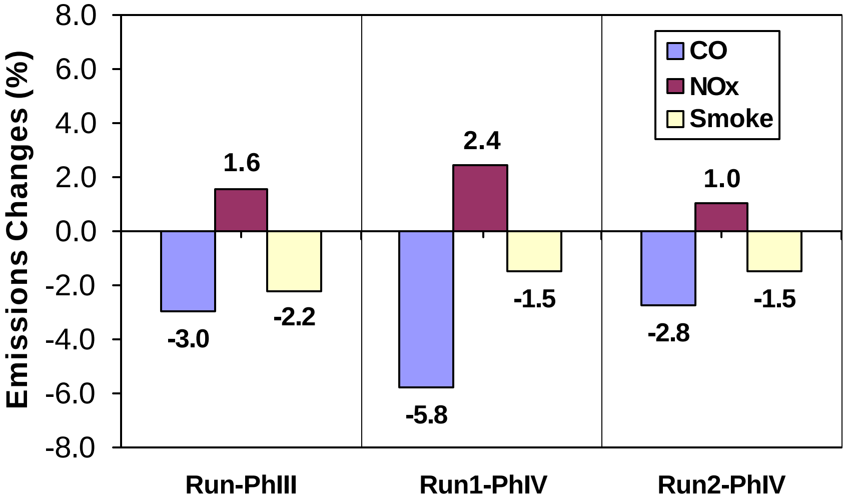


Figure 7: Emissions changes (%) of Phase III and Phase IV test runs for PEP-2B

3.4 Comparison with Other Investigator's Results

Comparison with existing test results obtained under controlled conditions may provide valuable information to the SFAT procedure. Unfortunately, there are not many published data that are obtained either under controlled conditions or for medium-speed engine applications. The only test for evaluating a fuel additive for locomotive engine applications was conducted at Southwest Research Institute (SwRI) by following the RP-503 procedure. Its results were compared to those obtained from using the present simplified procedure for the same fuel additive product (PEP-2B). The SFAT tests carried out, with the same results of SwRI, revealed non-significant effects of the additive on fuel chemical properties and engine emissions. However, both investigations suggested improvements on engine fuel BSFC (1.74% improvements were detected by SwRI and an average of 1.66% by the SFAT).

Results from the two tests might not be directly correlated since the EMD 645 is a two-stroke engine and SCRE-251 is a four-stroke engine. However, due to similar size in engine power components, the comparisons can provide preliminary information for evaluating the simplified test procedure.

3.5 Summary of Phase IV Test

Tests were carried out on the PEP-1A and PEP-2B to validate the SFAT test procedure. Triplicate runs were performed on the PEP-1A. Due to problems with an ECOM emissions analyzer sensor and the cylinder pressure transducer, only two runs were completed for the PEP-2B. However, it was enough to demonstrate repeatability of the evaluation tests with comparison of the Phase III results.

No clear advancement in fuel properties, engine emissions and combustion deposits was observed from using the PEP-1A and PEP-2B, though 1~2% improvements in BSFC were detected. Results from both the PEP-1A and PEP-2B appear to be very similar to those of Phase III. On average, the PEP-1A improved baseline BSFC by 1.46±0.2% and the PEP-2B by 1.66±0.05%. Similar evaluation results between SFAT and those of SwRI for the PEP-2B showed that reliable evaluation results can be obtained using the SFAT procedure.

4 SIMPLIFIED FUEL ADDITIVE TEST PROCEDURE

4.1 Scope

The SFAT procedure is intended to evaluate the effectiveness of engine performance-enhancing products (PEPs), including fuel additives and fuel system add-on devices, for medium-speed diesel engine use. Both positive and negative effects on engine performance, emissions and engine combustion deposits (based on observations and engineering judgments) arising from use of these products are determined from the test. The procedure provides results that may serve as one indicator to the potential user of the comparative use of an untreated fuel (or engine without an add-on device) versus that of an additive-treated fuel (or engine with an add-on device).

