DOE/NASA/0301-1
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CATALOG OF SELECTED HEAVY DUTY TRANSPORT ENERGY MANAGEMENT MODELS

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November 1983

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lewis Research Center
Under Contract DEN3-301

for

U.S. DEPARTMENT OF ENERGY
Conservation and Renewable Energy
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Under Interagency Agreement DE-A101-80CS50194

TABLE OF CONTENTS

1.0 INTRODUCTION

1.1 Program Objectives

Sponsor

This document presents a catalog of energy management models for heavy duty transport systems powered by diesel engines. The catalog was prepared under contract with NASA-Lewis Research Center (LeRC) as part of a program to survey, catalog and assess the major models currently used in the transportation industry.

Objective

The overall program objective was to aid NASA-LeRC in determining the most suitable models available for NASA to acquire, adapt and utilize for their specific analytical needs.

Scope

The scope of the energy management models included in this effort include:

- Heavy Duty Transport Systems
  - Highway Transport (vehicle simulation)
  - Marine Transport (ship simulation)
  - Rail Transport (locomotive simulation)
  - Pipeline Transport (pumping station simulation)
- Heavy Duty Diesel Engines
  - Models that Match the Intake/Exhaust System to the Engine
  - Fuel Efficiency
  - Emissions
  - Combustion Chamber Shape
  - Fuel Injection System
  - Heat Transfer
  - Intake/Exhaust System
  - Operating Performance
  - Waste Heat Utilization Devices
    - turbocharger
    - bottoming cycle

Time Frame

This catalog is a result of work performed in the time period from December 1982 to September 1983.

1.2 Description of Catalog Contents

Major Purpose

The main purpose of this catalog is to present detailed, comparable and structured information on major computer models used in the heavy-duty transport area related to diesel engines.

Contents of Each Chapter

Chapter 1.0 of this volume contains the background information on this project and the description of how the catalog is organized. Chapter 2.0 contains summary tables to be used as guides to rapidly access the models of interest. Chapter 3.0 contains the detailed individual model descriptions in common formats organized by category and access number. Chapter 4.0 is an index by model category and by organization that sponsored the model development.

1.3 Completeness and Future Updating

Researching the World Models

Although this program involved a comprehensive search of data bases, libraries, personal industry government and university contacts, it is possible that some references and models may remain undiscovered or uncataloged. Some of the model descriptions may be incomplete or contain inaccuracies due to unavailability of up-to-date documentation or original model authors/users.

Updating

With the possibility of continually updating and expanding our computer files containing the catalog model descriptions and references, any references regarding new or overlooked models or information would be welcomed by the authors.

1.4 Catalog Format and Definitions

The final set of information entries that were researched for each major model description are listed below. These entries are grouped so that entry descriptions of similar or related types of information would be easily referenced. The definition of the intended information for each entry follows:

Title	The model name refers to the commonly recognized name of the model if it has one. Otherwise, the name of the report in which the model is presented or the organization that developed the model
Date	When was the model completed and when did updates occur (if any)?
Authors	Who are the primary individuals that developed the model?
Organization	What organization or group developed the model?
Sponsor	What organization or groups provided funding for the development?
Transportation Mode	Highway, Rail, Marine or Pipeline.
Application	Military or civilian.
Objective	The objective of the model is the purpose for which the model was developed. This often includes the parameters which are analyzed in the model.
References	Papers, articles, manuals or other documents which describe the model or results of analysis on the model.
Relationship to Other Models	Is there any relationship between this model and other models? For example, is this a submodel or part of a family of models?
History of Model	What is the history of this model? For example, is this a second generation model based on an earlier, less sophisticated version?
Operational Capabilities	What is the model's range of capabilities for • primary output calculations, • steady-state, quasi-steady-state, or transient operation • ability to vary design factors of interest.
Assumptions	What are the major assumptions that the model is founded upon?
Limitations	What are the limitations or shortcomings of the current model and the comparison with other similar models?

Data Input Requirements	What data or parameters are required as givens or input to the model? For example, are engine maps required or the data from operating an actual engine.
Advantages	What advantages does this model have compared to other models with similar objectives and output?
Validation	What is the validation status of this model?
Computing Requirements	What is the computer hardware systems that have been or are presently used for processing this model? What language is the model code written in?
Cost of Operation	What is the average cost per run of operating this model on the current hardware referred to in previous entry?
Future Potential	What future modifications or changes are planned for this model?
Availability	What is the availability of this model for NASA-Lewis Research Center use or purchase?

2.0 SUMMARY GUIDE TO THE CATALOG

Type of Summary Tables.

As stated previously, this document presents a catalog of energy management models for heavy duty transport systems powered by diesel engines. The chapter that follows summarizes key features of these models in order to assist the reader in ascertaining those models of primary interest. First, the models are summarized according to application and transportation mode as follows:

- Table 2.1 - Applications of Heavy Duty Diesel Engine Models.
- Table 2.2 - Models by Transportation Mode

From these two tables the reader can select the category of interest. Models are summarized in more detail within categories in the following tables:

2.3.1 <u>Heavy Duty Transport Systems</u>

2.3.1.1 Highway Vehicle Models
2.3.1.2 Marine Models
2.3.1.3 Rail Models

2.3.2 <u>Heavy Duty Diesel Engine Models</u>

2.3.2.1 Models that Match the Intake/Exhaust System to the Engine
2.3.2.2 Fuel Efficiency Models
2.3.2.3 Emission Models
2.3.2.4 Combustion Chamber Shape Models
2.3.2.5 Fuel Injection System Models
2.3.2.6 Heat Transfer Models
2.3.2.7 Intake/Exhaust System Models
2.3.2.8 Operating Performance Models
2.3.2.9 Bottoming Cycle Models
2.3.2.10 Turbocharging Models

Description of Tables.

If one is interested in knowing which engine models have been developed for a particular functional application, Table 2.1 is a summary of the heavy duty diesel engine models by type of application. For each application, the scope is defined and the model title, organization and location in Chapter 3 is cited. For those interested in quickly ascertaining which models apply to a particular mode(s) of transportation, or those modes that are applicable to all models, Table 2.2 summarizes the models including title, organization and location in Chapter 3. Using either of these tables provides a group of two or more potentially interesting models. In order to select the appropriate model(s) for one's needs, the user can either read each of the model descriptions in detail in Chapter 3 or utilize the categorical summaries provided in Tables 2.3. Used as described below, these tables should enable the user to quickly ascertain the model(s) most likely to meet the particular needs and constraints of a given situation.

Selection of Model(s) from the Tables.

Model selection is highly dependent upon user constraints, such as: knowledge of computer programs, individual requirements (i.e., level of complexity), and facilities available for work. A potential user should ask the following questions in order to choose the appropriate program from Tables 2.3.

1. What issue am I interested in?
2. Does the program application meet my needs?
3. Is the annotated computer hardware system comparable to my own?
4. Can I operate the model within my budgetary constraints?
5. Has the model been sufficiently validated and documented? If not, will I be able to obtain assistance from the author(s)?

Hardware compatibility.

The third question is particularly important for determining the ease of using or adapting a program. For example, each program has been run on a particular type of computer system. Although software can be run on any system, some changes might be required in order to achieve operational performance on an alternative system. In addition, the cost of operation is frequently a concern among potential users. Therefore, the hardware has been described and cost estimates provided wherever possible.

The remaining details in the tables are provided for user convenience in model selection.

The access and page numbers are provided in the first column of the tables to assist the user in locating the more detailed information on the selected model(s) elsewhere in this document. The author and associated organization are also identified. The author(s) can be contacted in order to ascertain additional details with respect to recent updates, availability or the type and status of its validation, if any. The term "validation" as used in the following tables, is meant to imply that the model results have been favorably compared to experimental data. More complete details on the validation techniques are discussed in the individual summaries.

Concluding Remarks.

Finally, the reader should note that these tables serve merely as a summary guide to the catalog that follows; they are a tool for quickly assessing those models of primary interest. Detailed model descriptions can be found in Chapter 3, beginning on the page cited in the tables.

TABLE 2.1: APPLICATIONS OF HEAVY DUTY DIESEL ENGINE MODELS

APPLICATION	SCOPE	MODELS	ACCESS NO./ PAGE NO.
Matching Intake/Exhaust System to the Engine	• Simplified cycle thermodynamics yielding exhaust temperature and pressure	• Hitachi Model: HITACHI SHIPBUILDING, LTD	E-0034-72 pp. 3-83
		• University of Manchester: UMIST	E-0036-81 pp. 3-87
Efficiency or Fuel Consumption	• Heat release aattern • Accurate gas properties • Heat transfer • Wall temperature	• Computer Simulation of a Diesel Engine: I.I.T., DELHI	E-0063-76 pp. 3-109
		• The Problem of Predicting Rate of Heat Release in Diesel Engines C.A.V. LTD.	E-0005-70 pp. 3-97
		• Wisconsin Diesel Spray Combustion Model: University of Wisconsin	E-0032-69 pp. 3-101
		• M.A.N.: MAN Augsburg	E-0070-74 pp. 3-115
		• Manchester (white house) UMIST	E-0004-77 pp. 3-91
		• Imperial College (Watson) Imperial College, M.E. DEPT.	E-0044-80 pp. 3-105

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TABLE 2.1 (Continued)

APPLICATION	SCOPE	MODELS	ACCESS NO./ PAGE NO.
Emissions	• Detailed ignition and burning mechanisms of the spray	• Divided Chamber Diesel Engine Model: MIT	E-0001-81 pp. 3-119
	• Chamber temperature variations	• Cummins: CUMMINS ENGINE CO.	F-0003-78 pp. 3-131
	• Mixture composition variations; exchange between zones	• Ultrasystems Diesel Emissions Model: ULTRASYSTEMS, INC.	E-0006-74 pp. 3-135
		• Hiroshima: UNIVERSITY OF HIROSHIMA	E-0007-76 pp. 3-139
		• NREC Diesel Emissions Model: NREC	E-0008-71 pp. 3-143
		• C.A.V. Diesel Emissions Model: C.A.V. LTD	E-0026-73 pp. 3-147
		• Komatsu "DSA/DEC" KOMATSU/MIT	E-0002-78 pp. 3-125
		• Cranfield Model CRANFIELD INSTITUTE OF TECHNOLOGY	E-0071-75 pp. 3-151
Development of Combustion Chamber Shape	• Spatial resolution in 2-D or or 3-D of the spray formation & combustion process	• Livermore Fuel Spray Model LAWRENCE LIVERMORE LAB	E-0009-78 pp. 3-155
		• Imperial College Diesel Spray Model IMPERIAL COLLEGE	E-0029-FI-80 pp. 3-165

TABLE 2.1 (Continued)

APPLICATION	SCOPE	MODELS	ACCESS NO./ PAGE NO.
		• Los Alamos Direct Injection Engine Model LOS ALAMOS/GENERAL MOTORS RESEARCH LAB	E-0072-78 pp. 3-171
		• Princeton Internal Combustion Engine Model PRINCETON UNIVERSITY	E-0010-73 pp. 3-159
Fuel Injection System	• Examine the response of injector to control inputs	• Hybrid (Analog) Computer Simulation of the Sampled-Data Model for Compression Ignition Engines: UNIVERSITY OF SUSSEX	E-0021-FI-70 pp. 3-177
		• Diesel Fuel Injection System Simulation and Experimental Correlation: UNIVERSITY OF MICHIGAN	E-0039-FI-73 pp. 3-179
		• Simulation of Processes of Fuel Injection (INJEC): KYOTO UNIVERSITY	E-0048-FI-71 pp. 3-185
		• Computer Model of the Electronics Control System (ECS) for Diesel Fuel Injection Timing: UNIVERSITY OF MINN.	E-0069-FI-82 pp. 3-189
		• Characterization and Simulation of a Unit Injector: WAYNE STATE UNIVERSITY	E-0049-FI-75 pp. 3-187

TABLE 2.1 (Continued)

APPLICATION	SCOPE	MODELS	ACCESS NO./ PAGE NO.
Heat Transfer	• Through a series of assumptions, a classified heat transfer analysis is performed to study the affect on engine performance	• PROCES: NORWEGIAN INSTITUTE OF TECHNOLOGY	E-0023-HT-75 pp. 3-193
		• Computer Programs to Determine the Relationship Between Pressure Flow, Heat Release, and Thermal Load in Diesel Engines: M.A.N.	E-0067-HT-64 pp. 3-195
		• Mirrlees Heat Transfer Program DIESHT: MIRRLEES BLACKSTONE, LTD.	E-0073-HT-83 pp. 3-197
Intake & Exhaust System	• Optimize the design of the manifold system • Models based on steady compressible flow; unsteady compressible flow; pressure wave "organ pipe" theory	• Prediction of the Exchange Processes in a Single Cylinder Internal Combustion Engine: VARIOUS UNIVERSITIES	E-0014-IE-78 pp. 3-201
		• Computer Aided Design of the Exhaust of a Turbocharged Diesel Engine: UNIVERSITY OF MANCHESTER	E-0015-IE-74 pp. 3-205

TABLE 2.1 (Continued)

APPLICATION	SCOPE	MODELS	ACCESS NO./ PAGE NO.
Intake and Exhaust System		• Computer Aided Design Package for Engine Manifold System UMIST	E-0022-IE-80 pp. 3-209
		• A Generalized Computer Aided Design Package for I.C. Engine Manifold System: UMIST	E-0043-IE-80 pp. 3-213
		• Computer Program to Predict the Gas Exchange Process of a Diesel Engine: RUSTON PAXMAN DIESEL STD.	E-0055-IE-74 pp. 3-219
		• Breathing Cycle of the Four- Stroke Automotive Engine: USDOT/NHTSA	E-0056-IE-79 pp. 3-225
		• Characteristics of Exhaust Gas Pulsation of Constant Pressure Turbocharged Diesel Engines: KAWASAKI HEAVY IND.	E-0053-IE-79 pp. 3-217

TABLE 2.1 (Continued)

APPLICATION	SCOPE	MODELS	ACCESS NO./ PAGE NO.
Operating Performance	• Optimize the engine's performance for a given duty cycle • Transient response based on steady state maps	• Application Engineering Techniques Related to High Performance, Medium Speed Diesel Engines: MIRRLEES BLACKSTONE, LTD.	E-0059-OP-75 pp. 3-239
		• Development of a Real-Time Digital Computer Simulation of a Turbocharged Diesel Engine: PAKISTAN STATE OIL CO., LTD.	E-0013-OP-79 pp. 3-229
		• A Combustion Correlation for Diesel Engine Simulation: IMPERIAL COLLEGE OF SCIENCE AND TECHNOLOGY	E-0044-OP-79 pp. 3-233
		• Development of P.C. Engine Simulation Program: NIPPON KOKAN	E-0061-OP-74 pp. 3-243
		• Wholly Dynamic Model of a Turbocharged Diesel Engine for Transfer Function Evaluation UMIST	E-0062-OP-76 pp. 3-245
		• Title Unknown: NREC	E-0045-OP-69 pp. 3-235

TABLE 2.1 (Continued)

APPLICATION	SCOPE	MODELS	ACCESS NO./ PAGE NO.
Operating Performance		• Simulation of a Turbocharged Diesel Engine to Predict the Transient Response: JOHN DEERE	E-0068-OP-77 pp. 3-249
Bottoming Cycle	• Analysis of waste heat utilization systems	• Boiler Analysis Program: FOSTER MILLER	E-0002-70 pp. 3-251
		• Rankine Cycle, Waste Heat Recovery Engine Performance Model: THERMO ELECTRON CORP.	W-0003-74 pp. 3-255
		• DRC Modeling (Rankine Bottoming Cycle Engines): MECHANICAL TECHNOLOGIES, INC.	W-0004-70 pp. 3-259
		• Brayton Bottoming Systems Evaluation: HSD & UTRC	W-0005-70 pp. 3-261
		• Rankine Bottoming Cycle Performance Code: ARGONNE NATIONAL LAB	W-0006-70 pp. 3-263

TABLE 2.1 (Continued)

APPLICATION	SCOPE	MODELS	ACCESS NO./ PAGE NO.
Turbocharging	• Model turbocharges either alone or as part of an engine system • Simplified nozzle/orifice representation of turbine and compressor • Simplified nozzle/orifice losses included	• Turbocharged Diesel Engine Simulation to Predict Steady State and Transient Performance CUMMINS ENGINE CO.	E-0018-TC-77 pp. 3-267
		• Prediction and Measurement of Two-Stroke Cycle Diesel Engine Performance and Smoke at Altitude DETROIT DIESEL ALLISON	E-0019-TC-77 pp. 3-271
		• A Real Time Analogue Computer Simulation of a Turbocharged Diesel Engine UNIVERSITY OF MANCHESTER	E-0035-TC-75 pp. 3-275
		• A Dynamic Simulation of a Two-Stroke Turbocharged Diesel Engine: DETROIT DIESEL ALLISON	E-0036-TC-81 pp. 3-279
		• A Non-Linear Digital Simulation of Turbocharged Diesel Engine Under Transient Conditions: IMPERIAL COLLEGE OF SCIENCE AND TECHNOLOGY	E-0051-TC-76 pp. 3-283

TABLE 2.2: MODEL CROSSREFERENCE BY TRANSPORTATION MODE

HIGHWAY	RAIL	MARINE	PIPELINE
• Computer Simulation of a Diesel Engine: I.I.T. DELHI. pp. 3-109			
• Simulation of a Turbocharged Diesel Engine to Predict The Transient Response: JOHN DEERE pp. 3-249	• Computer Programs to Determine the Relationship Between Pressure Flow, Heat Release, and Thermal Load in Diesel Engines: M.A.N. pp. 3-195		
• Divided-Chamber Diesel Engine Model: MIT pp. 3-119		• Development of P.C. Engine Simulation Program: NIPPON KOKAN pp. 3-243	
• Cummins CUMMINS ENGINE CO. pp. 3-131			

TABLE 2.2 (Continued)

HIGHWAY	RAIL	MARINE	PIPELINE
• Ultrasystems Diesel Emissions Model: ULTRASYSTEMS, INC. pp. 3-135			
• Hiroshima: UNIVERSITY OF HIROSHIMA pp. 3-139			
• NREC Diesel Emissions Model: NREC pp. 3-143			
• Prediction of the Exchange Processes in a Single Cylinder Internal Combustion Engine: VARIOUS UNIVERSITIES pp. 3-201			
• Computer Aided Design of the Exhaust of a Turbocharged Diesel Engine: UNIVERSITY OF MANCHESTER pp. 3-209			

TABLE 2.2 (Continued)

HIGHWAY	RAIL	MARINE	PIPELINE
• Turbocharged Diesel Engine Simulation to Predict Steady-State and Transient Performance: CUMMINS ENGINE CO. pp. 3-267		• PROCES: NORWEGIAN INSTITUTE OF TECHNOLOGY pp. 3-193	
• Prediction and Measurement of Two-Stroke Cycle Diesel Engine Performance and Smoke at Altitude: DETROIT DIESEL ALLISON pp. 3-271		• Application Engineering Techniques Related to High Performance, Medium Speed Diesel Engines: MIRRLEES, BLACKSTONE, LTD. pp. 3-239	
• Hybrid (Analog) Computer Simulation of the Sampled-Data Model for Compression Ignition Engines: UNIVERSITY OF SUSSEX pp. 3-177			
• Computer Aided Design Package for Engine Manifold Systems: UMIST pp. 3-209			

TABLE 2.2 (Continued)

HIGHWAY	RAIL	MARINE	PIPELINE
• C.A.V. Diesel Emissions Model: C.A.V. LTD. pp. 3-147			
• Imperial College Diesel Spray Model IMPERIAL COLLEGE pp. 3-165			
• Wisconsin Diesel Spray Combination Model: UNIVERSITY OF WISCONSIN pp. 3-101			
• Hitachi Model: HITACHI SHIPBUILDING, LTD. pp. 3-83			
• A Real Time Analogue Computer Simulation of a Turbocharged Diesel Engine: UNIVERSITY OF MANCHESTER pp. 3-275		• A Real Time Analogue Computer Simulation of a Turbocharged Diesel Engine: UNIVERSITY OF MANCHESTER pp. 3-275	

TABLE 2.2 (Continued)

HIGHWAY	RAIL	MARINE	PIPELINE
• University of Manchester UMIST pp. 3-87			
• A Dynamic Simulation of a Two-Stroke Turbocharged Diesel Engine: UMIST pp. 3-279		• Computer Program to Predict the Gas Exchange Process of a Diesel Engine: RUSTON PAXMAN DIESEL STD. pp. 3-219	
• Diesel Fuel Injection System Simulation and Experimental Correlation: UNIVERSITY OF MICHIGAN pp. 3-179		• Characteristics of Exhaust Gas Pulsation of Constant Pressure Turbocharged Diesel Engines: KAWASAKI HEAVY IND. pp. 3-217	• Title unknown: NATIONAL RESEARCH COUNCIL OF CANADA pp. 3-235
• Komatsu "DSA/DEC" KOMATSU/MIT pp. 3-125			
• Manchester (Whitehouse) UMIST pp. 3-91			

TABLE 2.2 (Continued)

HIGHWAY	RAIL	MARINE	PIPELINE
• A Combustion Correlation for Diesel Engine Simulation: IMPERIAL COLLEGE OF SCIENCE AND TECHNOLOGY pp. 3-233		• USCG Icebreaker Propulsion System Simulation, Prog. No. ENE-11: USCG HEADQUARTERS pp. 3-41	
• A Generalized Computer Aided Design Package for I.C. Engine Manifold Systems: UMIST pp. 2-213			
• Simulation of Processes of Fuel Injection (INJEC): KYOTO UNIVERSITY pp. 3-185			
• Characterization and Simulation of a Unit Injector: WAYNE STATE UNIVERSITY pp. 3-187	• Train Performance Calculator: AIRESEARCH MNFG.CO. pp. 3-81	• Characterization and Simulation of a Unit Injector: WAYNE STATE UNIVERSITY pp. 3-187	

TABLE 2.2 (Continued)

HIGHWAY	RAIL	MARINE	PIPELINE
• A Non-Linear Digital Simulation of Turbocharged Diesel Engines Under Transit Conditions: IMPERIAL COLLEGE OF SCIENCE AND TECHNOLOGY pp. 3-283			
• Breathing Cycle of the Four-Stroke Automotive Engine: USDOT/TSC pp. 3-225			
• Wholly Dynamic Model of a Turbocharged Diesel Engine for Transfer Function Evaluation: UMIST pp. 3-245			
• M.A.N. MAN AUGSBURG pp. 3-115			

TABLE 2.2 (Continued)

HIGHWAY	RAIL	MARINE	PIPELINE
● HEVSIM: USDOT pp. 3-5	● TPS: USDOT/TSC pp. 3-55	● A Method of Predicting the Speed Reduction of Turbocharged Marine Diesel Engines: UNIVERSITY OF HANNOVER pp. 3-43	
● TCAPE: INTERNATIONAL HARVESTERS pp. 3-17	● FUEL: EMERSON CONSULTANTS pp. 3-61	● Analysis of Shipboard Energy Systems: PFR ENGINEERING SYSTEMS pp. 3-47	
● A Simplified Program for Evaluating Diesel Truck Performance: UNITED TECHNOLOGIES RESEARCH CENTER pp. 3-31	● Freight Train Fuel Consumption Program: MITRE pp. 3-63	● Systematic Design of Marine Propulsion Systems: UNIVERSITY OF NEWCASTLE pp. 3-49	
● Imperial College (WATSON): IMPERIAL COLLEGE pp. 3-105			
● Cranfield Model: CRANFIELD INSTITUTE OF TECHNOLOGY pp. 3-151			

TABLE 2.2 (Continued)

HIGHWAY	RAIL	MARINE	PIPELINE
• TRUKSIM: INTERNATIONAL HARVESTERS pp. 3-35	• The Transportation Energy Model: CARNEGIE-MELLON pp. 3-67	• Selection and Simulation of Marine Propulsion Control Systems: LIPS, NV, DRUNEN, HOLLAND pp. 3-51	
• BAP: FOSTER-MILLER pp. 3-251	• TPC: EE/CS DEPARTMENT OF UNION COLLEGE pp. 3-71	• Computer Aided Marine Power Plant Selection: MIT pp. 3-53	
• Rankine Cycle Waste Heat Recovery Engine Performance Model: THERMO ELECTRON CORP. pp. 3-255	→	→	→
	• TOS: SOUTHERN PACIFIC TRANS.CO. pp. 3-75		
	• Train Performance Calculator: pp. 3-79		
• A Computer Model of the Electronic Control System (ECS) for Diesel Fuel Injection Timing: UNIVERSITY OF MINN. pp. 3-189	→	→	→

TABLE 2.2 (Continued)

HIGHWAY	RAIL	MARINE	PIPELINE
• The Problem of Predicting Rate of Heat Release in Diesel Engines LTD. pp. 3-97	→	→	→
• Los Alamos Direct-Injection Engine Model: LOS ALAMOS/GM RESEARCH LAB pp. 3-171	→	→	→
• Princeton Internal Combustion Engine Model: PRINCETON UNIVERSITY pp. 3-159	→	→	→
• Mirrlees Heat Transfer Program, DIESHT: MIRRLEES BLACKSTONE LTD. pp. 3-197	→	→	→
• Livermore Fuel Spray Model: LAWRENCE LIVERMORE LAB. pp. 3-155	→	→	→

TABLE 2.2 (Continued)

HIGHWAY	RAIL	MARINE	PIPELINE
• GPSIM: GENERAL MOTORS pp. 3-1			
• Dynamic Model: FORD MOTOR CO. pp. 3-9		• Applied Computer Simulation in Marine Engineering-Clutch Maneuvering Assessment: Y-ARD LTD. pp. 3-45	
• TOFEP: FORD MOTOR CO. pp. 3-11			
• ASIM: USDOT/TSC pp. 3-13		• DRC Modeling (Rankine Bottoming Cycle Engines): MECHANICAL TECHNOLOGIES, INC. pp. 3-259	
• VMS: CUMMINS ENGINE CO. pp. 3-15			
• TSO: GENERAL MOTORS RESEARCH LAB pp. 3-25			
• HEAVY: BOEING COMPUTER pp. 3-21			

TABLE 2.2 (Contirued)

HIGHWAY	RAIL	MARINE	PIPELINE
• Diesel Urban Bus Simulation Program: USDOT/TSC pp. 3-27			
• DSLSIM: MIT pp. 3-29			
• Brayton Bottoming System Evaluation: UTRC & HSD pp. 3-261			
• Development of a Real-Time Digital Computer Simulation of a Turbocharged Diesel Engine: PAKISTAN STATEOIL CO. pp. 3-229			

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TABLE 2.3.1.1: HIGHWAY VEHICLE MODELS

ACCESS NO.	MODEL NAME	ORGANIZATION	AUTHOR(S)	APPLICATION
H-0002-77 pp. 3-5	Heavy Vehicle Simulation (HEVSIM)	U.S. Department of Transportation	E. Withjack S. Moffat A. Malliaris	o Civilian o Simulation of fuel economy over a given driving schedule
H-0010-78 pp. 3-17	Truck Computer Analysis of Performance and Economy (TCAPE)	International Harvester Group (IH)	Many	o Military and civilian o Sales promotion of IH trucks
H-0024-80 pp. 3-31	A Simplified Program for Evaluating Diesel Truck Performance	United Technologies Research Center	L.E. Greenwald	o Civilian, but applicable to military o To aid in the processes of driveline selection, engine sizing and parametric evaluation of driving cycle economy
H-0025-81 pp. 3-35	TRUKSIM	International Harvester Group (IH)	P. L. , et al.	o Military and civilian o Internal engineering analysis and development

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ADVANTAGES	AVAILABILITY	HARDWARE	COST OF OPERATION	VALIDATION	DOCUMENTATION
o Flexibility in I/O parameters	Yes - no charge	DEC 10, DEC 20, IBM	$25	Not stated	Extensive
o Easy to use as a sales promotion tool	o Not available outside IH o Customer access is available at no charge	DEC	Proprietary	Yes	Yes
o Easy to use o Simple input o Rapid turnaround o Graphical output	Yes; cost is user application dependent	Univac 1100/81A	3 sec/run	Currently underway	None
o Extremely flexible	o Proprietary	IBM or DEC	Proprietary	Yes	Proprietary

ACCESS NO.	MODEL NAME	ORGANIZATION	AUTHOR(S)	APPLICATION
H-0001-72 pp. 3-1	General Purpose Automobile Vehicle Performance and Economy Simulator (GPSIM)	General Motors Corporation	William C. Waters	o Civilian o Computes operating conditions of the engine, transmission and vehicle performance and economy
H-0003-81 pp. 3-9	Dynamic Model	Ford Company	Delosh; Brewer; Bush; Ferguson; Tobler	o Civilian o Simulates the dynamic behavior of the total vehicle system
H-0004-81 pp. 3-11	Testing Operations Fuel Economy Program (TOFEP)	Ford Motor Co.	Not stated	o Civilian o Evaluation of fuel and performance effects of power train changes
H-0005-78 pp. 3-13	Automotive Simulator (ASIM)	USDOT/TSC	E. M. Withjack	o Civilian o A tool for automotive fuel economy evaluation
H-0012-81 pp. 3-21	Hybrid & Electric Advanced Vehicle Systems (HEAVY) Simulation	Boeing Computer Services Co.	Hammond; McGehee	o Civilian o Evaluates electric and hybrid vehicle propulsion systems