4.2 Evaluation Procedure

The evaluation procedure consists of two steps: fuel properties test and engine test. A flow chart of the test procedure is shown in Appendix A. These tests are organized first to determine that the additive (or add-on device) will cause no harmful effects, and second to verify the claimed benefits. Before conducting these tests, a questionnaire (Appendices B and C) is issued to the customer to obtain information for identifying the claimed benefits, recognizing any features of the PEP that may have an adverse effect on engine component and engine performance, and defining possible errors due to preparation of the evaluation test.

Step I: Fuel Properties – Standard ASTM tests for baseline and treated fuel are mandatory. Class one railroad diesel fuel is used as baseline fuel.

Step II: Single-Cylinder Engine Test – Tests are conducted on a single-cylinder research engine (for specifications see [3]) with new engine power components such as piston, rings, cylinder liner, intake and exhaust valves, and injector. The tests are conducted in a "baseline-preconditioning-product-baseline" manner. The preconditioning test is necessary for stabilizing engine performance with additive-treated fuel. After the product test, a check-up baseline test follows to verify the test results.

4.3 Fuel Property Tests (Step I)

The following physical and chemical fuel properties are tested using ASTM methods. These ASTM tests should be performed on a sample of diesel fuel as well as a sample of the same fuel treated with a fuel additive or engine fuel-system add-on device. Diesel fuel conforming to ASTM specification grade 2-D is used unless otherwise specified. The purpose of these tests is to evaluate the effects of the additives or add-on devices on limiting fuel specification requirements. The tests are used as a general guideline and may be modified to include additional tests if necessary because of the nature of the additives or add-on devices being tested.

Property	**ASTM Test Method No.**
Density @ 15°C	D 1298
Flash Point	D 93
Cloud Point	D 2500
Pour Point	D 97
Kinematic Viscosity @ 40°C	D 445
Distillation, 50%, 90% and end points	D 86
Carbon Residue	D 524
Sulfur	D 1552, D 129, or D 2622
Copper Strip Corrosion	D 130
Ash	D 482
Water and Sediment	D 2709
Accelerated Stability	D 2274
Neutralization	D 974
Particle Contamination	D 2276
Cetane Number	D 613 or D 976
Heat of Combustion	D 240

4.4 SCRE Tests (Step II)

Engine power is measured either by dynamometer or by an engine-driven generator with load bank. The instruments are calibrated to an accuracy of ±2% of full scale. Engine fuel consumption is measured either by weighting scale or flow meter, and instruments are calibrated to ±1% of full scale. Emissions analyzers meeting specifications described in EPA locomotive emissions standards (40 CFR, Part 92) are used for emissions measurements. The analyzers are calibrated before a test according to the procedure recommended by manufacturer.

The test is conducted at engine full load (250 hp). Testing at additional engine operating modes is recommended and optional to customers. The test is conducted under the following engine conditions:

- Engine intake air temperature shall be controlled within ±5°F between the baseline and treated fuel tests at the same engine test modes.
- Engine oil sump temperature shall be controlled within ±5°F between the baseline and treated fuel tests at the same engine test modes.
- Engine coolant water outlet temperature shall be maintained within ±5°F between the baseline and treated fuel tests at the same engine test modes.
- Engine fuel temperature shall be maintained at 90±10°F, measured at the fuel supply line (or fuel filters) before the fuel pump.
- Engine intake air pressure shall be maintained within ±0.1 psi between the baseline and treated fuel tests at the same engine test modes.

The baseline test and the product test are conducted for minimum of 20 hours (at least three days). The preconditioning test is performed until stable engine conditions are obtained. A 35 hour preconditioning period (engine is operated at full load) is recommended; however, more preconditioning hours may be required due to the nature of the product. A baseline check-up test is performed to validate the evaluation test results. During the baseline and the product test, engine performance data are taken at every half-hour, and emissions (smoke, gaseous, and particulate matter) and combustion pressure data are recorded at least once midway or at the end of the tests.

Brake-specific fuel consumption (BSFC) data obtained for baseline and product (after preconditioning) should be plotted as a function of engine operating time to show any discernible trends and consistency of the data. The two sets of BSFC data should be statistically analyzed to determine whether there is a statistically significant difference in the mean values of the two sets of data. The difference should be evaluated at a 90% confidence level.

Engine emissions data is statistically analyzed to determine any changes due to the product. To investigate the effects of a product on the engine combustion process, the apparent net heat release rates are calculated from the recorded cylinder pressure data by applying the first law of thermodynamics to the content of the combustion chamber. The combustion temperatures are calculated from the cylinder pressure data by assuming a uniform temperature distribution and ideal gas within the cylinder.

5 CONCLUSIONS

The SFAT project was initiated in the hope of obtaining a test procedure that is a less expensive alternative to the existing AAR RP-503 for evaluation of PEPs for medium-speed diesel engine use. The project was divided into four phases to develop the procedure. On the basis of test results and discussions, the following conclusions were made.

a. The SCRE employs the same bore and stroke as GE 7FDL, a locomotive engine extensively used in North America and currently used by the Southwest Research

Institute (SwRI) for the AAR RP-503 evaluation procedure. It is representative of four-stroke multi-cylinder railway, marine and small power-plant diesel engines. With unique engine design features and many standard engine components the test facility centred around the SCRE can establish representative conditions that are directly related to an actual four-stroke medium-speed locomotive diesel engine. The SCRE has the flexibility of satisfying various research studies that were performed without major modifications to the engine. The engine component is accessible, without the need to remove unrelated items, and enables precise instrumentation. Testing systems can be set up quickly for an evaluation test and maintenance is much easier than that of the multi-cylinder engine. Unlike the AAR RP-503 procedure, the single-cylinder engine used in the SFAT requires less consumables (fuel, lubricating oil, etc.) for completion of an evaluation test, especially for tests conducted at different test modes. The SCRE facility is a useful platform for accurate PEP evaluation tests because of its flexibility in control, precise in-engine instrumentation, and lower operating cost, especially for the evaluation of an enhancing product for a medium-speed diesel engine used in rail, marine and stationary applications.

b. Stability of the SCRE facility was investigated through a repeatability analysis of controlled engine operating parameters, fuel consumption and emissions measurements. Engine operating parameters are largely dependent on the characteristics of engine systems design and control of instrumentation. As a powerful tool for medium-speed diesel engine research and development, the SCRE testing system has special design features, such as the fact that the engine intake air is supplied by an external compressor, which is designed to simulate the turbocharger pressure of locomotive engine. Because these are externally controlled, the reliability and accuracy of these devices and their control systems are the main factors in the stability of engine operating parameters. Overall measurement uncertainty of a system was experimentally determined by investigating the tolerance limit of controlled engine operating parameters. Results indicated that the tolerance limits of controlled engine operating parameters are within those specified in the AAR RP-503. Repeatability of engine measurements under controlled conditions is considered critical for evaluating fuel additives, since it represents precision of the measurement process. Unrepeatable data demonstrate errors in the magnitude of measurement, data recording or experimental equipment. In this project, engine power output was maintained constant and fuel consumption and emissions changes were used as indicators of performance of a PEP. Baseline fuel tests were conducted to investigate the repeatability of fuel consumption and emissions measurements. The testing system was proved to be effective in determining a minimum of 1% change in the BSFC and a minimum 5% (on average) in exhaust emissions.

c. The preliminary test procedure was proposed for evaluation of a PEP. It was verified through testing on eight aftermarket PEPs: three engine add-on devices, three fuel additives and two lube oil additives. The verification test results suggested that 75 hours of engine testing, including 20 hours of baseline testing, 35 hours of preconditioning testing and 20 hours of performance testing would be enough for an evaluation of fuel additives and fuel system add-on devices. In addition, no experimental evidence has come from studies of the same test sequence as being suitable for the evaluation of oil additives and oil system add-on devices.

d. The test procedure was validated and fine-tuned in Phase IV of the project by conducting repeated tests on a fuel additive and a fuel system add-on device, which were tested in Phase III. Test results showed good agreements with those of the verification tests (Phase III) for the same products. Additionally, test data obtained for the fuel additive appears to be very similar to those reported previously by Markworth [4]. These findings confirm that the SFAT procedure is reliable for the evaluation of fuel additives or engine add-on devices.