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ADVANTAGES	AVAILABILITY	HARDWARE	COST OF OPERATION	VALIDATION	DOCUMENTATION
o Can simulate a large variety of vehicles	Proprietary	IBM 360/65	Depends on type and degree of simulation	Limited	Yes
o Useful for design and analysis of electronic engine control systems	Proprietary, but possibly available	DEC 2050	9 sec of computer time for 1 second of vehicle system operation	Yes	Extensive
o Useful in all phases of power-train optimization	Proprietary	Honeywell or DEC	Less than 1 minute cpu	Some	Some
o Rapid execution o Easy operation	Yes	Not stated	Not stated	Not stated	Some
o Simple to use o Built in system components, description and operational descriptions	Yes	CDC Cybder	Minimal (Approximately $1 per run)	Some	Extensive

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ACCESS NO.	MODEL NAME	ORGANIZATION	AUTHOR(S)	APPLICATION
H-0009-76 pp. 3-15	Vehicle Mission Simulation (VMS)	Cummins Engine Co.	D.A. Klokkenga	o Civilian o Provides truck performance information
H-0013-78 pp. 3-25	Transient System Optimization (TSO)	General Motors Research Laboratory	Alan Dohner	o Civilian o Optimization of fuel economy by accounting for various phenomena
H-0018-79 pp. 3-27	Diesel Urban Bus Simulation Program	USDOT/TSC	G. Larson; H. Zuckerberg	o Civilian o Assesses the performance and fuel consumption of buses under various operating conditions
H-0023- pp. 3-29	DSLSIM (Diesel Engine Control Systems Computer Simulation Model)	Massachusetts Institute of Technology; Department of Mechanical Engineering	D. Wormley; J. Nye; J. Rife	o Civilian o Defines control system configurations o Identifies performance characteristics

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ADVANTAGES	AVAILABILITY	HARDWARE	COST OF OPERATION	VALIDATION	DOCUMENTATION
o Can be used by truck operators to choose options for particular routes	Proprietary	Honeywell DPS/8 CP/6	Less than 10 minutes cpu time needed/run	Yes	Yes
o Considers transient system operation o Can utilize test data	Proprietary	Not stated	Not stated	Some	Some
o Straightforward	Yes	Graphic output available Model 663 Calcomp Plotter	Not stated	Good	Some
o Output available in different representations	Proprietary	VAX	Not stated	Some	None

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TABLE 2.3.1.2: MARINE MODELS

ACCESS NO.	MODEL NAME	ORGANIZATION	AUTHOR(S)	APPLICATION	ADVANTAGES
M-0001-68 pp. 3-41	USCG Icebreaker Propulsion System Simulation, Program No. ENE-11	U.S. Coast Guard Headquarters, Office of Engineering, Icebreaker Design Branch	Lt. J. W. Lewis, LCDR Lecourt F. W. Scoville	o Military and Civilian o Icebreakers o Ice-Strengthened Cargo and Service Ships	o A wide variety of diesel-electric systems can be simulated
M-0002 pp. 3-43	A Method of Predicting the Speed Reduction of Turbocharged Marine Diesel Engines	University of Hannover	M. Grohn, Prof. Dr. Groth	o Military and Civilian o Medium Speed, 4-Cycle, marine diesels loaded by a fixed propeller	o As a design tool
M-0004-81 pp. 3-45	Applied Computer Simulation in Marine Engineering Clutch Manouvering Assessment	Y-ARD Ltd., Glasgow	K. W. McTavish	o Military and Civilian o Design evaluation for a CODOG Ship with controllable pitch propellers	o Different component characteristics can be inverted
M-0006-78 pp. 3-47	Analysis of Shipboard Energy Systems	PFR Engineering Systems	J. Puke; T. Rozenman; J. Pundyk	o Military and Civilian o Fuel consumption rate comparisons	o Permits substitution of reporting arrangements and profiles

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AVAILABILITY	HARDWARE	COST OF OPERATION	VALIDATION	DOCUMENTATION
o Yes	IBM 1130	Proportional to length of maneuver and time steps used	Yes	Yes
o Yes	Not stated	Not stated	Yes	Yes
o Proprietary	Not given	Not stated	Some	Some
o Yes	Not given	Not given	Some	Some

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TABLE 2.3.1.2: MARINE MODELS

ACCESS NO.	MODEL NAME	ORGANIZATION	AUTHOR(S)	APPLICATION	ADVANTAGES
M-0007 pp. 3-49	Systematic Design of Marine Population System	University of Newcastle	R. V. Thompson	o Military and Civilian o Comparison of alternative arrangements for a specialized mine sweeping with distinct operating modes	o A wide variety of systems can be simulated
M-0008-70 pp. 3-51	Selection and Simulation of Marine Propulsion Control Systems	Lips, N. V., Drunen, Holland	C. Pronk	o Military and Civilian o Diesel engines driving marine controllable pitch propellers	o Provides performance predictions during the design phase of maine propulsion systems
M-0009-73 pp. 3-53	Computer Aided Marine Power Plant Selection	MIT	R. I. Newton	o Military and Civilian o Merchant Type Ships	o Simplicity o Approach is with ship as a whole

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AVAILABILITY	HARDWARE	COST OF OPERATION	VALIDATION	DOCUMENTATION
o Proprietary	Not given	Not given	Some	Some
o Proprietary	IBM 1130	Not given	No	Yes
o Proprietary	IBM 370/165	Not given	Yes	Yes

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TABLE 2.3.1.3: RAIL MODELS

ACCESS NO.	MODEL NAME	ORGANIZATION	AUTHOR(S)	APPLICATION	ADVANTAGES
L-0002-78 pp. 3-55	The US DOT/TSC Train Performance Simulator (TPS)	DOT/TSC	M.E. Hazel	o Civilian o Simulation of train over a railroad route	o Useful for planning train operations over a particular route o Simple to use o Modifications easy
L-0005-81 pp. 3-63	Freight train Fuel Consumption Program	MITRE	J. D. Muhlenberg	o Civilian o Calculation of fuel consumption of a freight train	o Incorporates information on most commonly used railcars and locos o Easy to use and modify
L-0009-77 pp. 3-67	The Transportation Energy Model, Carnegie-Mellon	Carnegie-Mellon University	S.N. Talukdar and R.A. Uher	o Civilian o Prediction of energy consumption for diesel and electric powered trains	o Detailed modeling capabilities o Flexibility in modifying parts of program

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AVAILABILITY	HARDWARE	COST OF OPERATION	VALIDATION	DOCUMENTATION
Yes ($150 fee)	DEC 10 & IBM	Typical, $20	Extensive	Yes
Yes (cost of production)	IBM 370	100 cpu for a 100 gallon simulation	Yes	Extensive
Yes ($625 fee)	DEC 20, VAX	15 cpu sec for 50 mile run	Yes	Extensive

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ACCESS NO.	MODEL NAME	ORGANIZATIONS	AUTHOR(S)	APPLICATION	ADVANTAGES
L-0010-78 pp. 3-71	A Multi-Purpose Train Performance Calculator (TPC)	EE/CS Dept. Union College	R. Mittal and A. Rose	o Civilian o Simulation of passenger train operation	o Written specifically to simulate a limited case of passenger train operation
L-0011-83 pp. 3-75	Train Operations Simulator (TOS)	Southern Pacific Transportation Co.	N. W. Lutterlle	o Civilian o Performance simulation of diesel-electric loco and conventional freight car	o Simulates various methods of train handling and its effects on fuel consumption
L-0012-65 pp. 3-79	Train Performance Calculator -AAR	Association of American Railroads (AAR)	Operated by Stuart and McEwan	o Civilian o Prediction of energy usage	o Performs operations quickly
L-0013-79 pp. 3-81	Train Performance Calculator	AiResearch and Manufacturing Co. of California	J.J. Lawson & L. M. Cook	o Civilian o Performs train performance calculations	o Provides very detailed analysis o Can simulate diesel, electric or mixed-mode operations

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AVAILABILITY	HARDWARE	COST OF OPERATION	VALIDATION	DOCUMENTATION
Yes ($150 fee)	Burroughs B-6700 DEC 10		Train scheduling-- Yes Fuel Use - No	Yes
Yes ($50 fee)	IBM, DEC-20, Prime, Burr	12 cpu sec per 1 mile of calc.	Fuel calculations hand checked	Extensive
Yes (cost of production)	CDC 3500, IBM 370, DEC-20	1 cpu minute per 10 miles	No information available	Yes
Proprietary	Univac 1108		Yes	Some

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ACCESS NO.	MODEL NAME	ORGANIZATION	AUTHOR(S)	APPLICATION	ADVANTAGES
L-0004-75 pp. 3-61	Fuel Utilized Effective Locomotives (FUEL)	Emerson Consultants, Inc.	J. N. Cetinich	o Civilian o Investigation of the effect of train operating strategies	Provides overview of effects of train operating strategies on a territory

AVAILABILITY	HARDWARE	COST OF OPERATION	VALIDATION	DOCUMENTATION
Note stated	Not stated	Not stated	Yes	Some

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TABLE 2.3.2.1: MODELS THAT MATCH THE INTAKE/EXHAUST SYSTEM TO THE ENGINE

ACCESS NO.	MODEL NAME	ORGANIZATION	AUTHOR(S)	APPLICATION	ADVANTAGES
E-0034-72 pp. 3-83	Hitachi Model	Hitachi Shipbuilding, Ltd., Osaka	K. Mizushima, M. Nagai, T. Asada	o Civilian and government o Matching intake/ exhaust system to the engine	o Covers entire cycle o Predicts cylinder pressure accurately
E-0036-81 pp. 3-87	University of Manchester (UMIST)	University of Manchester	Winterbone, Lon, Benson, Wellstead, Thiruarooran	o Civilian and government o Matching intake/ exhaust system to the engine	o Particularly useful for detailed design of turbochargers

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AVAILABILITY	HARDWARE	COST OF OPERATION	VALIDATION	DOCUMENTATION
Probably Proprietary	Not stated	\$120-\$200/run (estimate)	Yes	Yes
From UMIST, at cost	Not stated	\$240-\$400/run (estimated)	Some	Yes

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TABLE 2.3.2.2: FUEL EFFICIENCY MODELS

ACCESS NO.	MODEL NAME	ORGANIZATION	AUTHOR(S)	APPLICATION	ADVANTAGES
E-0070-74 pp. 3-115	M.A.N.	M.A.N. Augsburg and Institut fur Kolbenmaschinen Technical University	G. Woschni F. Anisits	o Civilian and government o Efficiency or fuel consumption	o Simple to use
E-0004-77 pp. 3-91	Manchester (Whitehouse)	UMIST	Whitehouse, Way, Sareen, Clough, Abughres, Baluswamy	o Civilian or military o Efficiency or fuel consumption	o Simple o Inexpensive
E-0044-80 pp. 3-105	Imperial College (Watson)	Imperial College	N. Watson M. Marzouk	o Civilian and military o Efficiency or fuel consumption	o Inexpensive to run o Useful for extending known engine performance

AVAILABILITY	HARDWARE	COST OF OPERATION	VALIDATION	DOCUMENTATION
Yes	Not stated	$12-$20 run (estimate)	Yes	Yes
Unknown	Not specified	$60-$100/run	Some	Extensive
Unknown	Not specified	$30-$50/run	Yes	Yes

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TABLE 2.3.2.2 (Continued)

ACCESS NO.	MODEL NAME	ORGANIZATION	AUTHOR(S)	APPLICATION	ADVANTAGES
E-0005-70 pp. 3-97	The Problem of Predicting Rate of Heat Release in Diesel Engines	C.A.V. Ltd. -England	H.C. Grigg & M.H. Syed	o Civilian o Fuel consumption	
E-0032-69 pp. 3-101	Wisconsin Diesel Spray Combustion Model	University of Wisconsin	Shipinski, Myers, and Uyehara	o Civilian and military o Fuel consumption	o Covers, the effect of fuel injection o Emphasizes physical mechanisms
E-0063-76 pp. 3-109	Computer Simulation of a Diesel Engine: I.I.T., DELHI	I.I.T., DELHI	R. D. Garg K.K. Agarwal R. Desikachari	o Military or civilian o Fuel consumption	o Simple to use o Inexpensive

AVAILABILITY	HARDWARE	COST OF OPERATION	VALIDATION	DOCUMENTATION
Not stated	Not stated	Not stated	Not stated	Some
Yes	Not stated	$30-50/run	Fair	Yes
Yes	Not stated	$60-$100/run	Fair	Yes

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TABLE 2.3.2.3: EMISSION MODELS

ACCESS NO.	MODEL NAME	ORGANIZATION	AUTHOR(S)	APPLICATION	ADVANTAGES
E-0001-81 pp. 3-119	Divided Chamber Diesel Engine Model	Massachusetts Institute of Technology	S.H. Mansouri; J. B. Heywood; K. Radhakrishnan	o Civilian o Emissions	o Requires little computer time to run, therefore engine maps can be easily developed
E-0003-78 pp. 3-131	Cummins	Cummins Engine Company	S. M. Shahed, P. F. Flynn, W. T. Lyn, and W. S. Chin	o Military or Civilian o Emissions	o Allows for temperature gradient
E-0007-76 pp. 3-139	Hiroshima	University of Hiroshima	H. Horoyasu and T. Kadota	o Military and civilian o Emissions	o Cost effective o Predicts effects to changes in fuel injector

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AVAILABILITY	HARDWARE	COST OF OPERATION	VALIDATION	DOCUMENTATION
Proprietary	IBM370	$20 per run	Yes	Some
Unknown	Xerox Sigma 9	$60-$100/run	Some -- needs further work	Yes
Not stated	Not stated	Not stated	Some	Yes

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TABLE 2.3.2.3 (Continued)

ACCESS NO.	MODEL NAME	ORGANIZATION	AUTHOR(S)	APPLICATION	ADVANTAGES
E-0008-71 pp. 3-143	NREC Diesel Emissions Model	Northern Research and Engineering Corporation	Bastress, Chng, and Dix	o Military and civilian o Emissions	o Simplicity
E-0071-75 pp. 3-151	Cranfield Model	Cranfield Institute of Technology	P. Hodgetts, H. D. Shroff, I. R. Isaac	o Civilian and Military o Emissions	o Treats fuel-air ratio and temperature gradients
E-0026-73 pp. 3-147	C.A.V. Diesel Emissions Model	C.A.V. Ltd., Acton, London	Khan, Greeves, Probert, Grigg, and Syed	o Civilian and military o Emissions	o Handles soot formation, fuel injection parameters and air swirl level

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AVAILABILITY	HARDWARE	COST OF OPERATION	VALIDATION	DOCUMENTATION
From NREC (Cost in 1974 was $100)	CDC; IBM	$10-$20/run	Some	Some
Through inter-national technology exchange	Not specified	$30-$50/run	Yes	Extensive
Probably	Not stated	$60-$100/run	Adequate for design	Extensive

TABLE 2.3.2.3 (Continued)

ACCESS NO.	MODEL NAME	ORGANIZATION	AUTHOR(S)	APPLICATION	ADVANTAGES
E-0002-78 pp. 3-125	Komatsu "DSA/DCE"	Komatsu/ MIT	H. Hiraki, J. M. Rife	o Civilian, Military o Emissions	o Models cylinder heat transfer to coolant o Turbocharged calculation is included o Effect of fuel spray design parameters included
E-0006-64 pp. 3-135	Ultrasystems Diesel Emissions Model	Ultrasystems, Inc.	C. J. Kau, R. P. Wilson, L. J. Muzio, C. H. Waldman, M. P. Heap, T. J. Tyson	o Military or civilian o Emissions	o Can model fuel injection pressure orifice size, and air swirl

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AVAILABILITY	HARDWARE	COST OF OPERATION	VALIDATION	DOCUMENTATION
Unknown	Not specified	\$120-\$200/run (estimated)	Yes	Extensive
Yes	CDC 6600	\$180-\$300/run	Yes	Extensive

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TABLE 2.3.2.4: COMBUSTION CHAMBER SHAPE MODELS

ACCESS NO.	MODEL NAME	ORGANIZATION	AUTHOR(S)	APPLICATION	ADVANTAGES
E-0072-78 pp. 3-171	Los Alamos Direct-Injection Engine Model	Los Alamos/ General Motors Research Laboratory	T. D. Butler, L. D. Cloutman, R. B. Krieger, et. al.	o Civilian and military o Development of combustion chamber shape	o Can predict flow field, spatial flame propagation, spatial temperature profiles and locations of peak NO_x formation
E-0010-77 pp. 3-159	Princeton Internal Combustion Engine Model	Princeton University	F. V. Bracco, H. C. Gupta, P. J. O'Rourke	o Civilian and military o Development of combustion chamber shape	o Detailed description of spray crag and evaporation
E-0029-80 pp. 3-165	Imperial College, Diesel Spray Model	Imperial College	Gosman and Johns	o Civilian and military o Combustion chamber shape	o Describes the spatial distribution of the diesel spray
E-0009-78 pp. 3-155	Livermore Fuel Spray Model	Lawrence Livermore Lab	L. C. Haselman C. W. Westbrook	o Civilian or military o Combustion chamber shape	o Treats chamber shape effects o Models unsteady, effects of spray penetration

AVAILABILITY	HARDWARE	COST OF OPERATION	VALIDATION	DOCUMENTATION
Yes	Not stated	\$600-\$6000/run (estimated)	Yes	Extensive
Yes	IBM 360/91	Without spray: \$120-180/run with spray: up to \$5000/run	No	Extensive
On a contract basis	Not stated	\$600-\$1000/run	Some	Yes
Yes	CDC7600	\$5,000-\$6,000/ run	Some	Extensive

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TABLE 2.3.2.5: FUEL INJECTION SYSTEM MODELS

ACCESS NO.	MODEL NAME	ORGANIZATION	AUTHOR(S)	APPLICATION	ADVANTAGES
E-0039-FI-73 pp. 3-179	Diesel Fuel Injection System Simulation and Experimental Correlation	University of Michigan	Bolt, El-Erian, Wylie	o Military and civilian o Fuel injection	o Good accuracy and economy
E-0028-FI pp. 3-185	Simulation of Processes of Fuel Injection (INJEC)	Kyoto University	M. Ikegami H. Horike F. Nagao	o Military and civilian o Fuel injection	o Reduced computing time
E-0049-FI-75 pp. 3-187	Characterization and Simulation of a Unit Injector	Wayne State University	N.A. Henein T. Singh J. Rozanski	o Military and civilian o Simulation of fuel pressure histories	o Simple
E-0069-FI-82 pp. 3-189	Computer Model of the Electronic Control System (ECS) for Diesel Fuel Injection Timing	University of Minnesota	M. J. Pipho D. B. Kittelson	o Military and civilian o Performance simulation	o Provides complete engine response to an optimization control system
E-0021-FI-70 pp. 3-177	Hybrid (Analog) Computer Simulation of the Sampled-Data Model for Compression Ignition Engines	University of Sussex	C. R. Burrows, P.W. VanEctrelt, G. P. Windett	o Military or civilian o Fuel injection	Simple of use

AVAILABILITY	HARDWARE	COST OF OPERATION	VALIDATION	DOCUMENTATION
From the EPA	Not stated	Not stated	Yes	Yes
From Kyoto University	FACOM 230-60	12 seconds/ iteration (5 iterations/ run)	Some	Some
Yes	Not stated	Low	Some	Some
No	Not stated	Not st[illegible]d	Some	Yes
Yes	Not stated	Not stated	Poor to fair	Some

TABLE 2.3.2.6: HEAT TRANSFER MODELS

ACCESS NO.	MODEL NAME	ORGANIZATION	AUTHOR(S)	APPLICATION
E-0023-HT-75 pp. 3-193	PROCES	Norweigian Institute of Technology	H. Valland	o Military and civilian o Heat transfer
E-0067-HT-64 pp. 3-195	Computer Programs to Determine the Relationship Between Pressure Flow, Heat Release and Thermal Load in Diesel Engines	MAN	Gerhard Woschini	o Military and civilian o To determine the relationships between pressure flow, heat release and thermal load
E-0073-HT-83 pp. 3-197	Mirrlees Heat Transfer Program DIESHT	Mirrlees Blackstone Ltd.	R. T. Green K. Jambunathan, S. D. Probert	o Civilian and military o Heat transfer

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ADVANTAGES	AVAILABILITY	HARDWARE	COST OF OPERATION	VALIDATION	DOCUMENTATION
o Seemingly simple to use	Yes	Not stated	Not stated	Not stated	Little
o Heat transfer through each of the major components is done separately	Yes - Refer to SAE paper	IBM 1060	8 Minutes of machine time/run	No	Some
o Easily used by designers	Yes, with permission of Mirrlees Blackstone	Not stated	\$5-\$20/run	Yes	Extensive

TABLE 2.3.2.7: INTAKE/EXHAUST SYSTEM MODELS

ACCESS NO.	MODEL NAME	ORGANIZATION	AUTHOR(S)	APPLICATION
E-0015-IE-74 pp. 3-205	Computer Aided Design of the Exhaust of Turbocharged Diesel Engine	University of Manchester	J. D. Ledger	o Military or civilian o Intake and exhaust system
E-022-IE-80 pp. 3-209	Computer Aided Design Package for Engine Manifold System	University of Manchester, Institute of Science and Technology	S. C. Low, R. S. Benson, D. E. Winterbone	o Civilian o Intake and exhaust systems
E-0014-IE-78 pp. 3-201	Prediction of the Exchange Processes in a Single Cylinder Internal Combustion Engine	Various universities	P.A. Lakshmi-narayanan P.A. Janakiraman M.K. Gajendra Sabu B.S. Murthy	o Military and civilian o To model gas flow
E-0043-IE-80 pp. 3-213	A Generalized Computer Aided Design Package for I.C. Engine Manifold System	University of Manchester Institute of Science & Technology (UMIST)	S.C. Low P.C. Baruah	o Military and civilian o Performance prediction of manifolding systems

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ADVANTAGES	AVAILABILITY	HARDWARE	COST OF OPERATION	VALIDATION	DOCUMENTATION
o Rapid turnaround o Graphical display	Yes	DEC-PDP10	Not stated	None reported	Yes
o Rapid data changes possible o Relatively simple to use	Probably	CDC Cyber 72; DEC; Tectronics 4010	Not stated	Yes	Some
o Accuracy	Not stated	Not stated	Not stated	Some	Some
o Minimal input data needed o Interactive o Throttled and unthrottled	From UMIST	Not stated	Not stated	No	Some

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ACCESS NO.	MODEL NAME	ORGANIZATION	AUTHOR(S)	APPLICATION	ADVANTAGES
E-0053-IE-79 pp. 3-217	Characteristics of Exhaust Gas Pulsation of Constant Pressure Turbocharged Diesel Engines	Kawasaki Heavy Industries	T. Azuma Y. Tokunaga T. Yura	o Military and civilian o Clarify character-istics of exhaust and gas pulsations	o Unique (first to model exhaust pulsations and gas flow interactions)
E-0055-IE-74 pp. 3-219	Computer Program to Predict the Gas Exchange Process of a Diesel Engine	Ruxton Paxman Diesel Standard	A. J. Hallam S. Cottam	o Military and civilian o Intake and exhaust	o Flexible and user friendly
E-0056-IE-79 pp. 3-225	Breathing Cycle of the Four-Stroke Automotive Engine	U.S. Department of Transportation/ Transportation Systems Center	T. J. Trella	o Military and civilian o Model the intake system of a four-stroke open chamber engine	o Novel approach to gas flow calculations

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AVAILABILITY	HARDWARE	COST OF OPERATION	VALIDATION	DOCUMENTATION
No	Not [illegible]	Not stated	Yes	Some
Proprietary	Not stated	Not stated	Yes	Some
US DOT/TSC	DEC 10	Not stated	Yes	Some

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TABLE 2.3.2.8: OPERATING PERFORMANCE MODELS

ACCESS NO.	MODEL NAME	ORGANIZATION	AUTHOR(S)	APPLICATION
E-0013-OP-79 pp. 3-229	Development of a Real-Time Digital Computer Simulation of a Turbocharged Diesel Engine	Pakistan State Oil Company Ltd.	S. S. Shamsi	o Military and Civilian o Model response of a turbocharged diesel engine
E-0044-OP-79 pp. 3-233	A Combustion Correlation for Diesel Engine Simulation	Imperial College of Science and Technology	N. Watson A. D. Pilley M. Marzouk	o Military and civilian o To provide a means of increasing accuracy of engine models which do not incorporate combustion models
E-0061-OP-74 pp. 3-243	Development of P.C. Engine Simulation Program	Nippon Kokan	K. Shiraishi, K. Murakami; M. Mizushima T. Nakayama	o Military and civilian o To model a test engine to make performance predictions

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ADVANTAGES	AVAILABILITY	HARDWARE	COST OF OPERATION	VALIDATION	DOCUMENTATION
o It is the only digital engine response model available	Unknown	PDP10	o Considered "economical"	Some	Some
o Can be used to expand the accuracy of other models	Yes	Not stated	Not Stated	Some	Some
-	Unlikely	Not stated	Not stated	Yes	Some

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ACCESS NO.	MODEL NAME	ORGANIZATION	AUTHOR(S)	APPLICATION
E-0062-OP-76 pp. 3-245	Wholly Dynamic Model of a Turbocharged Diesel Engine for Transfer Function Evaluation	University of Manchester, Institute of Science and Technology (UMIST)	Winterbone, Thiruarooran Wellstead	o Military and civilian o To describe engine response
E-0068-OP-77 pp. 3-249	Simulation of a Turbocharged Diesel Engine to Predict the Transfer Response	John Deere	M. R. Goyal	o Military and civilian o To predict engine performance
E-0059-OP-75 pp. pp.239	Application Engineering Techniques Related to High Performance, Medium Speed Diesel Engines	Mirrlees Blackstone, Ltd.	R. Greenhalgh P. Tooth I.I. Bickley	o Military and civilian o Engine response to load, pressure and temperature
E-0045-C pp. 3-235	Not stated	National Research Council of Canada	F. Rueter A. Swiderski	o Civilian o Performance prediction of a turbocharged 2-cycle free piston diesel engine

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ADVANTAGES	AVAILABILITY	HARDWARE	COST OF OPERATION	VALIDATION	DOCUMENTATION
o Requires less empirical data than other models	From UMIST	PDP-10 CDC-7600	600 CPU/Engine ppm on a PDP10 20 CPU/Engine rpm for a CDC-7600	No	Some
-	Unlikely	Not stated	Not stated	Some	Some
o Accurate predictions of engine performance under new conditions	Unlikely	Not stated	Not stated	None	Some
o A free piston model	From NRC	Electronic Associates Model 690 Hybrid Computer	Not stated	None	Yes

TABLE 2.3.2.9: BOTTOMING CYCLE MODELS

ACCESS NO.	MODEL NAME	ORGANIZATION	AUTHOR(S)	APPLICATION
W-0002-70 pp. 3-251	Boiler Analysis Program (BAP)	Foster-Miller	J. Gerstman (recently modified by I.P. Krepchin)	o Military and civilian o Design and analysis of fired and waste heat boilers
W-0003-74 pp. 3-255	Rankine Cycle, Waste Heat Recovery Engine Performance Model	Thermo-Electron Corporation	F.A. DiBella, C. Wang	o Military and civilian o To determine the full and part load performance of a Rankine cycle system
W-0004-70 pp. 3-259	DRC Modeling (Rankine Bottoming Cycle Engines)	Mechanical Technologies, Inc.	Various	o Civilian o Performance and cost tradeoffs
W-0005-70 pp. 3-261	Brayton Bottoming System (BBS) Evaluation	United Technologies Corporation	Gene Wilmot, et al.	o Civilian o Design and performance calculations of Brayton cycle waste heat recovery systems
W-0006-81 pp. 3-263	Rankine Bottoming Cycle Performance Code	Argonne National Laboratory	Koruzinski; Ash	o Civilian and military o Estimates organized Rankine engine performance

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ADVANTAGES	AVAILABILITY	HARDWARE	COST OF OPERATION	VALIDATION	DOCUMENTATION
-	Fee for use	CYBER 170 VAX 11/780	$.20/run	Yes	Yes
o Versatile with various energy recovery scenarios	Unavailable--must be contracted from Thermo-Electron	Xerox	Not stated	Yes	Maintained by Thermo Electron
Analyses and cost data verified by tests and fabrication	Yes	IBM	Not Stated	Yes	Of results only
o Rapid execution of complex systems	o Proprietary o Indirectly available through contract	IBM 3380	$1/run	Yes	Proprietary manuals
o Useful for general scoping studies	o Needs more documentation prior to release	IBM 3033	$1.50-$2.50 (30-70 cases)	Some	Yes

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TABLE 2.3.2.10: TURBOCHARGING MODELS

ACCESS NO.	MODEL NAME	ORGANIZATION	AUTHOR(S)	APPLICATION	ADVANTAGES
E-0018-TC-77 pp. 3-267	Turbocharged Diesel Engine Simulation to Predict Steady State and Transient Performance	Cummins Engine Co.	A.S. Ghuman, M.A. Iwamuro, and H.C. Weber	o Military and civilian o Turbocharging	o Rapid assessment of parameteric changes
E-0019-TC-77 pp. 3-271	Prediction and Measurement of Two Stroke Cycle Diesel Engine Performance and Smoke at Altitude	Detroit Diesel Allison	Schmidt, Venhuis, and Hinkle	o Military and civilian o Turbocharging	o Rapid calculations
E-0051-TC-76 pp. 3-283	A Non-Linear Digital Simulation of Turbocharged Diesel Engine Under Transient Conditions	Imperial College of Science and Technology	Neil Watson Maged Marzouk	o Military and civilian o Turbocharging	o Appears to be a very powerful model
E-0036-TC-81 pp. 3-279	University of Manchester (UMIST)	University of Manchester	Winterbone, Loo	o Civilian and government o Turbocharging	o Applicable over a wide range of engines and speeds
E-0035-TC-75 pp. 3-275	A Real Time Analogue Computer Simulation of a Turbocharged Diesel Engine	University of Manchester	Benson, Winterbone, Shamsi, Closs, Mortimer, Keynon	o Military and civilian o Turbocharging	

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AVAILABILITY	HARDWARE	COST OF OPERATION	VALIDATION	DOCUMENTATION
Not available	Not stated	1 cpu minute	Some	Some
Refer to source document	o Hand calculator	Negligible	Some	Some
Unknown	Not stated	Not stated	Yes--"Excellent" agreement	Some
Unknown; possibly UMIST	Not stated	Not stated	Some	Some
Not stated	DEC PDP 15	Not stated	Some	Yes

3.0 MODEL CATALOG

TITLE	General Purpose Automotive Vehicle Performance and Economy Simulator (GPSIM)
DATE	Initially 1972 with successive revisions
AUTHORS	William C. Waters
ORGANIZATION	General Motors Corporation
SPONSOR	General Motors Corporation
TRANSPORTATION MODE	Highway
APPLICATION	Civilian
OBJECTIVE	GPSIM is an automotive vehicle simulator designed to compute the operating conditions of the engine and transmission and the performance and economy of the vehicle as the vehicle is operated in a prescribed manner.
REFERENCES	W.C. Waters, "General Purpose Automotive Vehicle Performance and Economy Simulator," SAE Automotive Engineering Congress, Detroit, MI, January 10-14, 1972, SAE Paper # 720043.
RELATIONSHIP TO OTHER MODELS/HISTORY OF MODEL	Vehicle simulation models have been developed and used at GM since 1960. The simulation/modeling program has been under development since then, and has led to GPSIM.
OPERATIONAL CAPABILITIES	GPSIM is used to estimate performance of a vehicle (e.g. acceleration, passing ability), fuel economy over specified driving schedules, and, to a more limited extent, exhaust emissions. GPSIM utilizes a combination of the stabilized vehicle concept and the integration method. In the first case, vehicle performance is calculated as a succession of distinct vehicle performance combinations, and is used to minimize computer time and provide quite acceptable accuracy. In the second case, the vehicle is defined by a set of differential equations driven by various functions. The equations are numerically integrated over time. The integration method is used during rapid vehicle transients. The basic assumptions behind GPSIM are:

- Look-up tables mapping out the various performance regimes can be used instead of a comprehensive set of equations to describe vehicle and component performance and characteristics;

- Steady-state tests can be used to predict dynamic operation because, unless explicitly accounted for, transient conditions are assumed to be short enough to be ignored;

- Hydrodynamic similarity laws apply to the torque converter.

- Simplified shift models can be used to simulate transmission shifts, wherein the amount of energy transferred during the shift is important, but how it is transferred is unimportant; and,

- The steady-state operation of the vehicle is defined by a set of tables that is used to generate more dense intermediate tables for reference during simulation.

Transient conditions modelled are shifts, engine lag due to hydraulic effects in the transmission, and certain gas turbine characteristics. Shifts can be either torque shifts such as from synchro mesh transmissions, or power shifts from automatic transmissions.

GPSIM has two operating modes: COMPUTE or SIMULATE. In the COMPUTE mode, the total or a well-defined subset of the vehicle's performance range and capabilities is characterized, enabling various vehicles to be compared in many respects. The SIMULATE mode generates the operating conditions for the vehicle, engine, and transmission vs. time and distance as the vehicle follows the specified schedule.

DATA INPUT REQUIREMENTS

Typical GPSIM data requirements are:

Engine: torque, fuel rate, throttle, etc.

Transmission: converters and/or clutch, Gear Ratios, Gear Efficiencies, Spin Losses, Inertias, Shift Pattern.

Vehicle: Weight, Frontal Area, Rolling Resistance Coefficients, CG, Location, other Rotational Losses, Driver half inertia.

Axle: Ratio, Efficiency, Additional Rotational Losses.

Tires: Rolling Radius, Contact Efficiency, Wheel Inertia.

Accessories: Alternator, Air Conditioner, etc.

GPSIM has built in data files for many vehicle components and characteristics. The program can be run with a minimum of input data descriptions but can accept more complete data if required.

Data handling features are designed to:

- Reduce input volume required to accomplish a given test;
- Allow user to structure input sequence to fit the problem;
- Simplify data submission rules.

There are various arrangements of data blocks that describe a part of the vehicle, a route, a schedule, or other simulation requirements. Specifications are statements that cause GPSIM to operate on the data in a particular fashion that is somewhat different from the normal methods. Commands can be given to cause particular actions within the program.

ADVANTAGES	The program can simulate a large variety of vehicles, using a set of limited data for proposed vehicle combinations. It can also use component tests from production vehicles to make more accurate computations. Program structure enables many types of simulations or performance calculations using built-in functions or commands. Model is quite comprehensive in its abilities to simulate in detail many aspects of vehicle performance.
FUTURE POTENTIAL	
VALIDATION	Because of the expense involved in running a sufficient number of tests to demonstrate the simulations ability to represent reality, the model has not been validated in this fashion. Limited attempts have been made, and the results of the simulation were within the range of the tests.
COMPUTING REQUIREMENTS	Program is written in PL/1 and is operating on an IBM 360/65. Program has 500 kbytes (8-bit) of machine instructions overlayed in 180 kbytes. Two to nine external online files of 10-300 kbytes are required. Example computation times are 30 sec for computation of intermediate tables, 30 sec to simulate four miles of urban driving and 3 sec to simulate 10 sec of wide-open throttle acceleration.
COST OF OPERATION	Depends on type and degree of simulation.
AVAILABILITY AND COST OF DATA BASE	Program has built-in data for specific components and user can add data for other components.
AVAILABILITY	Proprietary.

TITLE	Heavy Vehicle Simulation (HEVSIM)
DATE	1977, derived from VEHSIM
AUTHORS	Original VEHSIM authors - Withjack, E., Moffat, S., Malliaris, A.
ORGANIZATION	U.S. Department of Transportation
SPONSORS	UMTA, National Highway Traffic Safety Administration (NHTSA), and Society of Automotive Engineers (SAE)
TRANSPORTATION MODE	Highway
APPLICATION	Civilian
OBJECTIVE	The primary objective of this model is to simulate the fuel economy and performance of specified tasks and buses over a given driving schedule.
REFERENCES	SAE 760045; SAE 800215; R.E. Buck, A Computer Program (HEVSIM) for Heavy Duty Vehicle Fuel Economy and Performance Simulation, Volumes 1, 2 and 3.
RELATIONSHIP TO OTHER MODELS/HISTORY OF MODEL	HEVSIM is derived from VEHSIM which was developed at the U.S. Department of Transportation primarily for simulating the fuel economy and performance of specified automobiles.
OPERATIONAL CAPABILITIES	The model is capable of simulating performance and fuel economy of a given truck of bus over any drive schedule. HEVSIM utilizes the method of continuous incremental time step simulation to model the vehicles performance. HEVSIM has three primary modes of operation during a driving cycle; constant acceleration, constant velocity or constant throttle setting.

Output: The major output parameters resulting from the simulation are:
- Fuel economy
- Engine work/mile
- Average brake specific fuel economy
- Average speed
- Emissions (if simulated)
- Energy breakdown
- Work breakdown by various losses

DATA INPUT REQUIREMENTS

Input data are required for the following areas:

Specified Truck or Bus:
- Vehicle
- Engine
- Transmission
- Rear axle
- Tires
- Converter
- Gears
- Accessories

Driving Cycle:
- Driving schedule
- Route
- Shift logic

Input Data Accuracy: The accuracy of the input data reflects the requirements of the SAE specifications as described in the 1983 SAE handbook.

ADVANTAGES

This model has a large degree of flexibility in specifying the input and output parameters.

VALIDATION

This simulation process is currently being evaluated for validation. Battelle is performing sensitivity tests on bus components at TRC in Ohio. Results are expected in September 1983.

COMPUTING REQUIREMENTS	The model lode is Fortran 10 and the system used is the DEC 10. To date the program has been converted to use on DEC 20 and IBM systems with some difficulty.
COST OF OPERATION	The computer time cost is approximately $25, depending on the specification of the particular case to be run.
FUTURE POTENTIAL	No modifications are planned at this time.
AVAILABILITY	All bus data used is proprietary to the manufacturer but has been available to DOT with that constraint. This program is available free of charge.

TITLE	Ford Motor Company Dynamic Model
DATE	1981
AUTHORS	R.G. Delosh, K.J. Brewer, L.H. Buch, T.F.W. Ferguson, W.E. Tobler
ORGANIZATION	Ford Motor Company
SPONSOR	Ford Motor Company
TRANSPORTATION MODE	Highway
APPLICATION	Civilian
OBJECTIVE	The computer dynamic simulation is capable of modelling the engine, control system, and drive-train. It simulates the dynamic behavior of the total vehicle system for warm engine emissions and fuel consumption for the Federal Test Procedure and other driving cycles, and vehicle driveability and performance. Output permits detailed analysis of various factors influencing system performance. Generally is used to analyze vehicles on board computer system and vehicle performance due to changes in control features (engine, transmission, etc.).
REFERENCES	R.G. Delosh, et. al., "Dynamic Computer Simulation of a Vehicle with Electronic Engine Control," SAE Paper 810447; L.T. Wong, and W.J. Clemens, "Power-train Matching for Better Fuel Economy, "SAE Paper 790045; P.N. Blumberg, "Powertrain Simulation: A Tool for the Design and Evaluation of Engine Control Strategies in Vehicles," SAE Paper 760158; D.N. Hwang, "Fundamental Parameters of Vehicle Fuel Economy and Acceleration," SAE Paper 690541.
RELATIONSHIP TO OTHER MODELS/HISTORY OF MODEL	Model has been progressively developed as detailed in the References given above.
OPERATIONAL CAPABILITIES	The model consists of more than sixty linked sub-routines to simulate various components, control strategies, and other operational activities. The model is a mixture of physical and regression based submodels. In physical models, phenomena are described by physical process and properties. In regression models, complex phenomena are described

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by equations derived from regression data. The model is capable of analyzing engine operation, including power, torque, fuel flow, temperatures, emissions, drivetrain, including transmission, tires, axle and driveshaft, and gear shifting, and engine controls, including electronic systems.

DATA INPUT REQUIREMENTS

The model can be used by a non-expert with minimal computer experience. The program asks the user a series of questions to determine the test description, system and component specifications, control strategy requirements, and engine calibration. This procedure also determines output type. Each component requires rather extensive input data to describe its operation.

ADVANTAGES

The models appear to have particular relevance to design and analysis of electronic engine control systems. Dynamic programming techniques are used to optimize system performance.

FUTURE POTENTIAL

Model has been continuously upgraded to meet changing requirements.

VALIDATION

Extensive model verification has been done at four levels:

- Bench testing of individual components;
- Engine dynamometer testing of components and subsystems;
- Vehicle testing of subsystems over the FTP cycle; and
- Overall vehicle system function testing.

Agreement is quite good.

COMPUTING REQUIREMENTS

Model is implemented on DEC-System 2050. Written in structured Fortran.

COST OF OPERATION

Model uses about 9-10 sec up to 30 sec of computer time to simulate one second of vehicle system operation. Total drive cycle could be fairly expensive to run.

AVAILABILITY

Proprietary but could be accessible by outside users.

TITLE	Testing Operations Fuel Economy Program (TOFEP)
DATE	1981
AUTHORS	Contacts: Dave Wernette, John Manning, Joe Greenbaum
ORGANIZATION	Ford Motor Company
SPONSOR	Ford Motor Company
TRANSPORTATION MODE	Highway
APPLICATION	Civilian
OBJECTIVE	Primary purpose of TOFEP is the evaluation of fuel and performance effects of powertrain changes. A secondary purpose is the prediction of absolute fuel economy and performance.
REFERENCES	D.J. Bickerstaff, "Light Truck Fuel Economy by Design Efficiency," SAE, 1978.
HISTORY OF MODEL	Based on continuing program development.
OPERATIONAL CAPABILITIES	A vehicle is modelled and the model is put through a series of fuel economy cycles and performance tests. The model is used primarily to evaluate alternatives in vehicle performance rather than to determine absolute vehicle characteristics. Model does a second-by-second simulation of vehicle performance based on a specified driving cycle and component and system performance specifications. Emissions modelling is being developed.

Basic types of use for the model are:

- Comparison of multiple vehicle alternatives sharing a common engine;

- Comparison of different powertrains having different engines; and,

- Projection of fuel economy and performance.

DATA INPUT REQUIREMENTS

Model requires large quantity of input data, essentially a fairly complete description of a vehicle, i.e.:

- Vehicle physical description
- Engine information
- Transmission information
- Other drivetrain information.

ADVANTAGES/DISADVANTAGES

Program can be used in all phases of powertrain optimization. Model exhibits some inaccuracies in representing transient conditions, particularly at low speeds (0-10 mph).

FUTURE POTENTIAL

Emissions modeling is being developed. A new comprehensive model called CVSP is being developed by Dick Radtke and Phil Tuchynski.

VALIDATION

Not directly used for economy predictions because test results were not particularly good; performance results fairly good.

COMPUTING REQUIREMENTS

Fortran 77 program runs on Honeywell/DEC machines.

COST OF OPERATION

Depends on number of iterations. Less than minute CPU time.

AVAILABILITY AND COST OF DATA BASE

Engine maps must be developed based on bench tests. Other components must be specified based on tests at various operating conditions.

AVAILABILITY

Corporate proprietary.

TITLE	Automotive Simulator (ASIM)
DATE	August 1978
AUTHORS	E.M. Withjack
ORGANIZATION	U.S. Department of Transportation Transportation Systems Center Cambridge, Massachusetts
SPONSOR	U.S. Department of Transportation
TRANSPORTATION MODE	Highway - Automobile
APPLICATION	Civilian
OBJECTIVE	ASIM is an engineering tool for evaluation of automotive fuel economy and performance.
REFERENCES	E.M. Withjack, "A Description and User's Guide to the Automotive Simulator ASIM," Project Memorandum No. DOT-TSC-HS827-PM-78, U.S. Department of Transportation, Transportation Systems Center, Cambridge, MA, August 15, 1978.
HISTORY OF MODEL	ASIM is a more versatile version of an original program by K. Hegenrother and A.C. Malliaris.
OPERATIONAL CAPABILITIES	ASIM utilizes a continuous simulation approach in which initial vehicle conditions are set up, and at time intervals new vehicle conditions are computed using appropriate driving schedule data. Output is basically a summary of fuel economy. Performance values related to segments of the driving cycle, and other factors concerning engine performance, drivetrain efficiency, and fuel flow.
DATA INPUT REQUIREMENTS	Input data required is not particularly sophisticated, but each particular part must be described. The simulation parts requiring descriptions are: - Automobile; - The drive cycle; - Transmission - Shift logic.

ADVANTAGES	This program executes rapidly and is easy to operate. Data input requirements are not extensive or difficult. Primary use is for an evaluative engineering tool.
VALIDATION	The program was validated against DOT's VEHSIM (vehicle simulator) model, and was also validated against EPA certification test data. Validation is reported in SAE 760157.
FUTURE POTENTIAL	The model is currently out of use by DOT or any other organization.
COMPUTING REQUIREMENTS	Program is in FORTRAN and is not excessively large. Can be run on interactive system.
COST OF OPERATION	The program is relatively inexpensive to run.
AVAILABILITY	Program listing is available.

TITLE	Vehicle Mission Simulation (VMS)
DATE	1976
AUTHORS	D.A. Klokkenga
ORGANIZATION	Cummins Engine Company, Inc. Columbia, IN
SPONSOR	Cummins Engine Company, Inc.
TRANSPORTATION MODE	Highway Trucks
APPLICATION	Civilian
OBJECTIVE	The model is intended to provide sufficient truck performance information so that a user can make choices among alternative configurations.
REFERENCES	D.A. Klokkenga, "Selecting Powertrain Components for Heavy Duty Trucks" SAE 760830; P.W. Schutz, D.A. Klokkenga, and D.B. Stattenfield, "Vehicle Mission Simulation," SAE Paper 700567.
HISTORY OF MODEL	Originally built in late 60's.
OPERATIONAL CAPABILITIES	The program uses a specified route and its characteristics (grades, distances, speeds, etc.) to drive the vehicle simulation (gear changes, throttle required, fuel flow, engine load, etc.). At the end of the finite-time-step simulation, incremental performance characteristics are added to generate the summary of performance. Primary output data are driving time, average speed, fuel used, fuel mileage, percent of time at full throttle, engine load factor, and number of gear shifts. This can be done for different trucks to facilitate performance comparisons.
DATA INPUT REQUIREMENTS	The vehicle must be specified by weight, aerodynamic characteristics, and rolling resistance. The engine is described by a torque-throttle fuel flow map. The transmission gear, torque, and shift characteristics are given. Other drivetrain brake data are also needed. The driving route is specified in detail, with distances, grades, speeds, and starts/stops given. Wind is an input to use in aerodynamic calculations.

ADVANTAGES	The model is oriented particularly to truck performance over generalized driving routes. It is useful in helping truck operators choose among options for equipment on their particular routes. The model has a variable time increment to increase for computational efficiency. Model includes database for 140,000 miles of highway driving routes.
FUTURE POTENTIAL	Work progresses on expanding capabilities, in particular automatic transmissions, lighter vehicles, and urban congestion.
VALIDATION	Fairly well validated by actual road tests.
COMPUTING REQUIREMENTS	Uses Honeywell DPS/8 CP/6 op system 2 megabytes storage.
COST OF OPERATION	In proportion to length and complexity of route (less than 10 min CPU will almost all cases).
AVAILABILITY AND COST	Can be sold as service in certain circumstances.
AVAILABILITY	Code is proprietary.

TITLE	Truck Computer Analysis of Performance and Economy (TCAPE)
DATE	Announced in 1978.
AUTHORS	Many contributors.
ORGANIZATION	International Harvester Truck Group
SPONSOR	International Harvester Corporation
TRANSPORTATION MODE	Highway and off-highway.
APPLICATION	All applications of large and small trucks and similar vehicles.

OBJECTIVE

The primary use of this model is for sales promotion of IH trucks. Optimization of specifications for IH trucks prior to purchase by users through dealers with or without direct user input is a part of this promotion.

Output: The major output parameters resulting from the simulation are:

- An echo of the input data on the same page as output.
- A table of miles per gallon, average mph, and mission minutes for three selected routes, city, suburban, and highway.
  - City: 9.42 miles, 20 to 45 mph speed limit, 12 stops
  - Suburban: 34.5 miles, 25 to 55 mph speed limit, 7 stops
  - Highway: 157.76 miles, 35 5o 68 mph speed limit, 2 stops
- A table of vehicle speed (mph), engine speed (rpm) wheel power (HP) and gradeability for each gear at each of four different engine speeds: clutching rpm, peak torque rpm, rpm from which engine will be at governed rpm in the next lower gear and governed rpm (or maximum recommended

rpm if the engine does not use a governor). This table can be in graphical form if the user has access to a suitable terminal with a cathode ray tube (CRT terminal).

- An in-process table to help the user select the proper axle ratio. It shows geared speed (mph), engine power available, road load power required and reserve power available (all at the wheels in top gear) for each axle ratio available for the selected axle code. It also shows maximum low gear gradeability for the selected codes (axle and transmission) for each available axle ratio.

REFERENCES

IH Truck Group Product Bulletins, most recent CT-623Y, dated March 1983, includes descriptions of TCAPE and use manual.

RELATIONSHIP TO OTHER MODELS

Although it uses an entirely separate program, TCAPE shares some component library files with TRUKSIM and is based on the same background of simulation expertise.

HISTORY OF MODEL

TCAPE was announced in 1978 as a new program designed specifically for sales promotion. Changes since 1978 have been made only at specific intervals. It was preceded by some simple performance simulations.

OPERATIONAL CAPABILITIES

TCAPE is arbitrarily limited to three routes, two types of tires (or a mixture of these two), fixed ambient air conditions, and one driver pattern, but has an extremely wide variety of component variations. The purpose of the simulation is primarily to show the effects of changes in components.

ASSUMPTIONS

The major assumptions in the model are that transient events are simulated by steady-state minor increments in one mph steps. TRUKSIM allows the user to specify smaller steps and has demonstrated that one mph gives good results for TCAPE.

LIMITATIONS

Described under Operational Capabilities.

DATA INPUT REQUIREMENTS

As inputs, the interactive program asks the user a minimum of 23 questions with up to 32 questions depending on the responses given. As of March 23, 1983, there were 313 engine libraries, 214 main transmission libraries, 32 auxiliary transmission or transfer case libraries and 100 driving axle libraries in the component files. Any number of the 32 input variables can be changed for subsequent cases.

Accuracy: TCAPE is intended to show the effect of changes in specifications prior to purchase of vehicles and is not intended to reflect differences in ambient air conditions, driver patterns, nor specific route differences. To show these effects, refer to TRUKSIM (H-0025-81).

Input Data Accuracy: The accuracy of the input data requirements reflect:

- Improved availability of data from component suppliers determined using the new SAE test procedures:
  - Engines: J1312 (also J1349 and J816b)
  - Tires: J1379 (also J1380)
  - Aero: J1252
  - Driveline: J643b, J651c, J1266 and another for manual transmissions
  - Fans and Accessories: J56, J1339, J1340, J1341, J1342, and J1343
- Onboard recording, in sequence, of driver choice patterns for a variety of drivers on a variety of routes with a variety of vehicles.

ADVANTAGES

It is specifically designed for easy usage as a sales promotion tool. It is easily accessible by any interested customer or user through the IH truck dealer network.

VALIDATION

Results have been "verified by thousands of miles of actual truck usage" in user's normal operations. Twenty comparisons compiled for the original 1978 announcement shows absolute values 6 percent low to 5 percent high averaging a conservative 1.5 percent low. Relative results are even closer.

COMPUTING REQUIREMENTS	The program is written in Fortran on a Digital Equipment computer. Output is in tabular form unless a CRT terminal is available to the user.
COST OF OPERATION	Cost information is proprietary. User access (customer access) is available through the IH truck dealer network at no charge.
FUTURE POTENTIAL	Modifications will be made as needed, but only at well advertised intervals. Component library files are added or deleted at any time.
AVAILABILITY	Cost information on the data base and the component data files are proprietary. TCAPE can be accessed through IH Truck Group and IH truck dealers, but has not been made available outside IH. Negotiations for sale of the program might be possible.

TITLE	Hybrid and Electric Advanced Vehicle Systems (HEAVY) Simulation
DATE	November 1981
AUTHORS	Ronald A. Hammond Richard K. McGehee
ORGANIZATION	Boeing Computer Services Company Energy Technology Applications Division 565 Andover Park, West Tukwila, WA 98188
SPONSOR	U.S. Department of Energy Conservation and Renewable Energy Office of Vehicle Engine R&D Energy and Aero Branch Energy Section NASA Lewis Research Center (Mr. Raymond Beach, P.O.)
TRANSPORTATION MODE	Highway
APPLICATION	Civilian
OBJECTIVE	HEAVY is used to evaluate electric and hybrid vehicle propulsion systems by predicting the performance of a proposed drive train using a library of predefined component models.
REFERENCES	Final Report - Hybrid and Electric Advanced Vehicle Systems (HEAVY) Simulation, R.A. Hammond and R.K McGehee, U.S. Department of Energy, Washington, D.C., November 1981, NASA CR-165536, DOE/NASA/0151-1, BCS 40357 Hammond, R.A. and R.K. McGehee, "User's Guide to the Hybrid and Electric Advanced Vehicle Systems (HEAVY) Simulation," NASA Contract DEN 3-151, September 1981.
HISTORY OF MODEL	This model is a modification of the SIMWEST computer program.

OPERATIONAL CAPABILITIES

This model is intended for use early in the design process to:

- Evaluate concepts
- Compare alternatives
- Do preliminary designs
- Develop strategies for control and management
- Size components
- Do sensitivity studies

The model has component library that contains data for typical components in a vehicle drive train. The user can select drive system components and the model will formulate the complete vehicle and drive train. A simulation of vehicle performance is done based on specification of trip duration, driving cycle, and output data required. The model is general enough so that it can be effectively used by analysts and designers with little programming or simulation experience. Furthermore, a set of predefined, typical baseline vehicles contained within the program enables the user to make simple changes to a known data set in order to create a desired vehicle.

DATA INPUT REQUIREMENTS

The model contains descriptions of system components and simulation conditions. The user selects the desired components and organizes them into the vehicle system. Default values for many of the system components or operational parameters enable the user to bypass specific data inputs; however, if desired, the user may modify or specify values. Required values are prompted by the system and the user makes the choice whether to use or change default values.

ADVANTAGES

The advantages of this system are:

- Simple to use since it requires the analyst to make few data specifications;

- Built in system components, description, and operational descriptions;
- Model structure and language that is user oriented
- User specifies required output
- Multiple simulations in one computer run

FUTURE POTENTIAL

Activity has been limited since the 1981 report, but there is presently interest in modifying the model to run on desktop computers. A parameter optimization capability is also of interest.

VALIDATION

Model was compared to an ETV-1 drivetrain on the Cleveland road load simulator.

COMPUTING REQUIREMENTS

Code is available through COSMIC (Computer Program Library) for application on CDC CYBER computers. Code is in Fortran 66, and is 12000 lines long. Requires a minimum of 70k Octal storage. Also available through Boeing Computer Service timesharing system.

COST OF OPERATION

Cost is minimal--on the order of a dollar for individual cases.

AVAILABILITY AND COST OF DATA BASE

Data is contained within program or user can specify other values.

AVAILABILITY

(See Computer requirements above).

C-2

TITLE	Transient System Optimization (TSO)
DATE	1978
AUTHOR	Alan R. Dohner
ORGANIZATION	General Motors Research Laboratory
SPONSOR	General Motors Corporation
TRANSPORTATION MODE	Highway
APPLICATION	Civilian
OBJECTIVE	To optimize fuel economy subject to emissions constraints by accounting for transient system interactions, cold start/warm up, exhaust after treatment, driveability, and other phenomena.
REFERENCES	Transient System Optimization of an Experimental Engine Control System Over the Federal Emissions Driving Schedule, Alan R. Dohner, SAE Technical Paper 780286, February/March 1979.
RELATIONSHIP TO OTHER MODELS/HISTORY OF MODEL	Several theoretical treatments of the problem consider the steady-state vehicle operation during the Federal Test Procedure (FTP). This procedure extends to the transient behavior of the vehicle.
OPERATIONAL CAPABILITIES	The model procedure applies control/optimization in theory to an engine-controller-vehicle-catalytic converter system and methodically improves the feedback control functions with respect to fuel economy, emissions, and driveability constraints. This is an iteration model that uses actual test data rather than mathematical data to formulate improved feedback control functions. By applying the method to successive tests and by adjusting control variables, optimization is achieved. The experimental basis is used because realistic mathematical models do not exist (1978) to analyze transient performance. Parameter values acquired during a test are subjected to gradient optimization methods and increasingly better control is achieved. The end result is optimal control over the given cycle (FTP) to maximize fuel economy while controlling emissions.

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DATA INPUT REQUIREMENTS	From a test cell set-up consisting of an engine, transmission, catalytic converter, dynomometer (vehicle simulator), engine control computer, and automatic driver, a data acquisition records fuel flow, emissions, airflow, spark advance, speed, EGR, temperatures, and other engine/accessory parameters.
ADVANTAGES	The primary advantages of this model are that it considers transient system operation and that it can utilize actual test data rather than relying on as-yet (1978) undeveloped mathematical models of transient system operation.
FUTURE POTENTIAL	Extensions of the model to include control of EGR.
VALIDATION	System is applied to actual tests and results are immediately evident under actual operating conditions.
COMPUTING REQUIREMENTS	
COST OF OPERATION	
AVAILABILITY AND COST OF DATA BASE	Data comes from actual tests.
AVAILABILITY	Proprietary.