e. The finalized procedure is intended to evaluate the effectiveness, and ineffectiveness, of fuel additives and engine fuel system add-on devices for medium-speed diesel engine use. The test procedure consists of fuel property tests to determine whether a product causes harmful effects to the engine, and SCRE tests for verifying the claimed benefits. Before an evaluation test, a questionnaire form is issued to the customer to obtain product information. The engine test is a minimum of 75 hours at engine full load, including 20 hours of baseline testing, 35 hours of preconditioning testing and 20 hours of performance testing. The baseline check-up test is performed to verify that the same baseline as obtained before the test can be obtained after the performance test. Generally, more confidence in the test results is established by this back-to-back comparison test. New engine power components and fuel injector are used for the engine test. Combustion deposit and wear conditions are determined using a bore-scope detector and engineering judgment. Product performance was different on different engine test modes. Therefore, multi-mode tests are strongly recommended to fully evaluate the product.

f. The SFAT provides to potential users preliminary comparison results of using a fuel additive or an engine fuel system add-on device. The final procedure has proved to be useful in conducting evaluation tests of the product at low cost and high efficiency.

g. The procedure was submitted to SwRI and AAR for approval. Their feedback indicated a good possibility that the procedure would be adopted partially by the AAR for locomotive fuel additive evaluations.

6 RECOMMENDATIONS

Gaseous and smoke exhaust emissions were measured during the evaluation tests. However, particulate emissions data could not be obtained due to the absence of testing equipment. It is therefore recommended that a particulate measuring system be developed and that evaluation tests on a fuel additive be conducted.

REFERENCES

1. S. Lister, R. Hunginger and A. Taghizadeh, "Feasibility of a Simplified Fuel Additive Evaluation Protocol", Transportation Development Centre, Transport Canada, TP 13215E, 1998.

2. A. Taghizadeh, M. Payne, F. Su and M. Vasquez, "Simplified Fuel Additive Test Phase II: Procedure Development and Methodology", Transportation Development Centre, Transport Canada, TP 13494E, 1999.

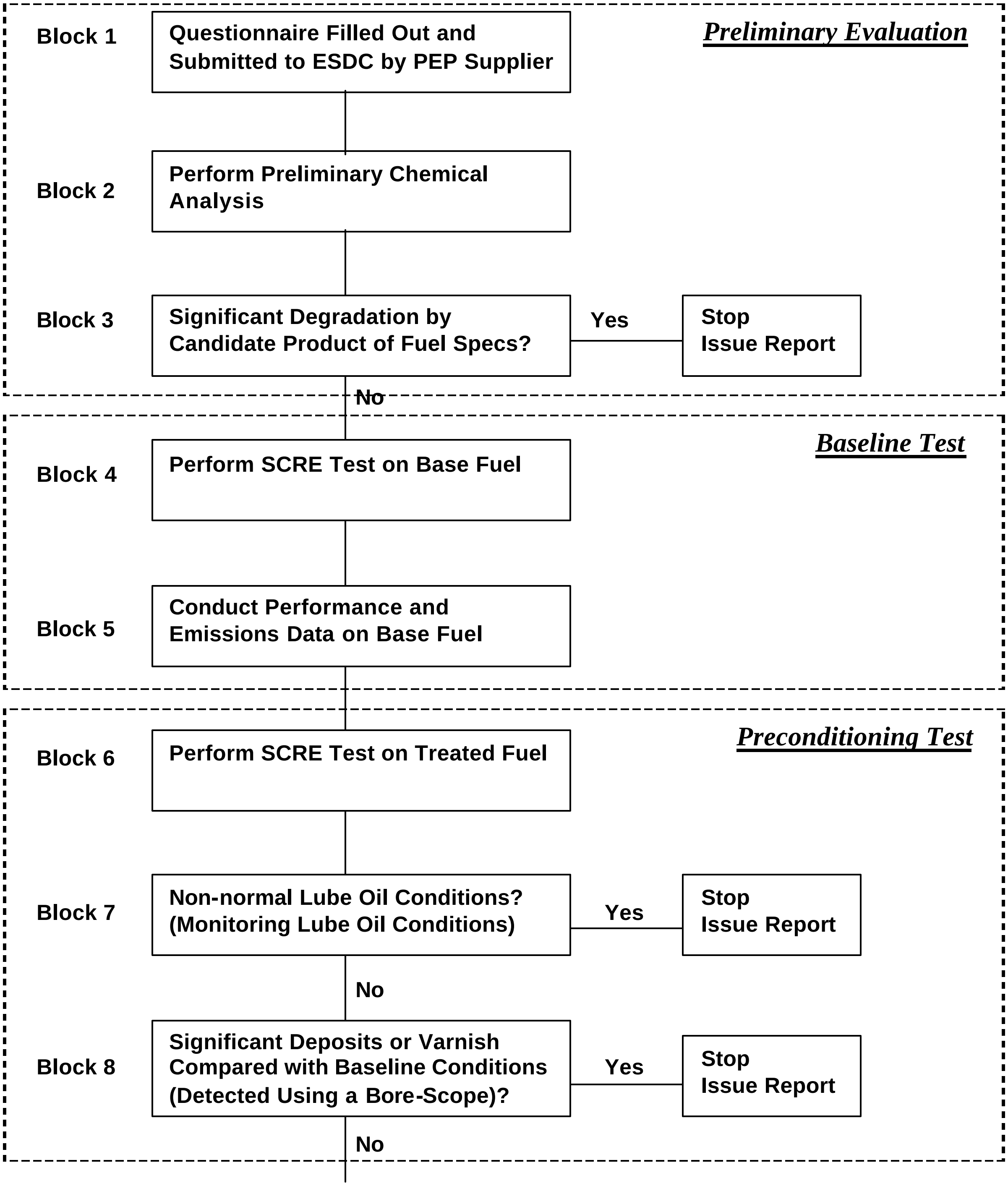
3. F. Su, M. Payne, M. Vasquez and A. Taghizadeh, "Simplified Additive Test Phase III: Testing and Verification", Transportation Development Centre, Transport Canada, TP 13823E, 2001.