TITLE	Diesel Urban Bus Simulation Program
DATE	April 1979
AUTHORS	G. Larson, H. Zuckerberg
ORGANIZATION	U.S. Department of Transportation, Research and Special Programs Administration, Transportation Systems Center, Cambridge, MA 02142
SPONSOR	U.S. Department of Transportation Urban Mass Transportation Administration Office of Technology Development and Deployment Washington, D.C. 20590
TRANSPORTATION MODE	Highway
APPLICATION	Civilian
OBJECTIVE	The Diesel Urban Bus Simulation Program is designed to assess the performance and fuel consumption of buses under various operating conditions and with various power drives.
REFERENCES	Diesel Bus Performance Simulation Program, Final Report, G. Larson and H. Zuckerberg, U.S. Department of Transportation Systems Center, Cambridge, MA, April, 1979, Report No. UMTA-MA-06-0044-79-1. NTIS PB-295-524.
RELATIONSHIP TO OTHER MODELS/HISTORY OF MODEL	Modeling technique similar to that described by Beachley, N.H. and Frank, A.A., "Digital Automotive Propulsion Simulator Programs and description, "Vol. II, Department of Electrical and Computer Engineering, University of Wisconsin-Madison, Contract No. DOT-OS-30112, December, 1974.
OPERATIONAL CAPABILITIES	The program was developed to simulate all elements of the power drive subsystem for transit bus operation over a given drive cycle. This is done by: - Determining sequence of engine operating conditions for each moment during the drive cycle; - Determining the instantaneous fuel flow;

- Integrating fuel flow and velocity vs. time to obtain total fuel consumed and total distance travelled;

- Estimating fuel economy and emissions.

Power levels are computed using drive cycle data, vehicle friction, aerodynamic drag, inertial acceleration, rotational inertias, rotational speeds and torques, and component performance characteristics. The driving cycle segments are specified - length, grade, dwell time or idling time; and desired vehicle cruise speed. Output includes torque and horsepower, velocity and acceleration, engine speed, fuel consumption and emissions.

DATA INPUT REQUIREMENTS

Input specifies the vehicle, driving cycle configuration, route terrain profile. Inputs are vehicle data, engine performance data, power drive characteristics, acceleration, cruising speed, deceleration, vehicle idle time at stops, number of stops per mile, grade profile along route, head or tail winds, and adhesion characteristics between tires and road.

ADVANTAGES

The model is straightforward in achieving its intended purpose and has no apparent advantages.

FUTURE POTENTIAL

VALIDATION

Model results have been compared to fuel economy test results for actual buses following prescribed driving cycles. Agreement is quite good.

COMPUTING REQUIREMENTS

Model written in Fortran IV. A Model 663 Calcomp Plotter and associated software provide graphic output. Storage requirements depend on number of drive cycle segments used in each run.

COST OF OPERATION

AVAILABILITY AND COST OF DATA BASE

Data is contained within program or user can specify other values.

AVAILABILITY

Available in reference.

TITLE	DSLSIM (Diesel Engine Control Systems Computer Simulation Model)
DATE	1980
AUTHORS	D. Wormley, J. Nye, J. Rife
ORGANIZATION	Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA
SPONSOR	Hamilton Standard Division of United Technologies Corporation
TRANSPORTATION MODE	Highway
APPLICATIONS	Civilian
OBJECTIVE	• Identification of control and performance characteristics for light and heavy duty diesel engines to meet 1980-1985 requirements of fuel economy, emissions, driveability • Define control system performance. • Develop basic control system configurations.
REFERENCES	
RELATIONSHIP TO OTHER MODELS/HISTORY OF MODEL	
OPERATIONAL CAPABILITIES	Models primary purpose is for investigating control strategies for engine operations, fuel economy, performance, and emissions. The model can analyze turbocharged or normally aspirated engines. Standard, automatic, or continuous gearing transmissions can be handled. Various velocity profiles, including EPA FTP, Fuel Economy test, or other user specified velocity profiles can be modelled. Output includes up to 27 engine and vehicle parameters as well initial conditions and final cumulative fuel economy and emissions. Data can be stored in a file. Plots of any of the variables can be made.

DATA INPUT REQUIREMENTS	The engine is represented by a quasi-static engine map (power, speed, torque, emissions, fuel flow, etc.). The transmission is represented by masses, friction, mechanical efficiencies, and shift points. Driving cycles initiate the calculation procedure by specifying vehicle velocity as a function of time.
ADVANTAGES	Model can provide output in many different representations and can accommodate a range of engine and transmission options.
VALIDATION	Simulation results have been compared to actual test results for EPA driving cycles. Areas for improvement are noticeable; however, some parameters agree fairly well.
COMPUTING REQUIREMENTS	VAX computer.
COST OF OPERATION	
FUTURE POTENTIAL	No follow-up work has been done.
AVAILABILITY	Proprietary.

TITLE	A Simplified Program for Evaluating Diesel Truck Performance
DATE	Basic program dates back to December 1980. Latest modification in March 1983.
AUTHOR	Greenwald, L.E.
ORGANIZATION	United Technologies Research Center
SPONSOR	Corporate
TRANSPORTATION MODE	Highway
APPLICATION	Primarily civilian but could be applied to military.
OBJECTIVE	The primary objective of this model is to aid in the processes of driveline selection, engine sizing, and parametric evaluation of driving cycle economy for large diesel trucks. Output: The major output parameters resulting from the simulation are: - Vehicle performance (grade capability, engine speed, available and required power). - Fuel economy. - Average speed and total cycle distance. - Emissions (requires additional input).
REFERENCES	No formal documentation available.
HISTORY OF MODEL	The model is one of a number of powertrain simulation programs developed by the United Technologies Research Center for the purposes of evaluating automotive engine and drivetrain concepts at the systems level.

OPERATIONAL CAPABILITIES

The basic dynamical equations are Newton's Laws which are common to all drivetrain simulations. It is the specific application as well as specialized graphics and output routines which make the model unique.

The model's capabilities are:

- Applicability to all vehicles with manual transmissions, including gasoline powered.
- Quasi steady-stated dynamics.
- All vehicle, chassis, and engine map parameters can be varied.
- Hard copy computer graphics output of vehicle performance.
- Versatility in synthesizing arbitrary driving cycles.

ASSUMPTIONS

The major assumptions are:

- Quasi steady-state dynamics.
- Simple gear shifting laws.

LIMITATIONS

The transient operation is ignored; this introduces error if a significant portion of the driving cycle cannot be approximated by steady-state operation.

DATA INPUT REQUIREMENTS

The data required as input to the model are:

- Vehicle and chassis data (weight, rolling distance, drag coefficient, wheel radius, etc.).
- Engine data (maximum torque curve and fuel flow map).
- Driving cycle specification.

Accuracy: No changes needed or anticipated.

Input Data Accuracy: The accuracy of the input data must be with ±5 percent.

ADVANTAGES

The advantages of this model are:

- Very rapid execution time (3 sec) making it desirable for systems level or parametric design and evaluation studies.
- Ease of operation (interactive or batch mode).
- Simple input (amount and format).
- Graphical output of vehicle performance, engine maps, and other data.

VALIDATION

The model is currently being validated. Some portions of model have been substantiated at this time.

COMPUTING REQUIREMENTS

The model code is written in Fortran 77 and currently run on a Univac 1100/81A.

COST OF OPERATION

The model requires approximately 3 sec per case on the Univac.

Costs would be user and application dependent. Truck chassis data is inexpensive and easy to obtain or approximate. The cost of engine maps depends on whether they can be approximated from the literature, must be obtained from test cells, etc. Engine map library for present use is proprietary, but any engine can be used as input to program.

FUTURE POTENTIAL

The model is continuously tailored for specific studies as the need arises.

AVAILABILITY

This model is proprietary to United Technologies. It is available for use in funded and internal studies. It is being used on current NASA/DOE program.

TITLE	TRUKSIM
DATE	Predecessor program ENG 008 in 1961-1962. Name changed, graphics added and made interactive in 1981.
AUTHORS	Bracht, P.L., with many contributors.
ORGANIZATION	International Harvester Truck Group (IH).
SPONSOR	International Harvester.
TRANSPORTATION MODE	Highway and off-highway.
APPLICATION	All applications of large and small trucks and similar vehicles.
OBJECTIVE	The primary use of this model is for internal engineering analysis and development; in addition special user applications are also performed. It is capable of simulation of day-to-day vehicle tests.

Output:
- The primary output from a route simulation is a summary page, usually a hard copy from a CRT terminal. There are also six optional tabulations and five optional graphical outputs currently available. Included in the output is:

Tabular Output:
- Summary page with line-by-line major increments.
- Engine fuel map.
- Numbers of upshifts and downshifts to each gear at various torque levels.
- Time and number of cycles in each gear at various torque levels.
- Matrix of time and percent of time in rpm bands for each gear.
- Energy audit - HP-hours energy to each end dissipation location.

Graphical Output:
- Gradeability - Wheel HP available and required for each gear and a series of grades vs. mph.
- Acceleration Performance - MPH and distance versus time on a specified grade.
- Steady-State Fuel Economy - MPH vs. vehicle mph, all gears, clutching rpm to governor run-out rpm.
- Gear Selection Chart - Engine rpm vs. mph for all gears.
- Engine fuel map.

REFERENCES

None published outside IH.

RELATIONSHIP TO OTHER MODELS

TRUKSIM was derived directly from ENG 008 and shares some component library files with TCAPE. Due to the large number of variables which can be modified for both hardware and driver or route variations, it is equivalent to a whole series of more rigid simulation programs.

HISTORY OF MODEL

The original program developed in 1961-62 was titled ENG 008 and used machine language in batch mode only with tabular output. It has been continuously upgraded and improved. In 1981, a major change was made to an interactive mode and cathode tube graphic output and it became known as TRUKSIM.

OPERATIONAL CAPABILITIES

The model has capabilities for both steady-state and transient operation.

Routes are divided into major increments of constant grade (+, - or 0) with assigned distance, initial speed limit and final speed limit for each of these major increments. Steady-state periods are combined with transient accelerations and decelerations, each calculated as a series of minor increments of one mph change. Smaller mph increments are optional to the user.

ASSUMPTIONS

It is assumed that transient operations can be accurately simulated by a series of steady-state minor increments which have a small mph change from one minor increment to the next. The magnitude of the mph change can be selected by the user.

LIMITATIONS

A limitation of the current model is that certain drivers' vehicle operation at times cannot be exactly simulated with the existing simulation options. More exact optional simulation of these would produce minor changes in the performance and economy calculated.

DATA INPUT REQUIREMENTS

The user must furnish answers to a minimum of 57 questions up to 133 questions depending on the responses given for the various optional choices.

Inputs include:
- Engine type and related data
- Transmissions
- Rear axle
- Body and trailer specifications
- Tire size
- Weights
- Shifting data
- Climate conditions (temperature, humidity, and wind)
- Accessories installed
- Driving cycle

Data Input Accuracy: The accuracy of the input data requirements reflect:

- Improved availability of data from component suppliers determined using the new SAE test procedures.
  - Engines: J1312 (also J1349 and J816b)
  - Tires: J1379 (also J1380)
  - Aero: J1252
  - Driveline: J643b, J651c, J1266 and another for manual transmissions.
  - Fans and Accessories: J56, J1339, J1340, J1341, J1342 and J1343.

- Onboard recording, in sequence, of driver choice patterns for a variety of drivers on a variety of routes with a variety of vehicles.

Accuracy: The long term development of the model has resulted in flexibility in input data, route data and optional driver variations such that final accuracy now depends very little on the model. Absolute accuracy depends on knowledge of all of the 57 to 133 input variables. Relative accuracy depends on knowledge of only those variables directly involved in a specific vehicle change. The input variables can be classified:

Descriptive of Exact Mathematically - 22 to 66 items (such as gear and axle ratios).

Reasonably Accurate Input Available - 6 to 26 items (such as gross weight and frontal area).

Driver Choices - 9 to 15 items (such as "Does the driver observe the speed limits?").

Difficult to Obtain Accurate Data - 7 to 13 items.

The vehicle related items that are most critical to absolute accuracy (difficult to obtain and wich a large effect) are tire rolling resistance and drag coefficients in the presence of wind at some yaw angle. On some routes with lower road speeds differences in driver extremes can double the fuel consumption.

ADVANTAGES

An advantage to this model is the extreme flexibility with optional procedures, assumptions, and a large library. New routes and/or components can be readily added once data is available. Changes in the program, the assumptions or the output can be made by IH whenever needed without accountability outside IH.

VALIDATION

Virtually all highway fuel economy tests run on controlled route profiles by IH Truck Group Engineering have been simulated as well as many fleet average results furnished by IH customers. When the critical input parameters and driver habits can be based on measured rather than on estimated input values, agreement close to two percent or better is expected. More typically, some of the parameters must be estimated. Even then, the effect of a change in a single component can be predicted with excellent accuracy if the parameters for the particular component (original and alternate) are well known.

COMPUTING REQUIREMENTS

The simulation program written in Fortran has been adapted to several different computer hardware systems, usually Digital Equipment or IBM.

COST OF OPERATION

Computers which can handle the program at all can complete the simulation calculations in a few seconds even on a complicated route. The interactive input/output time depends on the skill of the user, but is usually several minutes. Many manhours may be required to accumulate the input information. Exact cost information is proprietary.

FUTURE POTENTIAL

Continued enhancement whenever needed.

AVAILABILITY

This model is used by Truck Group Engineering. The program and the library files are competitive proprietary tools and to date have not been offered for use outside IH. Negotiations for sale of the program might be possible.

TITLE	USCG Icebreaker Propulsion System Simulation, Program No. ENE-11
DATE	Completed August 1968
AUTHORS	Lt. J.W. Lewis, USCG; LCDR E.J. Lecourt, USCG; F.W. Scoville, CONSULTEC
ORGANIZATION	U.S. Coast Guard Headquarters, Office of Engineering, Icebreaker Design Branch
SPONSOR	U.S. Coast Guard
TRANSPORTATION MODE	Marine
APPLICATION	• Icebreakers; Ice-strengthened cargo and service ships. • civilian and military.
OBJECTIVE	Powertrain design analysis and evaluation of alternatives.
REFERENCES	• Lewis, J.W., Lecourt, E.J., United States Coast Guard Icebreaker Propulsion System Simulation, United States Coast Guard, Office of Engineering, Phase I, II, III, IV, 1967-69. • Major, R.A., Kotras, T.V., Lawrence, R.G.A., Digital Simulation of a Diesel AC-DC Icebreaker Propulsion Systems
RELATIONSHIP TO OTHER MODELS	The model is an assemblage of accepted relationships between ship motion, shaft and propeller motion, motor controller, generator and motor armature currents, generator field, diesel engine with governor, and bridge controller.
HISTORY OF MODEL	A design project of a 12,000 ton 20,000 SHP icebreaker (M-13) generated the need for this simulation.
OPERATIONAL CAPABILITIES	The model can be adapted for diesel-electric propulsion of any ship. The modular form permits changes in components and loading.

ASSUMPTIONS	Various simplifying assumptions are implicit in the relationships used in the model. Others can be introduced via the Initial Conditions. Assumptions concerning component characteristics can be introduced via the Input Data.
LIMITATIONS	No direct fuel efficiency output is provided, nor is there a built-in optimization procedure. Integration of the diesel power over time would provide a measure of fuel consumption for a given maneuver under specified conditions. Optimization must be done by comparison of the results of individual runs.
DATA INPUT REQUIREMENTS	104 data cards (up to 7 values on each) are required to describe all system components, plus definition of Initial Conditions. The fifth section of the report gives instructions for each of the 104 data cards.
ADVANTAGES	The model describes relationships in sufficient detail that a wide variety of diesel-electric systems may be simulated.
VALIDATION	The icebreaker model has been compared to and calibrated by USCGC GLACIER performance data with good results. Extrapolation into other ship types would require similar procedure.
COMPUTING REQUIREMENTS	Developed for use on an IBM 1130, with disk in Fortran IV.
COST OF OPERATION	Proportional to length of maneuver and the time steps used (.08 sec to .20 sec). About 7 minutes of computer time for 15 seconds of ship time, i.e., about 28 sec computer time per 1 second real time.
FUTURE POTENTIAL	A library of subroutines and input data for different types of components can be assembled to make the program flexible and useful for a wide range of diesel-electric ships.
AVAILABILITY	Unclassified and in the public domain available from Defense Technical Information Center, Defense Logistics Agency. A full program listing is given in the report (Phases I to IV plus a volume entitled Ship Design and Maintenance Computer Program).

TITLE	A Method of Predicting the Speed Reduction of Turbocharged Marine Diesel Engines (in German)
DATE	Published 1978 (Motortechnische Zeitschrift)
AUTHORS	Michael Grohn, Prof. Dr. Ing., Klaus Groth
ORGANIZATION	University of Hannover
SPONSOR	Research funding from the government of Lower Saxony
TRANSPORTATION MODE	Marine
APPLICATION	• Medium speed, 4 cycle, marine diesels loaded by a fixed propeller. • Civilian and military.
OBJECTIVE	Design and sizing of turbochargers for engines with marine propeller loading.
REFERENCES	Grohn, Michael, Ein Verfahren Zur Ermittlung der Drehzahlaruckung aufgeladner Hochlerstungs-Schiffsdieselmotoren, Motortechnsiche Zeitschrift 39 (1978) 9.
RELATIONSHIP TO OTHER MODELS	Five thermodynamic systems are included: power cylinder; exhaust manifold; air receiver; compressor; exhaust turbine. The simulation basically is on an energy and mass exchange formulation.
HISTORY OF MODEL	Apparently extension of previous investigations at various places.
OPERATIONAL CAPABILITIES	Steady state performance to investigate stability of the turbocharger installation, and SFC variation.
ASSUMPTIONS	Ideal gas; homogenous cylinder charge; no leakage; stochiometric combustion; pressure and temperature uniform in space; structural component temperature uniform in space with no cyclical variation; no heat transfer to cool side; no variation in RPM of the combustion air system.
LIMITATIONS	Specific type of marine power plant.

DATA INPUT REQUIREMENTS	Description of the five thermodynamic systems and their interfaces.
ADVANTAGES	Valuable design tool.
VALIDATION	The model was validated by measurements taken by the firm of MAN on an MAN Model V6V 52/55 engine.
COMPUTING REQUIREMENTS	Unknown. However, since this is a steady state model, the requirements are not expected to be prohibitive.
COST OF OPERATION	Unknown.
FUTURE POTENTIAL	Further refinement and adaptation expected to be feasible.
AVAILABILITY	Via Government-to-government channels or via academic avenues.

TITLE	Applied Computer Simulation in Marine Engineering-Clutch Maneuvering Assessment
DATE	Published January/February 1981 (Shipbuilding & Marine Engineering International).
AUTHOR	K.W. McTavish
ORGANIZATION	Y-ARD Ltd., Glasgow
SPONSOR	Royal Navy
TRANSPORTATION MODE	Marine, naval
APPLICATION	• Design evaluation of transient loads, energy losses and control schemes for components of a twin screw CODOG ship with controllable pitch propellers during maneuvering. • Civilian and military.
OBJECTIVE	Assess the duty of a friction clutch in the diesel engine drive train.
REFERENCES	McTavish, K.W., "Applied Computer Simulation in Marine Engineering - Clutch Maneuvering Assessment," Shipbuilding and Marine Engineering International, Feb. 1981.
RELATIONSHIP TO OTHER MODELS	Based on Y-ARD experience in simulation. The governing general equations are given.
HISTORY OF MODEL	Not given
ASSUMPTIONS	Not given except as implicit in the general relationships provided.
LIMITATIONS	Assembled from accepted component modules for a specific type of propulsion plant.
DATA INPUT REQUIREMENTS	Individual ship (hull) characteristics and machinery component characteristics. The ship data requires preliminary tank testing of a model.
ADVANTAGES	Different component characteristics can be inserted. The model can be exercised for transient conditions.

VALIDATION	By practical trial results of a full scale ship.
COMPUTING REQUIREMENTS	Not given
COST OF OPERATION	Not given
FUTURE POTENTIAL	Expansion, adaptation and refinement feasible.
AVAILABILITY	Proprietary

TITLE	Analysis of Shipboard Energy Systems
DATE	Published 1978, Society of Automotive Engineers, Inc.
AUTHORS	J. Fake, T. Rozenman, J. Pundyk
ORGANIZATION	PFR Engineering Systems, Marina Del Rey, California
SPONSOR	U.S. Navy, David Taylor Naval Ship Research and Development Center, Carderock, Maryland.
TRANSPORTATION MODE	Marine, naval.
APPLICATION	• Fuel consumption rate comparisons for a marine power plant. The original simulation was for a DD 963 plant of two gas turbines with a diesel generator. • Civilian and military.
OBJECTIVE	Compare total fuel consumption for alternative arrangements under a given operation profile.
REFERENCES	Fake, J., Rozenman, T., Pundyk, J., "Analysis of Shipboard Energy Systems," SAE/P-78/75.
RELATIONSHIP TO OTHER MODELS	Each component is modelled according to some simplifying assumptions.
HISTORY OF MODEL	Contract development.
OPERATIONAL CAPABILITIES	Annual total fuel consumption and fuel rates at different speeds can be determined.
ASSUMPTIONS	A speed-power curve was stipulated, gas turbine performance was portrayed by a generalized map, diesel engine fuel curve was assumed and generator efficiency was assumed versus output, 3000 hours per year operation was assumed with no time at anchor.
LIMITATIONS	This is a steady state model. More detailed component characteristics may be required for finer results.

DATA INPUT REQUIREMENTS	Component characteristics in the form of arrays or functions and ship resistance data to give a speed-power curve.
ADVANTAGES	A reasonably accurate design tool which permits substitution of operating arrangements and profiles.
VALIDATION	From shop trial data.
COMPUTING REQUIREMENTS	Not given. Would appear to be reasonable.
COST OF OPERATION	Not given.
FUTURE POTENTIAL	Can be adapted to new types of prime movers and energy systems by modular substitution. The schematic diagram of the system permits adaptation by change of individual components and interface relationships.
AVAILABILITY	Unclassified, government property. Some of the original data may be classified.

TITLE	Systematic Design of Marine Propulsion Systems
DATE	Not shown. (Published in proceedings of International Symposium on Advances in Marine Technology.)
AUTHORS	Prof. R.V. Thompson
ORGANIZATION	University of Newcastle upon Tyne, England
SPONSOR	Vosper Thornycroft (UK) Ltd.; Royal Navy
TRANSPORTATION MODE	Marine
APPLICATIONS	• Comparison of alternative arrangements for a specialized minesweeping vessel. • Civilian and military.
OBJECTIVE	Evaluation overall dynamic performance capabilities of a minesweeper with distinct operating modes.
REFERENCES	Thompson, R.V., Systematic Design of Marine Propulsion Systems, International Symposium on Advances in Marine Technology.
RELATIONSHIP TO OTHER MODELS	Based on experimental relationships or previously accepted formulations, but a new ship and propeller model was devised for the slow speed drive mode.
HISTORY OF MODEL	A result of the long term program of mathematical analysis and simulation for design evaluation and for specification of components. In this case, the design of a shore test facility also was required and considered.
OPERATIONAL CAPABILITIES	Identify dynamic loads during maneuvering and various modes of plant operation.
ASSUMPTIONS	Linearized relationships applied where feasible. Generalized relationships and block diagram shown.
LIMITATIONS	This particular model is described to indicate the complex propulsion systems that can be simulated. Limitations become a matter of simulation economics rather than technical bounds.

DATA INPUT REQUIREMENTS	Individual component characteristics must be defined. Ship and propeller characteristics are derived from preliminary model test.
ADVANTAGES	Substitution of component modules is feasible and a wide variety of systems can be simulated under transient or dynamic conditions.
VALIDATION	Shore test facility results how good agreement. Full scale ship trial results for the plant described were not yet available at time of writing of the paper.
COMPUTING REQUIREMENTS	Not given.
COST OF OPERATION	Not given.
FUTURE POTENTIAL	The model can be expanded and adapted as necessary to suit specific power plant installations.
AVAILABILITY	Proprietary

TITLE	Selection and Simulation of Marine Propulsion Control Systems
DATE	Post- 1970
AUTHORS	C. Pronk
ORGANIZATION	Lips, N.V., Drunen, Holland
SPONSOR	Lips, N.V.
TRANSPORTATION MODE	Marine
APPLICATION	• Diesel engines driving marine controllable pitch propellers. (Lips produces marine propellers.) • Civilian and military.
OBJECTIVE	The selection of control parameters for the installation and behavior of the entire system while maneuvering can be examined.
REFERENCES	Pronk, C., "Selection and Simulation of Marine Propulsion Control Systems."
RELATIONSHIP TO OTHER MODELS	Not given. Some of the relationships used are shown.
HISTORY OF MODEL	Commercial project.
OPERATIONAL CAPABILITIES	Steady state performance and dynamic conditions.
ASSUMPTIONS	Ship motions other than ship translation and shaft rotation are considered as time dependent disturbances. Waves are considered as sine functions with a probability distribution of amplitude. Other assumptions are implicit in the equations shown.
LIMITATIONS	The simulation is designed for diesel or gas turbine drive of a single propeller.
DATA INPUT REQUIREMENTS	The system and the environment must be fully characterized, including the hull.
ADVANTAGES	Performance predictions, including fuel rates, and control requirements during the design phase of a particular type of marine propulsion system.

VALIDATION	Requires full scale ship trial data.
COMPUTING REQUIREMENTS	Coded for an IBM 1130 with 5.5K core storage. Uses approximately 9 minutes for a 25 second real time maneuver (67 time steps).
COST OF OPERATION	Not given.
FUTURE POTENTIAL	Can be modified for other types of prime mover.
AVAILABILITY	Proprietary

TITLE	Computer Aided Marine Power Plant Selection
DATE	1973
AUTHOR	R.I. Newton
ORGANIZATION	Massachusetts Institute of Technology
SPONSOR	U.S. Navy
TRANSPORTATION MODE	Marine
APPLICATION	• Merchant-type ships, 10,000 to 50,000 SHP range. • Civilian and military.
OBJECTIVE	Assist in power plant selection at the preliminary design stage, considering the ship as a whole including economic factors.
REFERENCES	Newton, Roy Irwin, Computer Aided Marine Power Plant Selection, Bachelor's Thesis, MIT, June 1973.
RELATIONSHIP TO OTHER MODELS	Derived from many other models.
HISTORY OF MODEL	Developed as Thesis in the Department of Ocean Engineering for the degree of Ocean Engineer.
OPERATIONAL CAPABILITIES	Gives comparable economic indices for 6 types of plant (steam turbine, non-reheat and reheat; medium speed diesel; direct-connected diesel; A/C derivative gas turbine; 2nd generation GT) for a given set of hull, speed, utilization conditions and cost functions.
ASSUMPTIONS	Steady operating profile at design speed and power. No alteration to hull structure costs due to varying plant + fuel weight or volume.
LIMITATIONS	Speed and power ranges; technical data inputs; inflexibility since some data is implicit in the program statements.
DATA INPUT REQUIREMENTS	21 Variables (3 data cards). All other data, relationships and cost factors are within the program and difficult to vary or update.

ADVANTAGES	Simplicity and ship-as-a-whole approach.
VALIDATION	Has been compared to similar type manual design estimates with good results.
COMPUTING REQUIREMENTS	Programmed for IBM 370/165 computer in Fortran IV, Level G-1. Listing (464 cards) is given.
COST OF OPERATION	Not given
FUTURE POTENTIAL	Modification and modularization feasible to provide greater flexibility as a preliminary design tool.
AVAILABILITY	Proprietary to M.I.T.

TITLE	The U.S. DOT/TSC Train Performance Simulator (TPS)
DATE	Completed 1978
AUTHOR	M.E. Hazel
ORGANIZATION	U.S. Department of Transportation Transportation Systems Center Kendall Square Cambridge, MA 02142
SPONSOR	U.S. Department of Transportation Federal Railroad Administration Office of Research and Development Washington, D.C. 20590
TRANSPORTATION MODE	Railway
APPLICATION	Civilian
OBJECTIVE	The objective of this model is to simulate the operation of a train over a railway route. It can be used for a variety of applications, e.g., for determining the effects of operational strategy or equipment change on energy consumption and schedule.
REFERENCES	1. Hazel, M.E., "The U.S. DOT/TSC Train Performance Simulator," Report No. FRA/ORD-77/48, U.S. Department of Transportation, Federal Railroad Administration, Washington, D.C., September 1978. 2. Hopkins, J.B., Hazel, M.E., and McGrath, T., "Railroads and the Environment, Estimation of Fuel Consumption in Rail Transportation, Volume III - Comparison of Computer Simulations with Field Measurements." Report No. FRA-OR&D-75-74. III, U.S. Department of Transportation, Federal Railroad Administration, Washington, D.C., September 1978.

3. Hitz, J.S., "Amtrak Fuel Consumption Study," Report No.FRA/ORD-81/42, U.S. Department of Transportation, Federal Railroad Administration, Washington, D.C., February 1981.

RELATIONSHIP TO OTHER MODELS

This model was originally developed by the Missouri Pacific Railroad. It has been adapted to the TSC DEC system-10 computer and has been modified to further expand its capabilities. Currently, it is available in two versions - one for DEC-10 and the other as an ANSI-compatible FORTRAN Source code.

OPERATIONAL CAPABILITIES

Results of Simulation: Calculates gallons of fuel used over a particular train route. In addition, it generates a listing which provides speed, coupler force, acceleration, throttle notch settings, brake application and release as well as, optionally, incremental energy used at every time or distance interval.

Structure: U.S. DOT/TSC TPS is a very flexible program. It has built-in (default) values for almost every parameter, including the complete specification of a train.

The program calculates fuel consumption from estimates of tractive effort and velocity at any instant. The acceleration and deceleration values are calculated based on balance between locomotive tractive effort and train resistance. Significant flexibility is built in for selecting the ideal train resistance equation for a particular application. Optional features allow for coasting overspeed and complete specification of the tractive effort curve.

ASSUMPTIONS

The fuel consumption is calculated based on horsepower being generated at any instant and running energy rate in gallons per horsepower-hour. This assumes a constant transmission efficiency and a running energy rate for the locomotive. These can, however, be curve fit with an accompanying data file.

LIMITATIONS

1. Velocity initialization is not permitted, i.e., the speed profile begins and ends at zero mph.

2. If wind effects are to be incorporated in calculating the train resistance, the velocity and direction of wind have to be constant for the entire run.

3. There are no provisions for simultaneous application of power and brakes as done in real life to keep the train stretched.

4. The train resistance models are not accurate above 80 mph.

5. The tractive effort is assumed to be in a continuous curve, not quantized by notch settings as is the case in a real locomotive.

DATA INPUT REQUIREMENTS

Locomotive Data:
- Wt. in tons
- Length in feet
- Rated HP
- Number of axles
- Running energy rate in gallons/HP-hour
- Idling energy rate in gallons/minute, and
- Transmission efficiency

Train Data:
- Number of loaded and empty cars
- Weights of loaded and empty cars, and
- If desired, all parameters for each car

Route Data:
- Lengths
- Stops
- Curvatures
- Elevations, and
- Speed limits for the route segments

Obtaining and inputing these data are very labor intensive tasks.

Train Resistance Model - Option of one of the following six models (see Ref. 1)
- Modified Davis
- Canadian National
- Canadian National-Erie Lackawanna for TOFC/COFC
- Totten-Streamlined passenger
- Totten-nonstreamlined passenger, and
- Custom coefficients

ADVANTAGES

This program is written primarily to assist a railroad in planning its train operation over a particular route. It can be, and perhaps has been, used to estimate the effects of various options on fuel consumption and schedule. Some of the options that can be considered are:

- Effects of adding or dropping a locomotive unit to or from the train,
- Effects of adding or dropping tonnage to or from the train,
- Effects of track relocation or reconstruction, etc.

The program is simple to use and changes can be made with relative ease.

VALIDATION

The program has been extensively validated (see Refs. 2 and 3). It has been used to simulate the operation of several different freight trains over different terrains. The overall agreement is shown to be within 2%; however, some specific runs have shown variations as large as 10% to 15% from test results.

COMPUTING REQUIREMENTS

The program runs on DEC-10, although an IBM version is also available. Both DEC and ANSI versions are available. A typical Northeast corridor run (New York to Boston) costs about $20 to run. However, the cost is strongly dependent on how many speed changes and how many track segments are included in the simulation.

AVAILABILITY

The program is available to any user for $150 from TSC. A 9-track tape (1600 bpi), control no. FR028, is provided. This tape includes the source code as well as user documentation.

TITLE	Fuel Utilized Effective - Locomotives (FUEL)
DATE	December 1975
AUTHOR	J.N. Cetinich
ORGANIZATION	Emerson Consultants, Inc. 30 Rockefeller Plaza New York, New York 10020
SPONSOR	Union Pacific Company
TRANSPORTATION MODE	Railway
APPLICATION	Civilian
OBJECTIVE	The model is used to investigate the effect of train operating strategies upon consequent changes in fuel consumption, horsepower required and minimum train running time over a territory.
REFERENCE	Cetinich, J.N., "Fuel Efficiency Improvement in Rail Freight Transportation," Report NO. FRA-OR&D-76-136, PB 250 673, Dept. of Transportation, Federal Railroad Administration, Washington, D.C., December 1975.
RELATIONSHIP TO OTHER MODELS	This model needs as an input the output of a Train Performance Calculator computer model.
OPERATIONAL CAPABILITIES	Results of Simulation: The model determines fuel consumption, horsepower required and minimum train running time for given maximum speeds allowed and horsepower per trailing ton limits between all power change points (i.e., locations where train consist may change, either the locomotive set or trailing cars, or both).
ASSUMPTIONS	The Modified Davis Formula in a Train Performance calculator is used to calculate train resistance for use in the model.

LIMITATIONS

1. The energy calculation assumes the train to be one mass, which would make the prediction for long train traversing an undulated terrain inaccurate.

DATA INPUT REQUIREMENTS

The following data are required:

- Dispatcher's record of movement of trains
- Listing of premium and regular trains (they have different speed limits)
- Locomotive horsepower list
- Manifest train schedules.
- Locomotive tonnage rating tables
- Terrain profile
- Train information, such as horsepower used and total trailing ton for each train
- Output from a Train Performance Calculation Computer Model

ADVANTAGES

The model provides a global overview of effects of train operating strategies on a particular territory.

VALIDATION

The output from the Train Performance Calculator (TPC) was validated as were other elements of the FUEL Program and the overall output of the program. The TPC validation included dynamometer car runs, as well as locomotive speed tapes. The TPC program was found to underestimate fuel consumption by 8%. From the extensive validation, it was concluded that the program can accurately provide differences in fuel consumed, horsepower required, and minimum running time for changes in operating strategies.

TITLE	Freight Train Fuel Consumption Program
DATE	February 1981
AUTHOR	John D. Muhlenberg
ORGANIZATION	The MITRE Corporation 1820 Dolly Madison Boulevard McLean, Virginia 22102
SPONSOR	U.S. Department of Transportation Federal Railroad Administration Washington, D.C. 20590
TRANSPORTATION MODE	Freight Train
APPLICATION	Civilian
REFERENCES	1. Muhlenberg, J.D., "Resistance of a Freight Train to Forward Motion - Volume IV, User's Manual for Freight Train Fuel Consumption Program", Report NO. FRA/ORD-78/0.4 IV, U.S. Dept. of Transportation, Federal Railroad Administration, Washington, D.C. 20590. 2. Computer program magnetic tape available as FRA/ORD/MT-78/0.4 IV.
RELATIONSHIP TO OTHER MODELS	Unlike most train operation simulator programs, this program was specifically written to calculate fuel consumption of a freight train. Although it provides values of other parameters needed to calculate fuel consumption, the program does not purport to be a train operation simulator.
OPERATIONAL CAPABILITIES	Structure: The program consists of a main program and two subroutines, one deals with the track characteristics and the other incorporates the tractive effort characteristics of various locomotives.

The program calculates energy usage (and consequently fuel consumption) by multiplying tractic effort by distance travelled at that effort. When the net tractive effort is zero, the engines are assumed to be idling and the fuel consumption reflects this idle rate.

Results of Simulation: The output of the program includes time, distance, fuel consumption, cumulative fuel consumption, velocity, acceleration, train resistance, throttle position or braking effort, and rate of fuel consumption.

ASSUMPTIONS

The fuel consumption at each iteration step is calculated based on multiplying train tractic effort by distance travelled in that iteration step. The transmission efficiency is assumed to be constant in doing so. Also, the track corresponding to each vehicle in the train is assumed to be described by the same track record. Thus, variations in track characteristics along a long train cannot be accommodated. Also, since the program is not intended to be a train performance simulator, some details of operating the braking system or throttle which could possibly affect fuel consumption are omitted.

LIMITATIONS

1. The program cannot handle the commonly used practice of train stretching (by applying power and brakes simultaneously).

2. The effects of cross wind are neglected.

3. The equation used to calculate acceleration of the train treats the whole train as a lumped mass. This will be inaccurate while simulating a long freight train over an undulating profile.

4. Locomotives can be located only in front of the train.

DATA INPUT REQUIREMENTS

The program already contains two general data files, one containing the characteristics (such as areas of cross-section, weight, aerodynamic parameters, etc.) of 21 types of rolling stock including three types of locomotives, the second containing additional information on locomotives (such as initial tractive effort, fuel consumption rates in idle and while dynamic braking, etc.)

The operator needs to prepare three other stored data files. The first among these is the train file which provides car type (referred to the above data file) and net weight of vehicle load in tons for each car. The second file contains order in which the cars are placed in the train. The third file includes track information, i.e., distance, grade, grade equivalent of curvature, and speed limit.

Finally, as it is set up, the operator is supposed to provide the following additional data on an interactive basis:

- No. of locomotives,
- No. of vehicles in train,
- No. of track record,
- Start print,
- Operational speed limit (max. speed limited for the simulated trip),
- Estimated headwind, and
- Data print option.

ADVANTAGES

Since this program already incorporates information on most commonly used railcars and locomotives, it is relatively easy to use. Also, it is easy to modify since it is extensively documented.

VALIDATION

The program is claimed to have been validated with comparative success and is expected to predict actual fuel consumption within +0% and -10%.

COMPUTING REQUIREMENTS

The program is written in FORTRAN IV for an IBM 370 system. A typical case which simulates consumption, 100 gallons of fuel, uses approximately 100 cpu secs.

AVAILABILITY

The program is available to any user. The reference cited earlier contains a listing of the program. Alternatively, MITRE will provide a card deck for the cost of producing it. Finally, NTIS can provide a magnetic tape of the program.

TITLE	The Transportation Energy Model, Carnegie-Mellon
DATE	July 1977
AUTHORS	S.N. Talukdar and R.A. Uher
ORGANIZATION	Carnegie-Mellon University Pittsburgh, Pennsylvania
SPONSORS	Department of Transportation AAR
TRANSPORTATION MODE	Electric and Diesel Powered Trains
APPLICATION	Civilian
OBJECTIVE	The model was originally developed to provide a realistic, computer-based tool to predict energy consumption and cost associated with an electric-powered transportation system. Later it was modified to incorporate diesel-powered trains as well.
REFERENCES	1. Talukdar, S.N., and Uher, R.A., "Energy Management for Electric Powered Transportation Systems," prepared by Carnegie-Mellon University for the Dept. of Transportation, July 1977. 2. Conversation with Dr. R.A. Uher, (412) 578-2961 (since no documentation exists for the modification incorporating diesel-powered trains).
RELATIONSHIP TO OTHER MODELS	The model contains two principal components which are linked together to simulate the actual operation of a transportation system. The components are: 1. The Train Performance Simulator 2. The Electric Network Simulator For the diesel-powered trains, the second component is not needed.

HISTORY OF MODEL

The model was originally developed to simulate only an electric-powered transportation system. Later it was modified to include capabilities to simulate a diesel-powered train. The research team at Carnegie-Mellon is now in the process of creating data files to simplify data input for standard vehicles and tracks.

OPERATIONAL CAPABILITIES

This model is one of the most detailed models available. Examples of its versatile capabilities are:

- Given a schedule, it can compute an optimum operational strategy which will minimize fuel usage.
- The train is split in cells to allow accurate simulation of a long train traversing a profile with many short length grades and curves.
- A complete graphic package is provided.
- It has the ability to predict the affect of track class on train resistance and, hence, on fuel usage.

Results of Simulation: Primary variables describing energy consumption, power demand, speed vs. position, time vs. position and cost of energy for a given schedule.

Structure: The program contains two components: The Train Performance Simulator and The Electric Network Simulator. An optional Energy Cost Simulator can be added if desired. For an application dealing with diesel-powered trains, the second component is unnecessary. Each component incorporates a large number of modules, which are easy to change. Also, the Train Performance Simulator has been designed to interact with the automated control and Optimization Program so that optimum speed profiles, etc. can be determined and tested.

ASSUMPTIONS

There are no major assumptions made in the program.

LIMITATIONS

The developers of the program are in the process of constructing libraries for track, freight car and locomotive data. Until these libraries are made available, the data input will take some effort.

DATA INPUT REQUIREMENTS

The following input parameters are required:

1. The physical characteristics of the train, e.g., weight, length, cross-sectional areas, etc.

2. The Performance Characteristics of the propulsion system, e.g. gallons/minute as a function of notch position, speed and tractive effort (if not available, gallons/minute as function of horsepower).

3. Vehicle braking system characteristics.

4. Transportation system layout, e.g., track, terminal, station location.

5. Track profile, e.g., speed limits, grade, curvature, etc. Also, PSD of track geometry variations, if available; otherwise, track class (1-6).

6. Train time table.

7. Control philosophy, e.g., acceleration-braking rates.

ADVANTAGES

This model is one of the most detailed models available. Also, it is structured in such a way that one can simulate as simple a case or as complicated a case as one wants to. The structure allows significant flexibility in changing and modifying parts of the program.

VALIDATION

The following validation tests have been performed:

- The Washington Metro Blue and Red Lines test in which the energy consumption was predicted within ±3%.
- The Metroliner test in which the energy consumption was predicted within ±5%.
- The Amtrak tests on 5 passenger train routes in which the energy consumption was found to be within ±5% of predicted values.

COMPUTING REQUIREMENTS

The program is written in FORTRAN to run on DEC-20 and VAX computers. A typical 50 mile run will use 15 seconds of CPU. It uses 60k Byte of space.

AVAILABILITY

The program is available to any user, in any format desired. For $625, the university will provide the tape, guideline books, and test cases.

TITLE	A Multi-Purpose Train Performance Calculator (TPC)
DATE	December 1978
AUTHORS	R. Mittal and A. Rose
ORGANIZATION	EE/CS Department Union College Schenectady, New York 12308
SPONSORS	U.S. Department of Transportation Federal Railroad Administration Washington, D.C. 20590
TRANSPORTATION MODE	Passenger Train
APPLICATION	Civilian
OBJECTIVE	The program simulates the operation of a passenger train over a rail route and predicts route schedule and fuel use.
REFERENCE	Heilman, H., Kahrs, C., and Williams, G., "A Multi-Purpose Train Performance Calculator, Volumes 1 and 2", prepared by Union College, Schenectady, prepared for the U.S. Dept. of Transportation, Federal Railroad Administration, Washington, D.C. 20590.
RELATIONSHIP TO OTHER MODELS	Although this program is similar to other train performance calculator programs, it seems to have been developed entirely at Union College.
OPERATIONAL CAPABILITIES	Results of Simulation: The TPC output is in the form of tables showing speed, time, fuel used, and energy consumption to reach each station along the route. In addition, plots of speed, time and fuel versus distance travelled are generated. Structure: TPC is designed to run in a batch-processing environment in which its input comes from data cards or from on-line disk files containing locomotive data, car data and track data.

The program is modular in structure with fifteen subroutines supporting the main program.

The train is treated as a point mass which is acted on by accelerating and retarding forces. The resulting acceleration (or retardation), speed, location and energy used are then calculated at each time interval. Two guidelines are followed in simulating the operating cycle:

- accelerate to the speed limit, using maximum effective motive power, and
- brake at the maximum rate permitted to maintain passenger comfort.

ASSUMPTIONS

The program assumes that the train can be modelled as one lumped mass. This is probably adequate to describe a relatively short passenger train (i.e., it would not be so for long freight trains).

The fuel consumption in gallons/hour is assumed to depend only on percent of available tractive effort being used at any instant. Also, the transmission efficiency is assumed to depend only on the speed of the train.

LIMITATIONS

1. The program uses the Davis' equation for calculating train resistance, which is accurate only up to speed of 50 mph. A more accurate equation (such as that developed by Tuthill) can be incorporated only by a program change.

2. Like in most programs of this type, the fuel consumption characteristic of the locomotive is not calculated explicitly from the design parameters, but has to be provided as a function of percentage tractive effort.

DATA INPUT REQUIREMENTS

Locomotive Data: The data for the most popular locomotives are already provided. For a locomotive not in the list, the following data are required:

- Weight in tons,
- Length in feet,
- Frontal area in square feet,
- Auxiliary power in kilowatts,
- Maximum traction horsepower,
- Fuel consumption in gallons/hour of auxiliary generators
- Tractive effort and transmission efficiency for each mph value from 0 to 120 mph, and
- Fuel consumption in gallons/per hour corresponding to each percent of its available tractive force.

Car Data: The data for the most popular rail cars are already provided. For a coach not in the list, the following parameters are required:

- Values of coefficients for the Davis'equation
- Car weight in tons,
- Car length in feet,
- Passenger capacity, and
- Frontal area in square feet.

Track Data: The following data are required for each track segment:

- Length,
- Grade,
- Curvature, superelevation,
- Speed limit for passenger train,
- Mile post,
- Station name, and
- Compensated grade (for a section with both grade and curve).

ADVANTAGES

This program is written specifically to simulate a limited case of passenger train operation. The advantages of making it so specific are:

- The data for most commonly used locomotives and coaches are already provided.

- The requirements which are specific to a passenger train operation, such as auxiliary power usage, are included in the program. This makes the fuel use prediction more accurate than if a freight train program were used for this application.

VALIDATION

The program has been used to study the energy intensity of AMTRAK trains in the New York to Buffalo corridor. Although the program is claimed to predict the schedule quite accurately, no information is available on the accuracy of its fuel use predictions for those runs.

The program has been validated against TSC's Train Performance Simulator.

COMPUTING REQUIREMENTS

The program is writen in FORTRAN and is designed for execution in a medium-sized machine. The model has been implemented on a Burroughs B-6700 at Union College and on DEC-10 at the Transportation Systems Center (TSC), U.S. DOT, Cambridge, Massachusetts.

AVAILABILITY

The program is available to any user. It is available from TSC on the same tape as TSC's Train Performance Simulator for a total price of $150.

TITLE	Train Operations Simulator (TOS)
DATE	1983 (Latest update)
AUTHOR	N.W. Luttrell
ORGANIZATION	The Southern Pacific Transportation Company
SPONSOR	The Track-Track Dynamics Program AAR
TRANSPORTATION MODE	Railway
APPLICATION	Civilian
OBJECTIVE	To simulate the performance of a diesel-electric locomotive and conventional freight car running over a specified territory. The user has the option of having the program calculate the in-train forces developed during the run or calculate the amount of fuel consumed.
REFERENCE	Luttrell, N.W., et al, "Train Operations Simulator, User's Manual, Track-Train Dynamics," Release 4.20, the Association of American Railroads (AAR) Technical Center, Chicago, IL, 1983.
RELATIONSHIP TO OTHER MODELS	Independently developed as a part of Track-Train Dynamics Research Program.
HISTORY OF MODEL	The TOS is one of the most widely used models in the industry. Initially developed to study train make-up and train handling, it is now capable of providing estimates of fuel consumption of a train over a given track.
OPERATIONAL CAPABILITIES	The program is exceptionally detailed in modeling the behavior of air brakes and dynamic braking. Also, the train handling instructions can be provided explicitly in terms of throttle and brake settings and specifications. An automatic train operation option is also provided, which attempts to operate the train over the specified track in the minimum running time. Finally, a relatively sophisticated method is used to estimate wheel/rail adhesion.

The program can be run either to calculate in-train forces or the amount of fuel consumed.

Results of Simulation:

When the program is used to calculate fuel consumption, the output includes:

- time,
- mile post,
- distance,
- speed limit,
- throttle position,
- actual speed,
- status of the air brake system,
- accumulated fuel consumption, and
- load factor (which indicates how "hard" the locomotives are working)

ASSUMPTIONS

- Tracks are considered to be perfect
- An arbitrary division between vehicle and load weight is made
- Locomotive tractive effort and dynamic braking data are approximated by linear, quadratic, and hyperbolic curve segments.

LIMITATIONS

1. Due to the detail and flexibility inherent in TOS, its execution time is higher than most other fuel consumption models.
2. TOS assumes perfect track. Thus, the effects of track irregularities on fuel consumption cannot be simulated.
3. There are still some bugs in the program which are being fixed.
4. The plotting routines require an inordinate amount of computer time.
5. Under the automatic operation command, the throttle position may advance unrealistically fast.

DATA INPUT REQUIREMENTS

The following input parameters are needed:

1. Title Information
2. Track Data
   - Direction
   - Speed limits and station names
   - Curvature data
   - Elevation data
3. Vehicle data

   The vehicle consist can be specified by either utilizing standard vehicle library or by entering relatively detailed vehicle characteristics. Data required in the latter case includes weight, lengths and specifications of coupler and brake systems, Davis equation coefficients, etc.

   For locomotives, additional data are required including tractive and dynamic braking data.

ADVANTAGES

One advantage of TOS is its ability to simulate various methods of train handling and its effects on fuel consumption. Most other programs do not have this option; they simulate automatic operation in which the train's running time is minimized within the constraints of the speed limits. The program, on the other hand, may be more expensive to run than the other programs.

VALIDATION

Many railroads are using the TOS program including Burlington-Northern, Chicago & North Western, CONRAIL, CSX, Illinois Central Gulf, Norfolk Southern, and Western Pacific. The fuel calculations have been hand checked.

COMPUTING REQUIREMENTS

Various versions of the program are available to run on IBM, DEC-20, PRIME and Burroughs computers. It needs 12 cpu sec. to produce fuel consumption estimates for one mile of track.

AVAILABILITY

The program is available to any user for $50, AAR will provide a tape and the following four documents.

- User's manual (to run the program).
- Technical manual (to understand the model).
- Programming manual (to make changes).
- Validation report (TOS against a Southern Pacific test train).

TITLE	Train Performance Calculator - AAR
DATE	Mid 1960s
AUTHOR	Operated by Stuart McEwan at AAR.
ORGANIZATION	Association of American Railroads (AAR)
TRANSPORTATION MODE	Freight and Passenger Trains
APPLICATION	Civilian
OBJECTIVE	To predict energy usage of a train with a diesel-electric, an electric or a steam propulsion system.
REFERENCES	Anon., "User's Manual for NRPC Train Performance Calculator," AAR. Available from Stuart McEwan (312-567-3593).
RELATIONSHIP TO OTHER MODELS	This model is a FORTRAN rewrite of Canadian National Railway's TPC.
OPERATIONAL CAPABILITIES	This model uses the original Davis formula for obtaining resistance of diesel-electric locomotives and passenger cars. The power being used at any instant is compared with the maximum power available at that velocity. The resulting load factor provides fuel consumption. Just one tractive effort curve is provided.
ASSUMPTIONS	1. The original Davis formula is used for calculating train resistance. This is accurate only at low speeds. 2. Only one tractive effort curve is used.
LIMITATIONS	No provision for throttle position changes.

DATA INPUT REQUIREMENTS	Locomotive, car, and track data are input from cards, with one card for each type of car and locomotive and separate track cards for speed, temporary orders, curvature and elevation.
ADVANTAGES	• Available in the public domain. • A relatively fast program.
VALIDATION	The program has been used by several railroads, but no information on validation is available.
COMPUTING REQUIREMENTS	The program is available in CDC 3500, IBM-370, and DEC-20 versions. One minute of CPU time is used for every 10 miles of track.
AVAILABILITY	The program is available to any user for the cost of writing the program on a user supplied tape and the cost of mailing the tape.

TITLE	Train Performance Calculator - AiResearch
DATE	February 1979
AUTHORS	J. J. Lawson and L. M. Cook
ORGANIZATION	AiResearch Manufacturing Company of California
SPONSORS	Initially, Department of Transportation Federal Railroad Administration. Subsequently, internally funded.
TRANSPORTATION MODE	Passenger and Freight Trains
APPLICATION	Civilian
OBJECTIVE	This model was developed to provide train performance calculations required by the FRA-sponsored wayside energy storage study. It was then extensively modified to simulate dual mode locomotive.
REFERENCES	Lawson, J.J., and Cook, L.M., "Wayside Energy Storage Study, Volume II -- Detailed Description of Analysis", Final Report, Report No. FRA/ORD-78/78, II, Department of Transportation, Federal Railroad Administration, Washington, D.C., February 1979.
RELATIONSHIP TO OTHER MODELS	None
OPERATIONAL CAPABILITIES	The TPC was designed to perform analysis of long-haul freight service, with an emphasis on energy and power demand requirements of multi-train operations. It can also be used to analyze intercity rail passenger service. The program simulates a diesel, electric, electric with regeneration or mixed mode operation.
ASSUMPTIONS	The train is modeled as a single point mass. The train resistance equation is the Modified Davis Formula.
LIMITATIONS	It is a proprietary model.

DATA INPUT REQUIREMENTS

Characteristics of the locomotives and rolling stock are internal program parameters. Route and Schedule data are input from a card reader or from disk or tape file in card-image form.

ADVANTAGES

This model is quite detailed. For example, drag calculations are performed for each car. Also, it can simulate diesel, electric or mixed mode operations.

VALIDATION

Calculations of energy usage were found to be within 6% of actual measured usage.

COMPUTING REQUIREMENTS

The program is written for a Univac-1108 computer in ANSI Fortran. A 1500 mile run takes 3-4 minutes on the Univac computer. The company is willing to provide a tape to run on any machine.

AVAILABILITY

The original program written for the U.S. DOT was significantly modified. This modified program and its documentation are considered proprietary by AiResearch. The company will, however, be willing to negotiate if a user is interested in acquiring the program.

TITLE	Hitachi Model
DATE	1972
AUTHORS	Mizushima, K., Nagai, M., and Asada, T.
ORGANIZATION	Hitachi Shipbuilding, Ltd., Osaka
SPONSOR	Same as above
TRANSPORTATION MODE	All modes
APPLICATION	Civilian or Government
OBJECTIVE	To predict thermodynamic performance of 2-stroke and 4-stroke diesel engines, including scavenging, exhaust, and turbocharger phenomena.
REFERENCES	Mizushima, K., Nagai, M., and Asada, T., "Some Analyses of Diesel Engine Performance by Means of Computer Simulation," J. MESJ, Vol. 1, No. 5, p. 35 (1972). See also J. MESJ, Vol. 6, No. 9, p.49 (1971) and Nagui, Mizushima, and Asada, J. MESJ, Vol. 5, No. 1, p. 41 (1970).
RELATIONSHIP TO OTHER MODELS	The authors paid close attention to the 1960-1961 work of Austen and Lyn.
HISTORY OF MODEL	Developed specifically for medium and large bore marine diesels (turbocharged); this early model is a rare combination covering. - Intake and exhaust flows; and - Detailed combustion rates.
OPERATIONAL CAPABILITIES	Results of Simulation: - Direct Injected Engines - Calculates Intake and Exhaust Flows - Calculates Thermal Efficiency and Fuel Consumption (isfc) - Calculates Heat Transfer to Walls

Structure: List of Submodels or processes included.

- Intake, exhaust
- Blower, turbocharger
- Ignition delay
- Combustion rate
- Gas properties
- Heat transfer
- Scavenging

ASSUMPTIONS

Intake, exhaust: Flow coefficients

Supercharger: specified blower characteristics

Ignition delay: Arrhenins Law, pressure coefficient minus .624.

Combustion rate/mixing of air-fuel: Two-stage combustion, semi-empirical, Weibe function.

Fuel-air ratio of burned gas: Not treated.

Gas properties: Polynominal functions.

Heat transfer: Separate wall temperatures for various components, depend on load. Pflamm (1961) expression.

NO_x Model: Not included.

Soot Model: Not included.

Burned gas mixing: Not included until scavenging process.

LIMITATIONS

(1) Inadequate treatment of fuel-air mixing and gas temperature non-uniformities: Fuel spray not modelled; burning rates must be specified empirically.

(2) Inadequate treatment of heat transfer:
- Heat transfer coefficient is different for each load
- No radiation, no boundary layer; and
- No gas temperature gradient.

(3) Inadequate treatment of burned gas mixing.

(4) Soot, NO_x not modelled.

(5) "Combustion efficiency" of about 92% to 97% had to be assumed, depending on load.

DATA INPUT REQUIREMENTS

Geometrical and Design Parameters:
- Bore
- Stroke
- Conn. rod length
- Chamber volume
- Valve areas vs. time

Coefficients:
- Flow coefficients and turbine efficiency
- Scavenging coefficient
- Heat transfer coefficient
- Combustion duration and rate

Operating Parameters:
- Load
- Speed
- Injection timing
- Intake manifold temperature
- Intake manifold pressure
- Injection rate
- Cylinder wall temperatures for each area

ADVANTAGES

- Covers entire cycle including intake and exhaust
- Has realistic heat release patterns and, therefore, predicts cylinder pressure accurately.