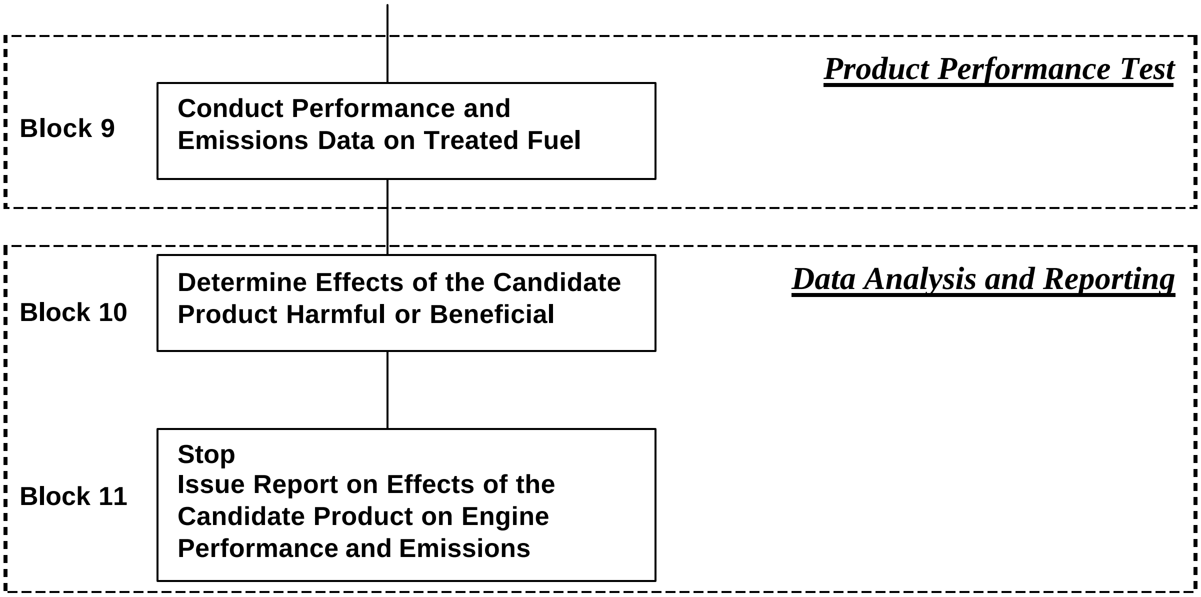
4. V. Markworth, "Evaluation of a Fuel Additives – Final Report", Vol. 1, SwRI report, July 1992.