VALIDATION

Engine description:

(1) 2-stroke
(2) 4-stroke

Variables tested; model agreement: Predictions of cylinder pressure, gas flow rate, and exhaust temperature as function of crank angle agree well with data.

Assessment of accuracy: Sufficient degree of accuracy for the intended purpose of the model.

COMPUTING REQUIREMENTS	Unknown
COST OF OPERATION	2 minutes of CPU time at \$60 to \$100/min (estimated)
FUTURE POTENTIAL	- Pulsations in exhaust - Emissions - Improved heat transfer model
AVAILABILITY	Presumably this model is unavailable to the public since Hitachi is a competitive shipbuilder.

TITLE	University of Manchester, Institute of Science and Technology (UMIST)
DATE	1976, 1981
AUTHORS	Winterbone, Loo, Benson, Wellstead, Thiruarooran
ORGANIZATION	University of Manchester
SPONSOR	Unknown
TRANSPORTATION MODE	All modes
APPLICATION	Civilian or Government
OBJECTIVE	To describe the transient response of diesel engines, including turbocharger speed, to load application.

REFERENCES

(1) Winterborne, D.E., Wellstead, P.E., and Thiruarooran, C., "A Wholly Dynamic Model of a Turbocharged Diesel Engine for Transfer Function Evaluation," SAE Paper 770123 (1977).

(2) Winterbone, D.E., and Loo, W.Y., "A Dynamic Simulation of a Two-Stroke Turbocharged Diesel Engine," SAE Paper 810337 (1981).

(3) Benson, R.S., "A Comprehensive Digital Computer Program to Simulate a Compression Ignition Engine, Including Intake and Exhaust Systems, SAE Paper 710173 (1971).

RELATIONSHIP TO OTHER MODELS/HISTORY OF MODEL

The University of Manchester, starting with Benson's steady-state model in 1971, has concentrated on diesel models which treat the transient turbocharger matching problem. The three papers summarized here cover digital computer models; see also the analogue simulations covered in Benson, Winterbone and Shamsi (1976), and Winterbone, Benson, Closs, and Mortimer (1976).

OPERATIONAL CAPABILITIES

Results of Simulation:
- Direct Injected Engines
- Calculates Transient Intake and Exhaust Flows
- Calculates Compressor Outlet Pressure and Temperature
- Turbine Inlet Pressure and Temperature
- Turbocharger speed and air flow rate
- Calculates turbocharger performance

Structure: List of Submodels or processes included.
- Air receiver (intake manifold)
- Exhaust manifold with wave action
- Turbocharger compressor
- Turbine
- Scavenge blower (roots)
- Intercooler
- Engine system (combustion rate, gas properties, heat transfer)

ASSUMPTIONS

- Compressor: Specified characteristics.
- Roots blower: Orifice plus positive displacement.
- Scavenging: Perfect mixing.
- Intake exhaust: Orifice equations, quasi-steady
- Intercooler: Pressure drop and cooling
- Turbine: Specified efficiency and flow rate as function of pressure ratio.
- Ignition delay: Prescribed.
- Fuel spray evaporation: Not treated.
- Combustion rate/mixing of air-fuel: Simplified prescribed model based on Whitehouse and Way (1969).
- Fuel-air ratio of burned gas: 2-zone system.
- Gas properties: Moles change is accounted for; polynominal functions. Perfect ideal gas during intake and exhaust.
- Heat transfer: Annand expression.
- No_x Model: Not treated.
- Soot Model: Not treated.
- Burned gas mixing: Not treated.

LIMITATIONS

(1) Not intended to cover engine combustion variables.

(a) Inadequate treatment of fuel-air mixing and gas temperature non-uniformities

(b) Inadequate treatment of heat transfer

(c) Inadequate treatment of burned gas mixing

(d) Soot, No_x not covered.

(2) Underestimates scavenging.

(3) Speed effect of turbine not modelled well.

DATA INPUT REQUIREMENTS

Geometrical and Design Parameters:
- Bore
- Stroke
- Conn. rod length
- Chamber volume
- Valve areas vs. time
- Manifold geometry
- Compressor and turbine characteristics
- Intercooler performance

Operating Parameters:
- Load
- Speed
- Injection timing
- Intake manifold temperature
- Intake manifold pressure
- EGR or residual fraction

ADVANTAGES

Primary advantage is for detailed design and development of turbochargers and intake/exhaust systems.

VALIDATION

(1) Engine description: GM, 6-cylinder, 2-stroke turbocharged engine, Model 6V-TAE.

(2) Variables tested; model agreement: In steady state, predicted power to 1.4%, compressor outlet pressure to 4.9%, turbine inlet pressure to 10%, turbocharger speed to 5%, and air flow to 7%.

(3) Assessment of accuracy: Model not tested in transient mode. Therefore, accuracy is unknown.

COMPUTING REQUIREMENTS — Fortran IV. Fourth-order Runge-Kutta solution.

COST OF OPERATION — 4 minutes of CPU time at $60 to $100/min (estimated)

FUTURE POTENTIAL

(1) Model needs to be validated against transient engine data.

(2) Would be advisable to add a transient smoke model to predict "puffs."

AVAILABILITY — Presumably available at cost. University of Manchester has a robust consulting activity with UK industry.

TITLE	Manchester (Whitehouse)
DATE	1971 - 1977
AUTHORS	Whitehouse, N.D., Way, R.J.B., Sareen, B.K., Clough, E., Abughres, S.M., and Baluswamy, N.
ORGANIZATION	University of Manchester, Inst. of Science and Technology (UMIST)
SPONSOR	Science Research Council, UK
TRANSPORTATION MODE	All modes
APPLICATION	Civilian or Government
OBJECTIVE	To predict performance and NO_x emissions of a direct injection diesel engine based on a simplified fuel spray model.

REFERENCES

(1) Whitehoue, N.D. and Way, R.J.B., "Rate of Heat Release in Diesel Engines and its Correlation with Fuel Injection Data," Symposium on Diesel Engine Combustion, IME, April 1970. Covers essentially the same material as SAE Paper 710134,1971.

(2) Whitehouse, N.D., and Sareen, B.K., "Prediction of Heat Release in a Quiescent Chamber Diesel Engine Allowing for Fuel/Air Mixing," SAE Paper 740084, 1974.

(3) Whitehouse, N.D., Clough, E., "The Effect of Changes in Design and Operating Conditions on Heat Release in Direct-Injection Diesel Engines," SAE 740085, 1974.

(4) Whitehouse, N.D. and Abughres, S.M., "Calculation of Fuel-Air Mixing in a Diesel Engine with Swirl for the Purpose of Heat Release Prediction," IME Publication C97/75, 1975.

(5) Whitehouse, N.D. and Baluswamy, N., "Calculation of Gaseous Products of Combustion in a Diesel Engine Using a Four-Zone Model," SAE Paper 770410, 1977.

RELATIONSHIP TO OTHER MODELS/HISTORY OF MODEL

In 1970, Whitehouse (NDW, hereafter) published an empirical burning rate model with all the gas in a single zone.

In 1974, NDW and Sareen extended this to a two-zone model which gives more realistic hot-zone temperature.

In 1975, Abughres and NDW extended the two-zone model to account for swirl effects.

In 1977, Baluswamy and NDW extended the two-zone model to four zones, in order to achieve enough temperature resolution to attempt NO_x emission predictions.

OPERATIONAL CAPABILITIES

Output of Simulation:
- Direct injected engines
- Calculates thermal efficiency or fuel consumption (isfc)
- Calculates heat transfer to walls
- Calculates emissions (NO_x only)
- Calculates fuel jet mixing with air

Structure: (List of submodels or processes included):
- Intake, exhaust
- Fuel injection (specified)
- Fuel-air mixing
- Ignition delay
- Combustion rate
- Gas properties
- NO_x model
- Heat transfer

ASSUMPTIONS

Intake, exhaust:
Incompressible flow through valves, taken from Baruch (1973).

Fuel spray evaporation:
Instantaneous evaporation assumed. No droplet atomization included.

Ignition delay:
Specified delay period.

Mixing of air-fuel:
Conical gaseous fuel jet entrains air (specified coefficient) according to Sareen and NDW (1974) model. Wall impingement effects included.

Combustion rate:
Taken from Whitehouse and Way (1970), the combustion rate expression is semi-empirical and requires five coefficients (K_1, ℓ, m, K_2, and "act").

Fuel-air ratio of burned gas divided into two zones:
(1) Stoichiometric burning zone and (2) products/air zone which is lean.

Gas properties:
Taken from Baruch (1973) and Vickland (1962)

Heat transfer:
Annand (1963) type of correlation for convective heat transfer, plus radiation proportional to the amount of carbon present in each zone.

NO_x model:
Extended Zeldovich Kinetics.

Burned gas mixing:
Arbitrary mixing coefficient.

LIMITATIONS

(1) Treatment of fuel-air mixing and gas temperature non-uniformities is quite simple: all burned gas is at only two temperatures. This limits the NO_x predictive capability.

(2) Treatment of heat transfer has over-simplified radiation and no boundary layer effects are included.

(3) Treatment of burned gas mixing is arbitrary in that the user specifies mixing coefficients for exchange of gas between zones.

(4) Soot production is not modeled.

(5) Burning rate expression has an Arrhenius term, which is not consistent with diffusion-controlled combustion.

(6) Excessive number of specified coefficients.

DATA INPUT REQUIREMENTS

Geometrical and Design Parameters:
- Bore
- Stroke
- Connecting rod length
- Chamber volume
- Valve areas vs. time

Model Coefficients:
- Jet entrainment coefficients (2)
- Burning rate coefficients (5)
- Burned gas entrainment rate (1)

Operating Parameters:
- Load
- Speed
- Injection timing
- Intake manifold temperature
- Intake manifold pressure
- EGR or residual fraction
- Injection rate
- Swirl level

ADVANTAGES

(1) Relatively simple and inexpensive

(2) Attempts to include the temperature differences in the combustion space in a very simple manner.

VALIDATION

Engine description:
130 psi bmep, 500 RPM

Variables tested; model agreement:
Timing, speed, number of injector holes

Assessment of accuracy:
Only tested at part load; agreement was fair. Needs further development and testing.

COMPUTING REQUIREMENTS — Not specified

COST OF OPERATION — 1 minute of CPU time at $60 - 100/min (Estimated)

FUTURE POTENTIAL — More than four zones are needed in the model. Future potential is limited.

AVAILABILITY — Unknown

TITLE	The Problem of Predicting Rate of Heat Release in Diesel Engines
DATE	1970
AUTHORS	H.C. Grigg and M.H. Syed
ORGANIZATION	C.A.V. Ltd., Acton, England
SPONSOR	C.A.V. Limited
TRANSPORTATION MODE	Engine model applicable to all modes.
APPLICATION	Civilian
OBJECTIVE	This relatively simple model was developed to predict rate of heat release diagrams based upon approximations of the physical factors involved. The model is based on the process of air entrainment into fuel sprays, turbulent mixing in fuel sprays, and chemical kinetics. Constants were chosen such that the predicted rate of heat release fit experimental data. The experimental data used were diesel engine rate of heat release diagrams calculated from cylinder pressure records furnished from tests on a turbo-charged Dorman 6LBT engine.
REFERENCES	Grigg, H.C. and M.H. Syed, "The Problem of Predicting Rate of Heat Release in Diesel Engines," Symposium on Diesel Engine Combustion, London, April 7-9, 1970, Institution of Mechanical Engineers.
OPERATIONAL CAPABILITIES	Model Description:

The following factors are the basis of this rate of heat release model:

1. Ignition delay (experimentally determined)
2. Engine dimensions including nozzle hole diameter and number of holes
3. Period of injection (experimentally determined)

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4. Rate of entrainment of air into sprays. The rate of entrainment is calculated by use of the Schweitzer formula for which it is assumed that the entrained air has the same velocity as the fuel droplets. Modifications are made to allow for air density changes arising from the piston motion during the development of the fuel spray by assuming that the fuel spray expands radially about its axis to maintain the equal pressure inside and outside the spray.

   The fuel spray was considered in two different forms: a set of conical plumes, issuing from the nozzle holes (the Schweitzer configuration) and an expanding doughnut of spray fed from a central nozzle. In the conical plume model the spray develops unimpeded as in an infinite atmosphere in a conical form. This is justified by recognizing that the air motions in an engine cylinder turn the spray so that it maintains a conical form with a bent axis. The cone angle of the plumes is a function of air density.

   In the doughnut model it is assumed that the doughnut cross-sectional area and circulating velocity relative to the surrounding air vary to conserve momentum. The rate of entrainment of air is the same as for a fuel spray of similar cross-sectional area and velocity relative to the surrounding air. The doughnut cross-sectional area is zero at the beginning of injection and increases as it is fed fuel and momentum from the central nozzle. At the end of injection no further momentum is added, but the cross-sectional continues to expand by entraining air.

5. Rate of turbulent mixing of fuel and air. It is assumed that the regions of weak mixture consist solely of air, and the regions of rich mixture consist solely of fuel vapor. The concentrations of fuel or air, or mixed fuel and air, are calculated by dividing the total mass of the component in the spray by the total instantaneous volume of the spray.

The turbulent mixing of fuel vapor and air within the body of the fuel spray is represented by a diffusion process. To simplify the treatment, the mean rate of diffusion per unit volume of the spray is equated to the concentration of the component (air or fuel vapor) which is diffusing, multiplied by a diffusivity coefficient.

6. Rate of burning of fuel based on chemical rate of fuel is calculated by an Arrhenius type formula in which the specific rate of burning is proportional to the product of mean concentrations of turbulently mixed fuel and air, and is a function of temperature. The temperature is calculated from the pressure and cylinder volume.

   The use of mean concentration of mixed fuel and air implies that the jet is geometrically similar from time to time.

Results of Simulation - Calculates rate of heat release. Calculates rate of air entrainment into the spray for the conical plume model.

ASSUMPTIONS

Swirl has no effect on the mixing rate, apart from turning the spray to prevent it hitting the wall of the combustion chamber.

LIMITATIONS

Droplet evaporation is not evaluated separately.

DATA INPUT REQUIREMENTS

Geometrical and Design Parameters:

1. Bore
2. Stroke
3. Nozzle hole size
4. Number of nozzles

Operating Parameters:

1. Speed
2. Instantaneous compression ratio
3. Inlet manifold air conditions
4. Volumetric efficiency
5. Mean fuel injection pressure
6. Period of injection

TITLE	Wisconsin Diesel Spray Combustion Model
DATE	1969
AUTHORS	Shipinski, Myers, and Uyehara
ORGANIZATION	University of Wisconsin
SPONSOR	Unknown
TRANSPORTATION MODE	All modes
APPLICATION	Civilian or Government
OBJECTIVE	To predict the burning rate of a diesel spray as a function of fuel injection parameters.
REFERENCES	(1) Shipinski, J., Myers, P.S., and Uyehara,, O.A., "A Spray-Droplet Model for Diesel Combustion," Proc. IME, Vol. 184, Part 3J, p. 28, 1969. (2) Shipinski, J.H., "Relationships Between Rates-of-Injection and Rates-of-Heat Release in Diesel Engines," Ph.D. Thesis, University of Wisconsin, 1967.
RELATIONSHIP TO OTHER MODELS/HISTORY OF MODEL	Shipinski's model was the forerunner of the current diesel models which attempt to describe the spray combustion in detail (Ultrasystems, Cummins, Hiroshima). He attempted to extend the work of Lyn (1961) on diesel burning rates, by using the gas turbine spray results of Probert (1946) and Tanasawa (1953).
OPERATIONAL CAPABILITIES	Results of Simulation: - For direct injected engines - Calculates fuel spray evaporation and mixing with air - Calculates thermal efficiency or fuel consumption (isfc) - Calculates heat transfer to walls

Structure: List of submodels or processes included.
- Fuel injection and atomization
- Fuel evaporation
- Ignition delay
- Combustion rate
- Gas properties

ASSUMPTIONS

Intake, exhaust: Not included

Fuel spray evaporation: Tanasawa (1953) dropsize distribution and vaporization coefficient C_b.

Ignition delay: Correlation of Wolfer (1939)

Combustion rate/mixing of air-fuel:

(a) Premixed combustion stage occurs at specified rate.

(b) Vaporization - limited combustion occurs according to a single droplet law with a specified burning coefficient C_E which depends on A/F, P, rpm, and temperature.

Fuel-air ratio of burned gas: 2-zone model

Gas properties: Standard tables

Heat transfer: Treated implicitly

No_x Model: Not included

Soot Model: Not included

Burned gas mixing: Not included - all burned gas in single zone.

LIMITATIONS

(1) No attempt to cover the air entrainment or variations in A/F ratio of burned gas and resulting gas temperature non-uniformities.

(2) Treatment of heat transfer is not clear from the paper; however, it can be surmized that the heat transfer model is not based on radiation or boundary layer details.

(3) Emissions (soot, NO_x) are not covered.

(4) Closed cycle only; intake and exhaust processes not included.

DATA INPUT REQUIREMENTS

Geometrical and Design Parameters:
- Bore
- Stroke
- Conn. rod length
- Chamber volume

Model Coefficients:
- Vaporization coefficient C_b
- Burning coefficient C_F

Operating Parameters:
- Load
- Speed
- Injection timing
- Intake manifold temperature
- Intake manifold pressure
- Residual fraction
- Injection rate
- Fuel orifice size and number
- Fuel injection pressure

ADVANTAGES

(1) Covers the effect of fuel injection variables such as hole size and injection pressure on the combustion rates.

(2) Emphasizes physical mechanisms of spray combustion rather than empiricism.

VALIDATION

Engine description: 2,000 rpm, 175 imep, automotive diesel (4.5 in bore, 4.5 in stroke)

Variables tested; model agreement: Predicted cylinder pressure vs. crank angle showed good agreement with data.

	Assessment of accuracy: Fair accuracy and more flexibility than empirical models such as Woschni.
COMPUTING REQUIREMENTS	Not specified.
COST OF OPERATION	0.5 minutes of CPU time at $60 to $100/min (estimated)
FUTURE POTENTIAL	This early work provided a foundation for many of the state-of-the-art diesel models.
AVAILABILITY	Presumably could be obtained from Prof. Borman at Wisconsin, or from Shipinski, who is at John Deere, Waterloo, Iowa.

TITLE	Imperial College (Watson)
DATE	1977-1980
AUTHORS	Watson, N., and Marzouk, M.
ORGANIZATION	Imperial College, Dept. of M.E., London
SPONSOR	Unknown
TRANSPORTATION MODE	All modes
APPLICATION	Civilian or Government
OBJECTIVE	To correlate diesel performance with operating parameters.
REFERENCES	(1) Marzouk, M. "Transient Response of Turbocharged Diesel Engines," Ph.D. Thesis, University of London, 1976. (2) Watson, N., and Marzouk, M., "A Non-Linear Digital Simulation of Turbocharged Diesel Engine Simulation," SAE Paper 770123, 1977. (3) Watson, N., Pilley, A.D., and Marzouk, M., "A Combustion Correlation for Diesel Engine Simulation," SAE Paper 800029, 1980.
RELATIONSHIP TO OTHER MODELS/HISTORY OF MODEL	Similar to the approaches of Shipinski et al (1968) and Woschni and Anisits (1974), this simulation does not describe the fuel-air mixing and combustion processes. Instead, the shape of the burning rate curve is postulated. The coefficients are then related to speed, load, timing, air temperature, etc.
OPERATIONAL CAPABILITIES	Output of Simulation: - For direct injected engines, calculates rate of pressure rise, maximum pressure - Calculates intake and exhaust flows - Calculates thermal efficiency or fuel consumption (isfc)

Structure: List of submodels or processes included
- Ignition delay
- Combustion rate; fuel-air mixing
- Gas properties

ASSUMPTIONS

(1) Intake, exhaust: Incompressible flow

(2) Ignition delay: Correlation based on Wolfer ($E = 4200$ cal/mole)

(3) Combustion rate/Mixing of air-fuel: Wiebe function for diffusion-controlled burning.

(4) Gas properties: Standard tables

(5) Heat transfer: Indirectly incorporated in choice of Wiebe function coefficients.

LIMITATIONS

(1) Does not predict temperature profiles within the combustion space.

(2) Does not predict soot or NO_x emissions

(3) Cannot be used to predict the effect of chamber shape, fuel injection parameters, air swirl, etc.

(4) Requires experimental data such as cylinder pressure trace for each specific engine to be simulated.

DATA INPUT REQUIREMENTS

Geometrical and Design Parameters:
- Bore
- Stroke
- Connecting rod length
- Chamber volume
- Valve areas vs. time

Combustion Rate Coefficients:
- Δ (combustion duration)
- β (premixed proportion)
- Cd_1 (rate of diffusion burning)
- Cd_2 (shape parameter)

Operating Parameters:
- Load
- Speed
- Injection timing
- Intake manifold temperature
- Intake manifold pressure
- EGR or residual fraction

ADVANTAGES

(1) Relatively inexpensive

(2) Useful for extending known engine performance to changing altitude, air temperature, boost, etc.

VALIDATION

Engine descriptions:
- Engine 2 - V8, turbocharged 2600 RPM, 10.7 bar bmcp
- Engine 1 - turbocharged truck engine, 6 cyl., deep bowl, 2500 RPM

Variables correlated:
- Peak pressure
- Apparent ignition delay

Assessment of accuracy:
- 5-10 percent error in predicting the effects of pressure, turbocharger speed, air-fuel ratio.

COMPUTING REQUIREMENTS

Not specified.

COST OF OPERATION

0.5 minutes of CPU time at $60 - 100/min (Estimated)

FUTURE POTENTIAL

Model is of limited use for detailed model predictions. Not intended to be readily modified for emissions or performance design studies.

AVAILABILITY

Unknown

TITLE	Computer Simulation of a Diesel Engine: I.I.T., Delhi
DATE	1974-1976
AUTHORS	Garg, R.D., Agarwal, K.K., and Desikachari, R.
ORGANIZATION	I.I.T., Delhi
SPONSOR	Indian Institute of Technology (Industry-Supported)
TRANSPORTATION MODE	All modes
APPLICATION	Civilian or military
OBJECTIVE	To evaluate the accuracy of various diesel heat transfer models. To predict basic thermodynamic performance characteristics (imep, P_{max}, $P(\phi)$, exhaust temperature, heat loss, and efficiency) subject to variations in (a) timing, (b) rate of heat release, (c) overall A/F, (d) engine speed, (e) compression ratio, (f) air pressure and temperature.
REFERENCES	(1) Garg, R.D., Agarwal, K.K., and Desikachari, R., "Computer Simulation of a Diesel Engine," IE (India) Journal ME, Vol. 55, p. 67, November 1974. (2) Garg, R.D., Gaur, R.R., and Jagota, H., "Parametric Studies of a Four-Stroke Diesel Engine on Digital Computer," IE (India) Journal ME, Vol. 57, p. 112, September 1976.
RELATIONSHIP TO OTHER MODELS/HISTORY OF MODEL	This model, which appears to be based on the dissertation of Agarwal and Desikachari, draws from the early work of Whitehouse, et al (1962), Austen and Lyn (1962), and Woschni (1967).

OPERATIONAL CAPABILITIES

Results of Simulation:

- Direct or Indirect Injected Engines
- Calculates Intake and Exhaust Flows
- Calculates Thermal Efficiency or Fuel Consumption (isfc)
- Calculates Heat Transfer to Walls

Structure: List of Submodels or processes included.

Included	Not Included
Intake, exhaust	Fuel injection
Combustion rate	Fuel evaporation
Gas properties	Ignition delay
Heat transfer	Fuel-air mixing
	NO_x Model
	Soot Model
	Mixing of burned gas

ASSUMPTIONS

Intake, exhaust: The 1976 paper treats the manifold and valve phenomena as 1-D compressible, quasi-steady flow; with specified volumetric efficiency and residual fraction. Flow may be either subsonic or sonic.

Fuel spray evaporation: Not treated.

Ignition delay: Specified. Ignores effect of variables such as engine speed on the delay period.

Combustion rate: Based on Lyn (1960) and Woschni (1962). Specified triangular rate law; 40 degrees duration.

Fuel-air ratio of burned gas: Not treated. Each successive burned gas element has an individual temperature, however.

Gas properties: From Keenan and Kaye.

Heat transfer: Wall temperature assumed. Four models examined:

- Nusselt
- Eichelberg (appeared best)
- Annand
- Woschni

NO_x Model: Not treated.

Soot Model: Not treated.

Burned gas mixing: Not treated.

LIMITATIONS

(1) Not intended to treat fuel-air mixing and gas temperature non-uniformities: variations in F/A of burned gas not treated.

(2) Inadequate treatment of heat transfer: Boundary layer near wall not treated. Also heat transfer by radiation not treated (and effect of soot).

(3) Does not calculate emissions (soot, No_x, HC. CO)

(4) Cannot predict effects of air swirl, fuel orifice changes, or piston shape.

(5) Arbitrarily assumes combustion efficiency is 92% to 96%, depending on CR.

DATA INPUT REQUIREMENTS

Geometrical and Design Parameters:
- Bore
- Stroke
- Conn. rod length
- Chamber volume
- Valve areas vs. time

Model Coefficients:
- Ignition delay
- Combustion duration
- Heat transfer coefficient

Operating Parameters:
- Load
- Speed
- Injection timing
- Intake manifold temperature
- Intake manifold pressure
- Residual fraction and volumetric efficiency
- Injection rate and duration
- Cylinder wall temperature

ADVANTAGES

- Does treat the complete cycle of a four-stroke engine, including intake and exhaust processes.
- Relatively simple and inexpensive.
- Could be used to estimate effect of engine parameters on imep, efficiency.
- Interesting framework for comparing heat transfer models.

VALIDATION

Engine description:

(1) 6-cylinder, precombustion chamber, 4.58 liter, 100 HP @ 3,000 RPM, CR = 19.5

(2) 6-cycle, direct injection, 11.1 liter, 147 HP @ 2,000 RPM, CR = 15.8

Variables tested; model agreement
- Speed
- Fuel timing and duration
- Air temperature
- Stroke/bore ratio

Model agreement is fair.

Assessment of accuracy: Stated in the reference, cylinder pressure phase error of about 5 degrees is disturbing. Model only checked against power output (20% lower than measured).

COMPUTING REQUIREMENTS	Program called "ENGINE"; Fortran IV
COST OF OPERATION	Approximately 1 minute of CPU time at $60 to $100/min (estimated)
FUTURE POTENTIAL	Not superior to other models of this type such as: • Manchester (Whitehouse) • Cummins (Austen & Lyn) • Wisconsin (Myers, et al)
AVAILABILITY	Presumably could be made available.

TITLE	M.A.N.
DATE	1974
AUTHORS	Woschni, G., and Anisits, F.
ORGANIZATION	M.A.N. Augsburg and Institut fur Kolbenmaschinen Technical University
SPONSOR	M.A.N.
TRANSPORTATION MODE	All modes
APPLICATION	Civilian or Government
OBJECTIVE	To predict the effect of altered operating conditions (i.e., fuel-air ratio, air temperature, engine speed, and timing) on heat release rate in a diesel engine. From heat release rate, then, one can determine thermal performance parameters such as maximum pressure, isfc, etc.
REFERENCES	Woschni, G., and Anisits, F., "Experimental Investigation and Mathematical Presentation of Rate of Heat Release in Diesel Engines Dependent Upon Engine Operating Conditions," SAE Paper 740086, 1974.
RELATIONSHIP TO OTHER MODELS/HISTORY OF MODEL	The present work developed from Woschni's earlier research into heat transfer (SAE Paper 670931, 1967), and on the computation of thermal loads on diesel engine components (MTZ Vol. 31, No. 12, p. 491, 1970). Woschni's approach relies on empirical determination of a four-parameter expression for heat release and deliberately avoids any attempt to model the fuel spray combustion mechanism.
OPERATIONAL CAPABILITIES	Results of Simulation: - Direct injected engines - Calculates cylinder pressure vs. crank angle, including pressure rise rate and maximum pressure - Calculates thermal efficiency or fuel consumption (isfc) - Calculates heat transfer to walls

Structure: List of submodels or processes included.
- Computation starts after valves close
- Ignition delay
- Combustion rate

ASSUMPTIONS

- Intake, exhaust: Not included
- Fuel spray evaporation: Not included
- Ignition delay: Arrhenius expression, following Wolfer (1938).
- Combustion rate/mixing of air-fuel: Weibe function with empirical coefficients.
- Fuel-air ratio of burned gas: Not included
- Gas properties: Presumably standard thermodynamic tables.
- Heat transfer: Not explicitly modelled; the Weibe function accounts for both burning rate and heat loss rate.
- No_x Model: Not included
- Soot Model: Not included
- Burned gas mixing: Not included

LIMITATIONS

(1) Limited treatment of heat transfer, which is "folded" into the Weibe function, which essentially gives the <u>net</u> heat release over and above the heat lost to the walls.

(2) Does not attempt to treat fuel-air mixing or gas temperature non-uniformities.

(3) No attempt to model emissions (soot, NO_x).

(4) Experiments required to fix coefficients for each engine to be modelled (this is true for most models).