APPENDIX A:

FLOW CHART OF RECOMMENDED SFAT EVALUATION PROCEDURE

Evaluation Test Flow Chart:





<u>Explanation of the Flow Chart:</u>

<u>Preliminary Evaluation</u> – includes three blocks (Block 1 to Block 3). Each block is described as below:

Block 1 **-** The procedure is initiated by issuing a questionnaire to the PEP manufacturer. The purpose is to identify the claims made by the manufacturer and to recognize any adverse effects of the PEP on engine components and performance.

Block 2 **-** Preliminary chemical analyses are performed on both base and treated fuel. These tests are used to evaluate the quality of treated fuel relative to that of untreated fuel and its suitability for engine testing. The required tests should evaluate the fuel for its ignition quality and combustion roughness, storability, contribution to engine deposits, and corrosiveness.

Block 3 **-** The gathered information from Block 2 tests enable ESDC to approve or reject an engine test.

<u>Baseline Test</u> – includes Blocks 4 and 5. Before the baseline test, deposit (or varnish) conditions are recorded using a bore-scope for engine piston, liner, intake valves and exhaust valves.

Block 4 **-** If the treated fuel is approved in Block 3, a baseline test is conducted for the engine operating with base fuel at the designed test mode. Otherwise, the evaluation procedure is stopped and a report issued.

Block 5 - During the baseline test, the engine performance and exhaust emissions are measured on untreated fuel.

Preconditioning Test – Blocks 6 to 8 are conducted during the preconditioning period.

Block 6 - The baseline test is followed by a preconditioning test with the treated fuel.

Block 7 - During this test, engine lube oil conditions are monitored by periodically analyzing oil samples. Oil properties, such as viscosity and concentration of metal components, are used to determine normal or non-normal conditions. If non-normal conditions are observed, the test is stopped.

Block 8 - After completion of this test, deposit (or varnish) conditions of engine piston, liner, intake values and exhaust values are detected using the bore-scope to compare to the baseline data. If the deposit (or varnish) is significant, the test is stopped. This test is based on observations and engineering judgments.

Product Performance Test – After the preconditioning test, the product performance test is conducted.

Block 9 - The engine performance and exhaust emissions are measured on treated fuel. During this test, the engine operating conditions are maintained the same as those of the baseline test.

Data Analysis and Reporting – Data is analyzed (Block 10) and reported (Block 11) in this part.

Block 10 - Results of the product performance test are compared to those of the baseline test to determine the effects of the product on engine performance and emissions, and thereby evaluate the claimed benefits.

Block 11 - A comprehensive test report is issued to give observations, discussions and conclusions on the effects of the product on engine performance and emissions.

APPENDIX B:
DIESEL FUEL ADDITIVE QUESTIONNAIRE FOR EVALUATION PROCEDURE

Complete and send the questionnaire, along with existing data pertinent to the additive's effects, to a laboratory capable of performing the SFAT procedure described herein.

COMPANY OR PATENT NAME: ____________________________________

ADDRESS & PHONE NO.: ____________________________________

____

____

PERSON TO CONTACT: ____________________________________

ADDITIVE NAME OR CODE: ____________________________________

ADDITIVE DESCRIPTION AND CATEGORY (CLEANER, CATALYST, ETC.):

____

____

____

What are the additive's effects on the following engine characteristics, and how long does it take to observe these effects?

(1) PERFORMANCE (Fuel Consumption, Exhaust Temperature, etc.)

____

____

____

(2) EXHAUST EMISSIONS (Including Smoke and Particulate Emissions)

____

____

(3) COMBUSTION DEPOSITS (Including Sparking)

____

____

(4) LUBE OIL

____

____

____

(5) WEAR

____

(6) FUEL SYSTEM

What are the effects of the additive on the following diesel fuel properties?

(1) Cetane Number:

(2) Viscosity:

(3) API Gravity:

(4) Distillation Range:

(5) Sulfur Content:

(6) Carbon Residue:

(7) Flash Point:

(8) Cloud Point:

(9) Pour Point:

(10) Ash Content:

(11) Corrosiveness:

(12) Aromatics:

(13) Filterability:

(14) Water Absorption: ____________________

(15) Stability: ____________________

(16) Foaming: ____________________

(17) Bacterial Resistance: ____________________

(18) Vapor Pressure: ____________________

(19) Miscibility Limits: ____________________

What are the effects of the additive on polymers, filter media and other fuel system components?

____

____

How is this additive used?

(1) How is it mixed with diesel fuel?

____

____

(2) In what proportions?

____

____

(3) How stable is the mixture?

____

____

(4) How long is the mixture storable?

____

____

(5) MSDS for safe handling

____

How does the additive react with winder fuel?

____

How stable is the additive itself?

____

Does the additive contain any zinc?

____

Are there any chemicals, elements, or physical conditions that can neutralize or otherwise influence the effectiveness of the additive? If so, describe in detail on a separate sheet.
What are the claimed effects of the additive? (Attach any pertinent material.)

____

____

What tests have been conducted to substantiate these claims? (Attach any pertinent material.)

____

____

What were the results of these tests? (Include formal report issued.)

____

____

Where were these tests performed?

____

____

Depending on the information supplied above, the testing laboratory selected will conduct the appropriate tests in accordance with the SFAT evaluation procedure.

APPENDIX C:
QUESTIONNAIRE FOR ENGINE FUEL SYSTEM ADD-ON DEVICE EVALUATION PROCEDURE

Complete and return questionnaire, along with existing data pertinent to the effects of the add-on device, to a laboratory capable of performing the SFAT procedure described herein.

COMPANY OR PATENT NAME:

ADDRESS & PHONE NO.:

PERSON TO CONTACT:

ADD-ON DEVICE NAME OR CODE:

DESCRIPTION OF THE DEVICE:

What are the device's effects on the following engine characteristics, and how long does it take to observe these effects?

(1) PERFORMANCE (Fuel Consumption, Exhaust Temperature, etc.)

(2) EXHAUST EMISSIONS (Including Smoke and Particulate Emissions)

(3) COMBUSTION DEPOSITS (Including Sparking)

(4) LUBE OIL

(5) WEAR

(6) FUEL SYSTEM

What are the effects of the add-on device on the following diesel fuel properties (if the device is for engine fuel system)?

(1) Cetane Number:

(2) Viscosity:

(3) API Gravity:

(4) Distillation Range:

(5) Sulfur Content:

(6) Carbon Residue:

(7) Flash Point:

(8) Cloud Point:

(9) Pour Point:

(10) Ash Content:

(11) Corrosiveness: ______________________________

(12) Filterability: ______________________________

(13) Water Absorption: ______________________________

(14) Stability: ______________________________

(15) Foaming: ______________________________

(16) Bacterial Resistance: ______________________________

(17) Vapor Pressure: ______________________________

(18) Miscibility Limits: ______________________________

What are the effects of the add-on device on the following lubricant oil properties (if the device is for engine lube oil system)?

(1) Viscosity: ______________________________

(2) Viscosity Index: ______________________________

(3) API Gravity: ______________________________

(4) Flash Point: ______________________________

(5) Fire Point: ______________________________

(6) Pour Point: ______________________________

(7) Zinc Content: ______________________________

(8) Total Base Number: ______________________________

(9) Corrosiveness: ______________________________

(10) Anti-Foaming: ______________________________

How is this add-on device used?

(1) How is the device installed?

____

____

(2) Are there special requirements for operation of the device?

____

____

Are there any chemicals, elements, or physical conditions that can influence the effectiveness of the device? If so, describe in detail on a separate sheet.

What are the claimed effects of the device? (Attach any pertinent material.)

____

____

____

What tests have been conducted to substantiate these claims? (Attach any pertinent material.)

____

____

What were the results of these tests? (Include formal report issued.)

____

____

Where were these tests performed?

____

____

Depending on the information supplied above, the testing laboratory selected will conduct the appropriate tests in accordance with the SFAT evaluation procedure.