Application is limited (this is true for most models).

DATE INPUT REQUIREMENTS

Geometrical and Design Parameters:
- Bore
- Stroke
- Conn. rod length
- Chamber volume
- Valve areas vs. time

Coefficients (empirical):
- Ignition delay coefficients (a,b,c)
- Effective air-fuel equivalence ratio
- Duration of combustion
- Weibe function parameter, m

Operating Parameters:
- Load
- Speed
- Injection timing
- Intake manifold temperature
- Intake manifold pressure
- EGR or residual fraction
- Cylinder wall temperature

ADVANTAGES

- Very simple to use, once coefficients are determined semi-empirically.
- Weibe function simulates the physical mechanisms of diesel combustion and heat transfer moderately well, even though it was developed by Weibe for spark ignition engines.

VALIDATION

Engine description:

(1) Low speed, 2-stroke engine of 39.4 in. bore.
(2) Medium speed, 4-stroke engine of 15.7 in. bore.

Variables tested; model agreement: Predicted power and peak pressure (not fuel consumption, on exhaust temperature) for variations in air temperature, air pressure, and timing.

	Assessment of accuracy: ±2% on heat release, but only after experimentation to establish coefficients for each engine.
COMPUTING REQUIREMENTS	Unknown
COST OF OPERATION	0.2 minutes of CPU time at \$60 to \$100/min (estimated)
FUTURE POTENTIAL	Woschni is of the opinion that diesel simulations will continue to rely on empirical data. He considers the modelling of details such as atomization, fuel jet spreading, wall impingement, and local gradients of temperature/concentration to be nearly impossible (and potentially expensive, if possible).
AVAILABILITY	This simple code could be written again by any user at low cost.

TITLE	Divided-Chamber Diesel Engine Model, MIT
DATE	Completed 1981
AUTHORS	S. Hossein Mansouri; John B. Heywood, and K. Radhakrishnan
ORGANIZATION	Massachusetts Institute of Technology
SPONSOR	General Motors Corporation
TRANSPORTATION MODE	Highway
APPLICATION	Civilian
OBJECTIVE	The model was developed for a divided-chamber automotive diesel engine which describes the intake, compression, combustion and expansion, and exhaust processes in sufficient detail to permit calculations of pressure, fuel-air ratio distribution, heat release distribution, NO formation, particulate mass loading, and particulate oxidation processes. A feature of this model is the use of a stochastic mixing approach during the combustion and expansion processes to describe the nonuniform fuel-air ratio distribution within the engine. In this approach, the fuel-air ratio distribution during the combustion and emissions formation processes can be followed as it evolves with time. Primary output variables of interest are the fuel efficiency and the NO_x emissions.

REFERENCES

1. Mansouri, S.H., Heywood, J.B., and Radhakrishnan, K., "Divided Chamber Diesel Engine, Part I: A Cycle Simulation Which Predicts Performance and Emissions," SAE Paper 820273, 1982 SAE International Congress and Exposition, Meeting February 22-26, 1982.

2. Kort, R.T., Mansouri, S.H., Heywood, J.B., and Ekchian, A., "Divided Chamber Diesel Engine, Part II: Experimental Validation of a Predictive Cycle Simulation, and Heat Release Analysis," SAE Paper 820274, 1982 SAE International Congress and Exposition, Meeting February 22-26, 1982.

RELATIONSHIP TO OTHER MODELS

This is an original model which after its completion has been modified into a Spark Ignited Model and a Wankel Configuration Engine Model. It is currently being modified into an Open Chamber Diesel Engine Model under the sponsorship of NASA LERC.

HISTORY OF MODEL

No prior history.

OPERATIONAL CAPABILITIES

Model Description:

The flow into the engine cylinder during the intake process is modeled using quasi-steady one-dimensional flow equations. Mass flows past valves and between the two chambers are modeled by the equations for isentropic adiabatic flow through a nozzle. Discharge coefficients are used to relate the effective areas for the particular constriction (intake valve, connecting passageway, or exhaust valve) to the ideal areas for the isentropic flow. Plenum assumptions are used for the intake and exhaust manifolds.

The cycle-simulation uses a stochastic mixing approach during the combustion and expansion processes to describe the nonuniform fuel-air ratio distribution within the engine, including the way in which this distribution evolves with time. The combustion chamber is divided into three zones: the pre-chamber, the connecting passageway, and the main-chamber. In each zone, equal mass elements of air, fuel, and fuel-air mixture are present in proportions which agree with the overall fuel-air ratio in that region. These elements mix and react according to rules derived from classical models for turbulent reacting flows and combustion fundamentals. In this way, the fuel-air ratio distribution during the mixing, combustion, and emissions formation processes can be followed as it evolves with time.

The cycle-simulation is used to examine the origin of NO_x and particulate emissions in a divided-chamber diesel engine. The NO_x formation model is based on the extended Zeldovich kinetics in the burned gases. The particulate oxidation kinetic model proposed by Nagle and Strickland-Constable is coupled with the cycle-simulation. The particulate mass loading and the initial particulate size are regarded as inputs for particulate oxidation calculations. The initial value of particulate mass loading level, assigned to each element after it burns, is assumed to be the amount of solid carbon calculated from the chemical equilibrium model.

Results of Simulation:
- Calculates Volumetric Efficiency
- Calculates Heat Transfer During 4 Cycles
- Calculates Thermal Efficiency
- Calculates NO_x in Chamber and Total NO_x
- Calculates Particulate Emission

Modular Structure - Separate modules allow easy replacement or change:
- Intake
- Combustion
- Heat Transfer
- Property Routines, i.e., Gas Properties
- NO_x Model
- Particulate Formation Model

ASSUMPTIONS

This model is zero dimensional or quasi dimensional model. The model is based on a stochastic mixing model.

LIMITATIONS

A major limitation of this model is that it can't calculate local heat transfer, bulk heat transfer only. It does not have a detailed combustion model as the kinetics are not really known. The combustion model is a stochastic one based on modelling of steady state gas burners. The other limitation is the nondimensionality of the model compared to others which are two or three dimensional.

DATA INPUT REQUIREMENTS

The input data requirements are in addition to those addressed as givens:

Geometrical and Design Parameters:
1. Bore
2. Stroke
3. Connecting rod length
4. Prechamber volume
5. Main chamber volume
6. Passageway diameter
7. Intake valve diameter
8. Exhaust valve diameter
9. Intake valve opening time
10. Intake valve closing time
11. Exhaust valve opening time
12. Exhaust valve closing time

Data Base Requirements:
For this model, the pressure data required was generated from an experimental test of the 5.7L (350 cu. in.) diesel engine. The data from this engine which were compared to the model results for calibration are volumetric efficiency, pressure data for each chamber, thermal efficiency, and NO_x emission levels.

Operating Parameters:
1. Intake manifold pressure
2. Inlet mixture temperature
3. Exhaust system pressure
4. EGR rate in intake
5. Load: mass of fuel injected per cycle
6. Speed
7. Injection timing
8. Prechamber wall temperature
9. Main chamber wall temperature
10. Passageway wall temperature

ADVANTAGES

The main advantage to this model particularly as compared to the two or three dimensional models is that it requires a relatively small amount of computer time per run. Therefore, it is possible to run many cases at many different conditions to develop engine maps, to identify areas for engine tests for comparison, and to take various parameters or variables to their limits to understand the boundaries of the potential for the engine.

VALIDATION

Experimental data generated on a single-cylinder divided-chamber diesel engine (1979 5.7L GM) were used to verify the accuracy of the model predictions. Agreement between experimental data and predicted values of engine performance and NO_x emissions levels was good. The validation data is presented in the SAE paper referenced in this catalog entry.

Accuracy:
This model results in good agreement between the predicted values and experimental data for thermal efficiency, indicated mean effective pressure, peak pressure values, NO_x emission levels, and chemical ignition delay time. This agreement is obtained over the normal load, speed, and injection timing. The accuracy of the model prediction of particulate formulation is only fair.

Input Data Accuracy:
The actual values of the pressure data from an actual engine which is used as input data can be recorded to within $\pm 1\%$.

COMPUTING REQUIREMENTS

The program code is written in Fortran and is currently used on an IBM 370. Therefore, any major facility would likely have the capability to run the code. It is relatively easy to run and should take approximately one day to set up in another computing facility.

COST OF OPERATION

As it is currently used, the model requires about two minutes of CPU time. Each run costs approximately $20.

FUTURE POTENTIAL

This model is currently being modified under contract to NASA here to model an open chamber, turbocharged, turbo compounded, and four cycle diesel engine.

AVAILABILITY

The Divided-Chamber Diesel Engine model was developed with General Motors as a sponsor. Therefore, permission would need to be obtained from General Motors before the code could be made available to other users.

TITLE	Komatsu "DSA/DCE"
DATE	1978
AUTHORS	H. Hiraki J. M. Rife
ORGANIZATION	Komatsu/Massachusetts Institute of Technology
SPONSORS	Komatsu Ltd., Kawasaki, JAPAN
TRANSPORTATION MODE	Diesel engines used in buses, trucks, locomotives, marine
APPLICATION	Civilian and Government diesel engines
OBJECTIVE	To predict the performance and NO_x emissions of a direct injection diesel engine, given - Engine dimensions - Valve timing - Turbocharger characteristics - Cooling conditions
REFERENCES	Hiraki, H. and Rife, J.M., "Performance and NO_x Model of a Direct Injection Stratified Charge Engine," SAE 800050 (1980). Hiraki, H., "Performance and NO_x Model of a Direct Injection Stratified Charge Engine," S.M. Thesis, MIT, April 1978. Rife, J.M. and Heywood, J.B., "Photographic and Performance Studies of Diesel Combustion with a Rapid Compression Machine," SAE 740948, 1974. Hiraki, H. and Rife, J.M., "Performance Model for a Direct Injection Diesel Engine."
RELATIONSHIP TO OTHER MODELS/HISTORY OF MODEL	Texaco funded Hiraki and Rife at M.I.T. to develop a stratified-charge, spark-ignition engine model, which then served as the basis for a direct injection diesel model developed for Komatsu. (Hiraki now works for Komatsu.)

OPERATIONAL CAPABILITIES

Output of Simulation - Direct injected engines of four types:
- naturally aspirated
- turbocharged
- turbocharged - aftercooled
- turbocompound

Calculates intake and exhaust flows, including turbocharger performance matching.

Calculates thermal efficiency or fuel consumption (isfc).

Calculates wall temperatures and exhaust temperatures based on heat transfer to walls and coolant.

Calculates emissions (NO_x only).

Calculates fuel spray evaporation and mixing with air.

Structure: List of submodels or processes included
- Intake, exhaust, turbocharger
- Fuel injection and evaporation
- Mixing of fuel and air
- Ignition delay
- Combustion rate
- Gas properties
- NO_x model
- Heat transfer

ASSUMPTIONS

(1) Intake, exhaust:
Incompressible flow equations; turbocharger matching is performed

(2) Fuel spray evaporation:
Assumed instantaneous

(3) Mixing of fuel and air:
Turbulent jet entrainment expressions of Hoult and Well (1972). Air squish and swirl effects are also included. Took α = .11 for jet spreading angle.

(4) Ignition delay:
Derived from purely fluid mechanic description

(5) Combustion rate:
Each element is conical and starts burning at the boundary; "flame" propagates inward at at the turbulent flame speed (u' = s). Behind the "flame", eddies are assumed to exist which burn according to a turbulent entrainment law (Blizzard and Keck, 1970).

(6) Fuel-air ratio of burned gas:
Mixture is divided into elements of individual fuel-air ratio derived according to turbulent jet mixing theory.

(7) Gas properties:
Standard property equations for hydrocarbon air mixtures, developed by Heywood and Martin (1977).

(8) Heat transfer:
Separate Woschni (1967)-type heat equations for burned gas region and unburned region; area assumed proportional to mass.

(9) NO_x model:
Zeldovich kinetics with equilibrium values of H, O, O_2, and OH.

(10) Burned gas mixing: assumed to be negligible.

LIMITATIONS

(1) Does not treat the effect of fuel injector design changes on evaporation rate or atomization.

(2) Ignition delay treatment includes no chemical reaction rate effects. Initial ignition delay is user-specified.

(3) Inadequate treatment of heat transfer: No boundary layer included.

(4) Inadequate treatment of burned gas mixing: Cells are not allowed to mix with one another.

(5) Soot not included.

DATA INPUT REQUIREMENTS

Geometrical and Design Parameters:
- Bore
- Stroke
- Connecting rod length
- Chamber volume
- Valve areas   time

Operating Parameters:
- Load (fueling rate)
- Speed
- Injection timing
- Intake manifold temperature
- Intake manifold pressure
- EGR or residual fraction
- Injection rate
- Cylinder wall thickness and thermal properties
- Piston bowl diameter
- Fuel orifice size and number
- Swirl level
- Turbocharger characteristics
- Coolant flow rate and temperature

ADVANTAGES

(1) Includes detailed model of cylinder heat transfer to the coolant.

(2) Includes turbocharger matching calculation.

(3) Can predict the effect of fuel spray design parameters (orifice size, piston bowl diameter).

VALIDATION

Engine description:

(1) Komatsu S6D155 (155mm bore, 170mm stroke, 2000 RPM, CR - 14.5, 6 cyl, 380 hp)

(2) CAV engine (4 cyl, 1 liter, CR = 16)

C-3

Variables tested; model agreement:

(1) Effect of load:
Generally good agreement

(2) Effect of Timing:
Trends correct, but absolute bsfc values underpredicted by 5 - 10% and absolute NO_x values in error by up to 40%.

(3) Effect of swirl level:
Very good agreement for bsfc, ±20% for NO_x

Assessment of accuracy:

- Exhaust temperatures and wall temperatures incorrectly predicted because of oversimplified heat transfer model.
- Maximum pressure correctly predicted.
- NO_x predictions are useful to reveal trends but not absolute values.

COMPUTING REQUIREMENTS

Not specified

COST OF OPERATION

2 minutes of CPU time at $60-100/min (estimated)

FUTURE POTENTIAL

(1) Excellent framework for an improved heat transfer model.

(2) Includes turbocharger matching, which makes this model suitable for analyzing turbo-compound and adiabatic engines.

AVAILABILITY

Unknown; Current MIT model (by Mansouri et al) has taken a different direction.

TITLE	Cummins
DATE	1973 - 1978
AUTHORS	S.M. Shahed, P.F. Flynn, W.T. Lyn, W.S. Chiu
ORGANIZATION	Cummins Engine Co.
SPONSOR	Cooperative efforts with Mack Trucks, Inc.
TRANSPORTATION MODE	All diesel engines
APPLICATION	Civilian or Government
OBJECTIVE	Predictive capability for: - BSFC, rate of heat release - Emissions, (NO_x, soot, HC) - Direct Injection Engines
REFERENCES	Engine Modeling Conference, 1979 Combustion Institute, 1978 SAE Paper No. 760128, 1976 IME, 1975 SAE 730083, 1973
RELATIONSHIP TO OTHER MODELS/HISTORY OF MODEL	1962 Lyn's paper was the first to take "scientific" approach to diesel combustion modeling. Now R&D director at Cummins. 1970 Adler and Lyn (IME 1970) spray-in-swirl study; this paved the way. 1971 Shahed advised on CRC/EPA diesel model project. 1972 Preliminary model published. 1975 Added "fuel spray" submodel based on experimental results.
OPERATIONAL CAPABILITIES	See list of data input requirements. Model can predict the effect of these parameters on NO_x and isfc, including pressure as a function of crank angle.

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ASSUMPTIONS

- User specified ignition delay
- (1973)--All burned gas packages are at stoichiometric fuel-air ratio (no spray formation, droplet evaporation, or fuel-air mixing).
- (1973)--Heat release rate taken from empirical expression of Lyn (1972).
- Droplets not treated.
- Spray model for fuel-air mixing (1975):
  - (a) Hyperbolic distribution of F/A along spray axis
  - (b) Distribution across the spray obeys: $c/c_m = 1 - (y/b)^{1.5}$
  - (c) Spray growth equations for tip portion ($x \alpha t^{0.6}$) and width ($b \alpha x$)
- Flammable zones ignite and burning is controlled by the rate of entrainment of air.
- Flammability limits taken at $\phi = 0.5$ and $\phi = 3.0$.
- NO_x formation rate is single step Arrhenius expression with adjustable pre-exponential.
- Annand type heat transfer expression.
- Combustion does not affect mixing rates.

LIMITATIONS

- Only treats portion of cycle between ignition and valve opening.
- No droplet treatment.
- Direct injection only.

- 1973 version did not use authentic NO_x kinetic constants (fixed in 1975 version).
- 1973 version ignored details of spray combustion process. All burning gas is at single F/A ratio (fixed in 1975).
- No heat exchange between packages. (Some stay hot too long.)
- 1973 version used empirical heat release function (fixed in 1975).
- 1973 version could not predict smoke or CO, because no fuel rich zones (fixed in 1975).
- No spray impingement model.
- Instantaneous flame propagation after ignition.
- Radiation not treated well (not T^4).

DATA INPUT REQUIREMENTS

Operating Conditions	Engine Geometry
Injection timing	Bore
Injection duration	Stroke
Fuel orifice size and number	Conn. and length
Fuel injection pressure	Clearance volume
Swirl level	Angle of valve closure
Air temperature	
Air pressure	
Residual fraction	

ADVANTAGES

Does allow for temperature gradient (successive packages of burned gas have individual temperatures).

VALIDATION

1973 Version

(1) Validated against three engines.

(2) Agreement poor at light load naturally aspirated, high swirl, or high smoke conditions.

(3) Able to predict trends of NO_x vs. load, RPM, air temperature, timing, EGR.

1975 Version

(1) Validated against single cylinder engine

- speed	- injection pressure	- hole diameter
- load	- injection duration	- air pressure
- timing	- number of holes	- air temp.
- CR		

(2) Only presented results for injector hole diameter and air swirl.

(3) No_x predicted within ± 30% or so (needs further work).

COMPUTING REQUIREMENTS

Xerox Sigma 9 Computer. Presumably Fortran.

COST OF OPERATION

This model requires 3-5 minutes of CPU time ($60-100 per run) since it is iterative for each package at each crank angle.

FUTURE POTENTIAL

No further development of the Cummins Model is planned in the near future. When 1975 Model was published, the following capabilities were being added:

- Soot
- Hydrocarbon
- Radiation
- Heat transfer between zones
- Wall effects

AVAILABILITY

Unknown

TITLE	Ultrasystems Diesel Emissions Model
DATE	1974
AUTHORS	Kau, C.J., Wilson, R.P., Muzio, L.J., Waldman, C.H., Heap, M.P., and Tyson, T.J.
ORGANIZATION	Ultrasystems, Inc.
SPONSORS	EPA and Coordinating Research Council (CRC)
TRANSPORTATION MODE	Engine model applicable to all modes.
APPLICATION	Civilian or Government. Funded by Civilian sector.
OBJECTIVE	To predict NO_x and soot emissions of direct-injection engines based on detailed model of spray atomization, air entrainment, and droplet combustion.

REFERENCES

(1) Wilson, R.P., Waldman, C.H., and Muzio, L.J., "Foundation for Modeling NO_x and Smoke Formation in Diesel Flames," Final Report EPA-460/3-74-002a, January 1974.

(2) Wilson, R.P., and Waldman, C.H., "Assessment of Existing Models of Pollutant Formation in Diesel Combustion," Western States Section, Combustion Institute, Paper 74-1 (1974).

(3) Kau, C.J., Tyson, T.J., and Heap, M.P., "Study on Oxides of Nitrogen and Carbon Formation in Diesel Engines," Final Report Phases II and III, EPA-460/3-76-008a (March 1976)

(4) Kau, C.J., Heap, M.P., Tyson, T.J., and Wilson, R.P., "The Prediction of Nitric Oxide Formation in a Direct Injection Diesel Engine," Combustion Institute, 16th International Symposium, p. 337 (1976).

(5) Kau, C.J., and Tyson, T.J., "Computer Program Users Manual," March 1976, EPA-460/3-76-008-b.

RELATIONSHIP TO OTHER MODELS/HISTORY OF MODEL

Wilson, Waldman and Muzio (1974) surveyed previous diesel models and developed the framework for a new model which would include details such as fuel spray atomization, air entrainment, ignition, premixed and droplet combustion, and swirl effects. The model emphasis is on realistic temperature and fuel-air ratio variations within the chamber so as to accurately describe NO_x and soot formation. This model was put into a working computer code by Kau and Tyson (1976), who adjusted the model structure to agree with experimental data.

OPERATIONAL CAPABILITIES

Results of Simulation:
- Direct injected engines
- Calculates intake and exhaust flows
- Calculates thermal efficiency and fuel consumption (isfc)
- Calculates heat transfer to walls
- Calculates emissions (NO_x, soot)
- Calculates fuel spray evaporation and mixing with air

ASSUMPTIONS

Intake, exhaust: Compressible flow equations.

Fuel injection: Quasi-steady fuel jet with "Upper Limit" dropsize distribution.

Fuel evaporation: Godsave equation.

Air entrainment: turbulent jet with swirl, based on Adler and Lyn (1966).

Ignition delay: Based on Shipinski (1969) and Wolfer (1938).

Combustion rate:
(a) Premixed burning rate according to flame propagation.
(b) Mixing-limited burning rate according to both air entrainment and droplet combustion.

Gas properties: NASA equilibrium except carbon and NO_x.

NO_x model: Extended Zeldovich kinetics; formation in the burned gas and around droplets.

Soot model: Formation and oxidation rates of the Arrhenius form.

Mixing of burned gas with air: Dilution rate proportional to size of package and available air.

Heat transfer: Radiation, convection, and boundary layer effects.

LIMITATIONS

(1) Model does not predict spatial position of various phenomena.

(2) Cannot predict effect of chamber shape.

(3) Coupling of turbulence and burning rate needs further work.

DATA INPUT REQUIREMENTS

Geometrical and Design Parameters:
- Bore
- Stroke
- Conn. rod length
- Chamber volume
- Valve areas vs. time

Model Coefficients:
- Mixing coefficient for burned gas/air
- Air entrainment coefficient
- Vitiation coefficient
- Heat transfer coefficient

Operating Parameters:
- Load
- Speed
- Injection timing
- Intake manifold temperature
- Intake manifold pressure
- EGR or residual fraction
- Injection rate
- Cylinder wall temperature
- Fuel orifice size and number
- Swirl level

ADVANTAGES	(1) Model can handle design details such as fuel injection pressure, orifice size, and air swirl. (2) Model includes powerful heat transfer submodel, and includes a submodel for burned gas quenching (which most other models omit).
VALIDATION	Engine description: Single cylinder, 2.34 ℓ displacement, 1,500 RPM, CR = 17:1 Variables tested; model agreement: - Predicted cylinder pressure gave excellent agreement with data - Effects on NO_x of CR, turbocharging, timing, load, speed, swirl, and EGR all predicted to about 10-20%.
COMPUTING REQUIREMENTS	Fortran IV, CDC 6600
COST OF OPERATION	3 minutes of CPU time at $60 to $100/min
FUTURE POTENTIAL	Next plateau for this model is multi-dimensional coordinate system.
AVAILABILITY	Available through listing in reference (3) if not from Ultrasystems directly.

TITLE	Hiroshima
DATE	1974-1976
AUTHORS	Hiroyasu, H., Kadota, T.
ORGANIZATION	University of Hiroshima
SPONSOR	Japan Automobile Research Institute
TRANSPORTATION MODE	Applicable to all (highway, rail, marine or pipeline).
APPLICATION	Applicable to both military and civilian.
OBJECTIVE	To guide the design and development of direct injection diesel engines in order to achieve low emissions. Proposed low-emission designs are screened.
REFERENCES	SAE 760129 (Also see RELATIONSHIP TO OTHER MODELS).
RELATIONSHIP TO OTHER MODELS	Diesel counterpart to spark ignition engine model described in "Computer Simulation for Combustion and Exhaust Emissions in Spark Ignition Engine," 15th Symp. (Int'l) on Combustion, 1974, pp. 1213-1222, by same two authors. This model contains several submodels published separately: (1) Fuel Spray Model: Bulletin of the Faculty of Engineering, Hiroshima Univ. 23 #1 (1974), p. 55. (2) Droplet Model: SAE Paper 740445, SAE National Power Plant Meeting, Milwaukee, 1974. (3) Evaporation Model: JSME National Meeting, Paper 740-16, 1974.

(4) Ignition Model: Trans. JSME 41 #348 p. 2475 (1975).

(5) Fuel Injector Model: Trans. JSME 34 #260 p. 755 (1968).

ASSUMPTIONS

The major assumptions that the model is founded on are:

- Jet spreads at specified angle (no radial distribution) and entrains air.
- Same penetration for all packages.
- All droplets at same initial diameter; they evaporate without affecting each other.
- Vapor ignites after an ignition delay which is given by the expressions of Mullaney (1959), Hurn (1951).
- Diffusion flame exists around groups of droplets.
- Rate of burning controlled by fuel evaporation or air entrainment.
- All combustion at stochiometric.
- Heat transfer to walls by Woschni (1968) - no radiation.
- Each burnt gas package has its own temperature.
- Eleven species plus soot (all but NO_x and soot in equilibrium).

LIMITATIONS

- Restricted to portion of cycle when valves are closed. (No intake, exhaust, or turbocharger.)
- No rigorous treatment of wall impringement.
- Radiation heat transfer not explicitly treated.

- No mixing between neighboring packages.
- No way to model chamber shape effects.
- Weak on air motion and turbulence.

ADVANTAGES

- Cost effective.
- Minimum of empiricism.
- Includes spray details and thus can predict the effects of changes to fuel injector.

VALIDATION

Validated against Mitsubishi DT-6 engine, as shown in SAE Paper 760129 (1976).

Accuracy is sufficient to show emissions trends but not absolute values.

Accuracy: Model could be improved in the areas shown in LIMITATIONS. These improvements would make model more versatile but not necessarily more accurate.

Input Data Accuracy: Nothing special here: fuel schedule to nearest degree CA.

FUTURE POTENTIAL

Hiroyasu's plans - unknown.

TITLE	NREC DIESEL EMISSIONS MODEL
DATE	1971
AUTHORS	Bastress, Chng, and Dix
ORGANIZATION	Northern Research and Engineering Corp.
SPONSOR	EPA
TRANSPORTATION MODE	Non-specific (all diesel engines)
APPLICATION	Originally inter led for civilian, but applicable to military engines as well.
OBJECTIVE	Emissions predictions for developing design criteria for fuel injection systems for two types of diesels: - Direct injection - Indirect injection Output: - Emissions (NO_x) - Performance (isfc) Coefficients: - Specified evap. duration of rate (C_1) - Specified burn duration or burn rate (C_2) - Average fuel/air ratio during burning (F1) - Specified increment of fuel-air ratio (dispersion F) - Specified mixing cc efficient (C_3) - Specified heat tran fer coefficient (C_4)
REFERENCES	Bastress, E.K., Chng, I.M., and Dix, D.M., "Models of Combustion and Nitric Oxide. Formation in Direct and Indirect Injection Compression Ignition Engines." SAE Paper 7 9053, 1971.
RELATIONSHIP TO OTHER MODELS	This model was developed based on NREC's experience modeling gas tu bine engines. Some of the same assumptions are used for diesel engine combustion as were u ed for gas turbines (e.g., distribution of fue -air ratios).

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HISTORY OF MODEL

Model was constructed under contract to EPA.

OPERATIONAL CAPABILITIES

Model has the capability to predict the effect of each of the input parameters on NO_x emissions and performance (isfc).

ASSUMPTIONS

- Evaporation rate specified as Gaussian shape (Lyn 1960).
- Ignition delay correlation of Tsao (1962).
- "Backlog" of fuel vapor burns over a range of F/A, "new" fuel vapor burns at average F/A (specified).
- Mixing rate proportional to available volume of each package.
- Specified burn rate equal to or exceeding the evaporation rate.
- Heat transfer: coefficient which is specified.

LIMITATIONS

- Only portion of cycle with valves closed is modeled.
- Mixing law is arbitrary not mechanistic (no jet theory).
- Evaporation law is arbitrary not mechanistic (no spray, no droplets).
- Six arbitrary coefficients must be specified (some rules of thumb given in the paper for how to do this).
- No soot prediction.
- Poor heat transfer capability (adiabatic engine not readily modeled).

DATA INPUT REQUIREMENTS

Engine geometry: bore, clearance volume, conn-rod length, stroke (crank diameter), valve closing.

Operating conditions:
- Fuel mass, injection rate and timing
- Wall temperature
- Air pressure, temperature
- Residual fraction
- RPM
- Fuel schedule

Coefficients:
- Specified evaporation duration or rate (C_1)
- Specified burn duration or burn rate (C_2)
- Average fuel/air ratio during burning (F1)
- Specified increment of fuel-air ratio (dispersion F)
- Specified mixing coefficient (C_3)
- Specified heat transfer coefficient (C_4)

ADVANTAGES

- Simplicity
- Non-uniform temperature and fuel-air ratio is included.

VALIDATION

- Validated at single load and speed with 8-cylinder automotive engine (4 1/2" bore, 200 hp, 3200 RPM).
- Suspect that agreement would be relatively poor if the timing, speed, load, etc., of that engine had been varied.
- Attempts were made by Wilson and Kau in 1974 to use this model to fit some data from a 6"-bore Cummins diesel engine. Agreement was poor no matter what coefficients were picked.

Assessment of Accuracy

This model contains a number of mathematical (non-physical) expressions for evaporation, ignition, mixing, combustion. The coefficients must be changed for every engine the model is set up to simulate.

Substantial revisions would have to be made to improve this situation; it is doubtful if the effort would be worth it, compared to just using more physical models such as the Ultrasystems or Hiroyasu model.

COMPUTING REQUIREMENTS

Fortran; CDC, IBM machines. (Some code errors must be caught and fixed.)

COST OF OPERATION	Cost is relatively low, abcut $10-$20 per run.
FUTURE POTENTIAL	NREC is no longer ac*ive in this area.
AVAILABILITY	Public domain; was available from NREC for $100 in 1974; probably currently available.

TITLE	C.A.V. Diesel Emissions Model
DATE	1970-1973
AUTHORS	Khan, Greeves, Probert, Grigg, and Syed
ORGANIZATION	C.A.V. Ltd., Acton, London
SPONSOR	C.A.V. Limited
TRANSPORTATION MODE	All modes
APPLICATION	Civilian or Government
OBJECTIVE	This model is designed to predict soot and NO_x formation in direct-injection engines, as well as rate of heat release, isfc, and related performance parameters.
REFERENCES	(1) Grigg, H.C., and Syed M.H., "the Problem of Predicting Rate of Heat Release in Diesel Engines," Paper 18, Symposium on Diesel Engine Combustion, Institution of Mechanical Engineers, 1970. Also SAE Paper 700503, 1970. (2) Khan, I.M., Greeves, G., and Probert, D.M., "Prediction of Soot and Nitric Oxide Concentrations in Diesel Engine Exhaust," IME Publication C142, p. 205, 1971. (3) Khan, I.M. and Greeves, G., "A Method of Calculating Emissions of Soot and Mitric Oxide from Diesel Engines," SAE Paper 730169, 1973.
RELATIONSHIP TO OTHER MODELS/HISTORY OF MODEL	Grigg and Syed (1970) developed the fuel-air jet mixing model as a basis for improved heat release predictions. Based on this model and emissions data of Khan and Wang (1971), an extended diesel emissions model was developed by Khan, Greeves, and Probert (1971). Then in 1973, an improved version was presented as SAE Paper 730169.

OPERATIONAL CAPABILITIES

Results of Simulation:
- Calculates fuel spray evaporation and mixing with air
- Direct injected engines
- Calculates rate of heat release
- Calculates thermal efficiency or fuel consumption (isfc)
- Calculates heat transfer to walls
- Calculates emissions (NO_x, soot, HC)

Structure: List of submodels or processes included:
- Fuel injection; fuel vapor jet
- Ignition delay
- Combustion rate (fuel-air macro-mixing and micro-mixing).
- NO_x Model
- Soot Model
- Heat transfer

ASSUMPTIONS

- Intake, exhaust: Not included
- Fuel spray evaporation: Instantaneous vaporization. Schweitzer formula for conical spray penetration and dispersion.
- Ignition delay: Specified empirically.
- Mixing of air-fuel: Air is entrained according to the fuel jet spreading expression. Entrainment and diffusion coefficients must be specified. Swirl effects on mixing rate are not treated.
- Fuel-air ratio of burned gas: Three zones (fuel vapor, burned gas, and air).
- Combustion rate: Proportional to air entrainment.
- Heat transfer: Annand-type expression.
- No_x Model: Zeldovich mechanism, but with adjusted coefficient.

- Soot Model: Arrhenius law for soot formation. Oxidation model not included.
- Burned gas mixing: Not included.

LIMITATIONS

(1) Inadequate treatment of fuel-air mixing and gas temperature non-uniformities. Predicted temperatures are too low.

(2) Inadequate treatment of heat transfer: single bulk gas temperature assumed rather than local hot zones.

(3) Inadequate treatment of burned gas mixing: some zones stay hot too long.

(4) Soot, NO_x: Neglects soot oxidation rate; also modified the NO_x rate constant.

DATA INPUT REQUIREMENTS

Geometrical and Design Parameters:
- Bore
- Stroke
- Conn. rod length
- Chamber volume
- Valve closure time

Model Coefficients:
- Soot rate coefficient
- Ignition delay
- Diffusion coefficient
- Entrainment coefficient as function of RPM and swirl

Operating Parameters:
- Load
- Speed
- Injection timing
- Trapped gas temperature and pressure
- EGR or residual fraction
- Fuel injection pressure
- Injection rate
- Cylinder wall temperature
- Fuel orifice size and number
- Swirl level

ADVANTAGES

(1) Takes into account fuel injection parameters and air swirl level in a simplified manner.

(2) One of few models to include treatment of soot formation.

VALIDATION

Engine descriptions:

(1) Turbocharged Dorman, 6LBT
(2) 0.97 ℓ engine
(3) 1.36 ℓ engine
(4) 1.89 ℓ engine

Variables tested; model agreement:

- Cylinder pressure traces were matched by the model with suitable coefficients.
- Soot predicted to ± 30% with variations in timing, rate of injection, load, swirl, and speed.
- NO_x trends predicted fairly well but not absolute values.

Assessment of accuracy: Sufficient for design guidelines but not a predictive emissions model.

COMPUTING REQUIREMENTS

Not specified.

COST OF OPERATION

1 minutes of CPU time at $60 to $100/min (estimated)

FUTURE POTENTIAL

No further work on this model has been published in the last 10 years.

AVAILABILITY

Possibly available from C.A.V.

TITLE	Cranfield Model
DATE	1971-1975
AUTHORS	D. Hodgetts, H.D. Shroff, I.R. Isaac
ORGANIZATION	Cranfield Institute of Technology
SPONSORS	UK government and industry
TRANSPORTATION MODE	All modes
APPLICATION	Civilian or Government
OBJECTIVE	To predict nitric oxide emissions of a diesel engine, taking into account gradients of temperature and concentration

REFERENCES

(1) Shroff, H.D., "The Simulation and Optimization of the Thermodynamic Processes of a Diesel Engine," Ph.D. Thesis, Cranfield I.T., 1971.

(2) Shroff, H.D., "The Simulation and Optimization of the Thermodynamic Processes of a Diesel Engine," SAE paper 740194, 1974.

(3) Isaac, I.R., "A Study of the Formation of Nitric Oxide in a Diesel Engine," Thesis, Cranfield I.T., 1971

(4) Hodgetts, D. and Shroff, H.D., "More on the Formation of Nitric Oxide in a Diesel Engine," Combustion in Engines, page 129, IME, London, 1976.

RELATIONSHIP TO OTHER MODELS/HISTORY OF MODEL

This model extends the earlier published diesel spray work of Austen and Lyn with the thesis works of Isaac and Shroff into a two-dimensional multi-zone diesel model. The authors also rely on the simple semi-empirical expressions of Whitehouse (IME, 1970), for combustion rate.

OPERATIONAL CAPABILITIES

Output of Simulation:
- Direct Injected Engines
- Calculates fuel spray evaporation and mixing with air
- Calculates heat transfer to walls
- Calculates emissions (NO_x only)

Structure: List of submodels or processes included
- Fuel injection
- Fuel evaporation
- Ignition delay
- Fuel-air mixing
- Combustion rate
- Gas properties
- NO_x model
- Heat transfer

ASSUMPTIONS

(1) Fuel spray evaporation: Rate of evaporation proportional to amount of liquid fuel remaining in each zone (Whitehouse, 1970).

(2) Mixing of air-fuel:
- Macromixing by jet entrainment (cosine variation of radial velocity);
- Micromixing controlled by fuel evaporation

(3) Ignition delay: Wolfer type expression

(4) Combustion rate
- Proportional to fuel and/or air available
- Arrhenius with 11 kcal/mole activation energy (essentially instantaneous combustion)

(5) Fuel-air ratio of burned gas:
Varies according to jet entrainment of air.

(6) Gas properties:
From McBride et al (NASA SP 3001)

(7) Heat transfer:
Used Woschni (SAE 670931) as the source, modified by turbulence coefficient;

(8) NO_x model:
Extended Zeldovich equations with partial equilibrium

LIMITATIONS

(1) Combustion rate expression is arbitrary and not physically related to the local mixing of fuel and air.

(2) Treatment of heat transfer does not include boundary layer. Heat transfer rate is proportional to volume of the zone instead of surface area.

(3) Inadequate treatment of burned gas mixing.

(4) Soot, HC, CO emissions are not included in the calculations.

(5) Fuel spray atomization and droplet surface area are not modelled.

DATA INPUT REQUIREMENTS

Geometrical and Design Parameters:
- Bore
- Stroke
- Connecting rod length
- Chamber volume

Computational Parameters:
- Number of zones across the jet

Operating Parameters:
- Load
- Speed
- Injection timing
- Gas composition and density (Intake manifold temperature, pressure and EGR or residual fraction) at valve closure
- Fuel injection rate
- Cylinder wall temperature
- Piston bowl diameter and volume
- Fuel orifice size and number
- Swirl level
- Turbulence factor

ADVANTAGES	This model is one of few diesel combustion simulation which attempts to treat the actual fuel-air ratio and temperature gradients produced by the burning fuel jet.
VALIDATION	Engine description: 6-cylinder, direct injection, 98mm bore, 127mm stroke Variables tested; model agreement: - Cylinder pressure versus crank angle (agrees to ±10%) - Rate of fuel injection (agrees) - Below 70% load NO_x emission agrees to ±20% for variations in load and speed. Above 70% load, model seriously in error because fuel jet predicted to be too fuel rich. Assessment of accuracy: Relatively poor accuracy due to limitations noted above. This model was a step in the right direction but (as the authors note) more work is needed in several areas.
COMPUTING REQUIREMENTS	Not specified
COST OF OPERATION	1 minute of CPU time at $60-100/min (Estimated)
FUTURE POTENTIAL	Model would need refinements in order to be useful: - Add a fuel spray atomization model - More work needed on wall impingement of fuel jet and associated air entrainment. - More work needed on overspill of burning mixture from piston bowl into the quench area. - More realistic combustion rate model. - Improved model for mixing of burned gasses.
AVAILABILITY	Possibly available through international technology exchange programs; Cranfield is analogous to NASA Lewis for the UK.

TITLE	Livermore Fuel Spray Model
DATE	1978
AUTHORS	Haselman, L.C. and Westbrook, C.K.
ORGANIZATION	Lawrence Livermore Lab., University of California, Livermore, CA.
SPONSOR	ERDA
TRANSPORTATION MODE	All modes
APPLICATION	Civilian or Government
OBJECTIVE	Two-dimensional model for fuel spray (applicable to either diesel or stratified charge).
REFERENCES	Westbrook, C.K., "Three-Dimensional Numerical Modeling of Liquid Fuel Sprays", 16th Symposium (Int'l) on Combustion, Cambridge, 1976. Westbrook, C.K., "Numerical Solution of the Spray Equation", UC. Lawrence Livermore Lab Report UCID-17361, 1977. Haselman, L.C., and Westbrook, C.K., "A Theoretical Model for Two-Phase Fuel Injection in Stratified Charge Engines", SAE 780318, 1978.
RELATIONSHIP TO OTHER MODELS/HISTORY OF MODEL	This Livermore computational effort on reciprocating engines was part of the ERDA/DOE joint industry/gov't. effort to further basic research on engines. General Motors Research Laboratories worked with Westbrook on the model.
OPERATIONAL CAPABILITIES	Output of Simulation: - Direct or indirect injected diesel engines, stratified charge engines also. - Calculates fuel spray evaporation and mixing with air.

Structure: List of submodels or processes included
- Fuel injection
- Fuel evaporation
- Fuel-in mixing
- Gas properties

ASSUMPTIONS

(1) Fuel spray injection and evaporation: Basic unsteady two-phase conservation equations are solved in two dimensions, with a minimum of simplifying assumptions. A droplet distribution function represents the location and size of the droplets. The effect of the droplet ensemble momentum on the air flow is included. The effect of fuel vapor saturation in dense sprays is also included. A source term for momentum (S_V) is used to simulate the spray.

(2) Mixing of air and fuel: Turbulent diffusion (coefficient specified) and spray evaporation determines the amount of air and fuel vapor in each call. Within each computational cell, the fuel is considered instantaneously well mixed.

(3) Gas Properties: Constant specific heat, unity Lewis Number, ratio of specific heats 1.4.

LIMITATIONS

(1) Covers fuel spray evaporation and mixing only, not ignition, combustion, heat transfer or emission formation.

(2) Relatively large computation time requirement.

DATA INPUT REQUIREMENTS

Geometrical and Design Parameters:
- Bore
- Stroke
- Connecting Rod Length
- Chamber volume
- Valve areas vs. time

Computational Parameters:
- α, turbulence coefficient
- grid spacing (typical 2 mm)

Operating Parameters:
- Load
- Speed
- Injection timing
- Intake manifold temperature
- Intake manifold pressure
- EGR or residual fraction
- Injection rate
- Cylinder wall temperature
- Piston or cylinder head shape
- Fuel orifice size and number
- Swirl level

ADVANTAGES

(1) Two-dimensional, can treat chamber shape effects.

(2) More realistic and accurate treatment of spray jet and air entrainment than most other models, except perhaps the GM or Princeton model.

(3) Includes unsteady effects of the spray penetration (most other diesel spray models are quasi-steady)

VALIDATION

Engine description: Model not tested against an actual engine. Instead, calculations were carried out for an ideal case of a flat circular disk chamber of 4 cm radius, 25 atm pressure, and 750°K temperature (similar to CR = 10/1 engine). Injector operates for 2 msec with fuel spray velocity 500 m/sec.

Assessment of accuracy: Cannot be gauged without measurements. However, model predictions appear qualitatively reasonable.

COMPUTING REQUIREMENTS

CDC 7600, Fortran IV

COST OF OPERATION

60-80 minutes of CPU time at $60-100/min for a 40x40 grid (droplet model). Approximately $5,000 - $6,000 per case.

FUTURE POTENTIAL	(1) Explore ways to shorten computer time (2) Couple with combustion model (3) Introduce ignition model (4) Add heat transfer (5) Add pollution formation
AVAILABILITY	Presumably available, since DOE sponsored the work.

TITLE	Princeton Internal Combustion Engine Model
DATE	1973-1977
AUTHORS	F.V. Bracco, H.C. Gupta, P.J. O'Rourke
ORGANIZATION	Princeton University
SPONSORS	National Science Foundation, EFDA, Volkswagen and Curtiss-Wright
TRANSPORTATION MODE	Diesel engines used in highway, rail, pipeline and marine transportation.
APPLICATION	Civilian and Military Engines
OBJECTIVE	To develop a multi-dimensional, spatially detailed model applicable to stratified change and diesel engines.

REFERENCES

(1) Bracco, F.V., "Introducing a New Generation of More Detailed and Informative Combustion Models," S.A.E. Transactions, 1975, Vol. 84, Presented at the S.A.E. International Stratified Charge Engine Conference, 30 October 1974.

(2) Bracco, F. V., "Theoretical Analysis of Stratified, Two-Phase Wankel Engine," Combustion Science and Technology, Vol. 8, Nos. 1 and 2, October 1973, pp. 69-84.

(3) Gupta, H.C., Bracco, F.V., and Westbrook, C.K., "Mathematical Modeling of Two-Phase, Unsteady, Two-Dimensional Flows", Paper G5 presented at the Fifth International Colloquium on Gas-dynamics of Explosions and Reactive Systems, 8 Sept. 1975.

(4) Bracco, F.V., Gupta, H.C., Krishnamurthy, L., Santavicca, D.A., Steinberger, R.L., and Warshaw, V., "Two-Phase, Two-Dimensional Unsteady Combustion in Internal Combustion Engines: Preliminary Theoretical-Experimental Results," Paper 760114 presented at the SAE Automotive Engineering Congress, 23rd Feb. 1976.

(5) Bracco, F.V., "Unsteady Combustion of a Confined Spray," American Institute of Chemical Engineers Symposium Series, Vol. 70, No. 138, 1974, pp. 48-56.

(6) Bracco, F.V., "Modelling of Two-Phase, Two-Dimensional Unsteady Combustion for Internal Combustion Engines," I. Mech. E. Paper C171-77, p. 167, 1977.

RELATIONSHIP TO OTHER MODELS/HISTORY OF MODEL

Related to the Los Alamos model; in that both use the "RICE" computer program for two-dimensional unsteady combustion. P.J. O'Rourke worked at both Los Alamos and Princeton on this model.

OPERATIONAL CAPABILITIES

Output of Simulation - For Direct and Indirect Injection Engines:

- Calculates fuel spray evaporation and mixing with air

- Calculates rate of heat release by combustion

- Calculates heat transfer to walls

- Calculates thermal efficiency and fuel consumption (isfc)

- Calculates emissions (NO_x)

Structure; List of submodels or processes included:
- Fuel injection and evaporation
- Mixing of fuel and air
- Ignition delay
- Combustion rate
- Gas properties
- Mixing of burned gas
- NO_x model
- Heat transfer

ASSUMPTIONS

Chamber dimensions: Fixed; No piston motion. The model is directed at the 30 degrees crank angle after TDC during which piston motion is negligible.

Fuel spray evaporation: Ranz-Marshall vaporization rate, Stokes' drag equation, mono-disperse spray, specified spreading angle.

Mixing of fuel and air: Turbulent mixing of evaporated fuel and air according to simple diffusivity model (isotropic). Entrainment of spray not modeled.

Ignition delay: At specified time, ignition is accomplished numerically in a corner of the chamber.

Combustion rate: One step irreversible reaction rate. Fuel and air react in stoichiometric proportions.

Gas properties: Constant ratio of specific heats (over simplified - no dissociation). Constant and equal specific heats and molecular weights for all species.

Mixing of burned gases: Turbulent mixing of burned gas according to simple diffusivity model.

NO_x model: Extended Zeldovich with all species in equilibrium except NO.

Heat transfer: Fractional reduction of the heat of combustion (user designated) (McAdams-type correlation used to estimate the fraction).

LIMITATIONS

(1) No simulation of compression and its effect on gas motion.

(2) Excessive computer time, particularly for spray case.

(3) Does not include model for entrainment of air into fuel jet which controls combustion rate, emissions and bsfc. Emphasis placed on flame propagation through the gas mixture, which is not critical for the diesel engine.

(4) Inadequate boundary layer heat transfer and turbulence models.

DATA INPUT REQUIREMENTS

Geometrical and Design Parameters:
- Bore
- Chamber volume
- Chamber shape (piston and head)

Operating Parameters:
- Load (fueling rate)
- Speed
- Injection timing
- Intake manifold temperature
- Intake manifold pressure
- EGR or residual fraction
- Injection rate
- Fuel orifice size and number
- Swirl level

Computational Parameters:
- Chemical reaction rate parameters
- Ignition time and location
- Eddy diffusivity (500 cm^2/sec)
- Spatial resolution (0.5 cm)
- Wall temperature
- Initial spray dropsize coefficient

ADVANTAGES

(1) One of the first models to appear which was spatially detailed.

(2) Attempts a detailed description of spray drag and evaporation

VALIDATION

Not validated against real engine data. Predicted profiles appear qualitatively reasonable but accuracy is untested.

COMPUTING REQUIREMENTS

Run on IBM 360/91, Fortran.

COST OF OPERATION

Without spray (flame motion only):
2 to 3 minutes computer time for each 1 msec (12°CA) engine process duration.

With spray:
Factor of 10 larger (20 to 30 minutes for each 12°CA engine process duration; estimated $5000 to $10000 for complete (360°CA) revolution).

FUTURE POTENTIAL

(1) Better way of accounting for turbulent mixing than the "diffusivity" approach.

(2) Inclusion of boundary layer concepts for wall heat transfer.

(3) Better coupling of spray equations with gas-phrase equations (e.g., Los Alamos approach).

AVAILABILITY

Presumably available, since ERDA/NSF sponsored much of the work.

TITLE	Imperial College Diesel Spray Model
DATE	1978-1980
AUTHORS	Gosman, A.D., Johns, R.J.R., Watkins, A.P., and Melling, A.
ORGANIZATION	Imperial College
SPONSOR	Perkins Engine Company and UK Scientific Research Council
TRANSPORTATION MODE	All modes
APPLICATION	Civilian or Government
OBJECTIVE	To predict the three-dimensional characteristics of a diesel spray mixing with air, including turbulence, droplet trajectory, droplet evaporation, and impingement. (Heat release and pressure rise are not predicted.)

REFERENCES

(1) Gosman, A.D., Melling, A., Whitelaw, J.H. and Watkins, A.P., "Axisymmetric Flow in a Motored Reciprocating Engine," Proc. I. Mech.E. 192, No. 11, p. 213, 1978.

(2) Gosman, A.D., and Johns, R.J.R., "Development of a Predictive Tool for In-Cylinder Gas Motion in Engines," SAE 780315, 1978.

(3) Gosman, A.D., Johns, R.J.R., Tipler, W., and Watkins, A.P., "Computer Simulation of In-Cylinder Flow, Heat Transfer and Combustion," 13th CIMAC Conference, 1979.

(4) Gosman, A.D., and Johns, R.J.R., "Computer Analysis of Fuel-Air Mixing in Direct Injection Engines," SAE Paper 800091, 1980.

(5) Gosman, A.D., Johns, R.J.R. and Watkins, A.P., "Development of Prediction Methods for In-Cylinder Processes in Reciprocating Engines," Combustion Modeling in Reciprocating Engines, p. 69, ed. by J.N. Mattavi and C.A. Amann, Plenum Press, 1980.

RELATIONSHIP TO OTHER MODELS/HISTORY OF MODEL

Gosman's group has pioneered the use of detailed multi-dimensional models for furnaces and gas turbines; these papers represent an attempt to apply these modeling techniques to diesel engines. The fuel spray model (SAE 800091) relies on the earlier work of Borman and Johnson (1962) on droplet evaporation and ballistics.

OPERATIONAL CAPABILITIES

Output of Simulation:
- Direct injected engines
- Calculates fuel spray evaporation and mixing with air in three dimensions, spatially resolved
- Calculates air motion and turbulence
- Does not calculate combustion rate or cylinder pressure

Structure; List of Submodels or processes included:
- Intake, exhaust
- Air motion
- Fuel injection and droplet trajectories
- Turbulence level
- Fuel evaporation
- Gas properties

ASSUMPTIONS

- Three-dimensional, axisymetric.
- Air motion: Conservation equations in moving, curvilinear orthogonal coordinates for axial, radial and circumferential velocity.
- Intake, exhaust: Orifice flow
- Turbulence: Two-equation model for turbulence energy and dissipation rate.
- Fuel spray: Pintle nozzle creates "ring" of spray. Discrete droplet parcels issue from atomization zone and are followed in Lagrangian coordinates.
- Dropsize distribution based on Hiroyasu (1978).

- Evaporation rate: Droplets evaporate by the d^2 Law.
- Assumes no effect of the spray on the turbulence.
- Wall impingement: droplets adhere to wall but continue to evaporate by the d^2 Law.
- Ignition delay: Not included
- Fuel-air ratio of burned gas: Not included
- Gas properties: Standard tables
- Combustion: Not included
- Heat transfer: Detailed gas temperature profile available, but boundary layer treatment not described (if any) and radiation not included.
- NO_x model: Not included
  Soot model: Not included

  Burned gas mixing: Not included, but easily added.

LIMITATIONS

(1) No ignition or combustion (fuel-air mixing only)

(2) Requires large amount of computer time.

(3) Inadequate treatment of heat transfer, which could be readily corrected to include boundary layer and radiation phenomena.

(4) Not capable of predicting emissions (soot, NO_x).

(5) Spatial resolution needed for the spray is much finer than that needed for the engine.

DATA INPUT REQUIREMENTS

Geometrical and Design Parameters:
- Bore
- Stroke
- Connecting rod length
- Chamber volume
- Valve area vs. crank angle

Model Coefficients:
- Turbulence energy coefficient
- Dissipation rate coefficient
- Mean droplet size
- Dropsize distribution coefficient
- Grid size
- Boundary conditions

Operating Parameters:
- Load
- Speed
- Injection timing
- Trapped gas pressure and temperature
- EGR or residual fraction
- Injection rate
- Cylinder wall temperature
- Piston or cylinder head shape
- Fuel orifice size and number
- Swirl level
- Spray angle

ADVANTAGES

This type of model is uniquely capable of describing the spatial distribution of the diesel spray, and the effect of chamber shape on air motion. Only the Los Alamos model is comparable in these ambitious features.

VALIDATION

Engine description: Open-chamber DI engine (9.14 cm bore, 12.7-cm stroke) with CR=21 at 1,400 RPM.

Variables tested; model agreement: Model not tested against experimental measurements. Computer plots appear plausible, however, and show that the spray creates its own turbulence.

Assessment of Accuracy: Agreement with motored engine velocity data was considered unacceptable by the authors.

COMPUTING REQUIREMENTS	IBM 360/195
COST OF OPERATION	40 minutes (about $3,000) for motored engine cycle (no fuel spray or combustion) with 30x30 grid. Presumably several hours ($10,000 or more) for a run with fuel spray, but still no combustion.
FUTURE POTENTIAL	(1) Need improved sub-models to avoid grid resolution problems. (2) Need to add ignition and combustion including the coupling between turbulence and heat release. (3) Need improved atomization model.
AVAILABILITY	Available through Gosman's consulting firm.

TITLE	Los Alamos Direct-Injection Engine Model
DATE	1978
AUTHORS	Butler, T.D.; Cloutman, L.D.; Krieger, R.B.; Dukowicz, J.K.; Ramshaw, J.D.
ORGANIZATION	Los Alamos/General Motors Research Lab.
SPONSORS	DOE (Contract W-7405-ENG-36)
TRANSPORTATION MODE	Diesel engines used in highway, rail, pipeline and marine transportation.
APPLICATION	Civilian or Military engines
OBJECTIVE	To compute the detailed (spatially-resolved) flow and temperature profiles in a direct-injection engine, and the resulting NO_x and power output (isfc).

REFERENCES

(1) Butler, T.D.; Cloutman, L.D.; Dukowicz, J.K.; Ramshaw, J.D.; and Krieger, R.B., "Toward a Comprehensive Model for Combustion in a Direct-Injection Stratified-Charge Engine," Combustion Modeling in Reciprocating Engines, p. 231, Ed. by J.N. Mattavi and C.A. Amann, Plenum Press, 1980.

(2) Hirt, C.W.; Amsden, A.A.; and Cook, J.D., "An Arbitrary Lagrangian-Eulerian Computing Method for All Flow Speeds," J. Comp. Phys. 14, p. 227, 1974.

(3) Dukowicz, J.K., "A Particle-Fluid Numerical Model for Liquid Sprays," J. Comp. Physics, 1980.

RELATIONSHIP TO OTHER MODELS/HISTORY OF MODEL

This model has an unusual history in that, unlike most engine simulations, the original computer code was developed by Los Alamos for nuclear fireball calculations. The "YAQUI," "RICE," and "APACHE" computer codes, developed from 1973 to 1979, provided the basis for computing turbulent fluid flow with chemical reactions. The idea of using a computational mesh which moves with the flow (with the piston) was an important break-through with these codes. The spray model is also taken from work on nuclear reactor two-phase flow.

OPERATIONAL CAPABILITIES

Output of Simulation - For Direct Injection Diesel Engines and Stratified-Charge Engines:

- Calculates fuel spray evaporation and mixing with air
- Calculates rate of heat release by combustion
- Calculates heat transfer to walls
- Calculates thermal efficiency and fuel consumption (isfc)
- Calculates emissions (NO_x only)

Structure; List of submodels or processes included:
- Compression/Expansion
- Fuel injection, atomization and evaporation
- Mixing of fuel and air
- Ignition delay
- Combustion rate
- Gas properties
- Mixing of burned gas
- NO_x model
- Heat transfer

ASSUMPTIONS

Compression/Expansion: 2-D axisymetric turbulent flow, with mesh moving with the piston. Turbulence represented by eddy diffusivity.

Fuel spray, atomization and evaporation: Spray is represented by a restricted number of discrete particles rather than as a continuum; this saves computer time. Each particle evaporates and exchanges momentum and energy with the gas. Dropsize distribution taken from Hiroyasu (SAE 740715) experiments.

Mixing of fuel and air: Spray entrainment calculated from an assumed spray angle by a "Monte Carlo" method,based on ballistics of the spray particles.

Ignition delay: Specified delay (1.7 msec), mixture ignited by artificially raising one zone to 1600K.

Combustion rate: Finite chemical reaction rates are taken into account using a single step global first order reaction for octane. Flame propagation rate determined by turbulent transport equations.

Gas properties: Temperature dependent ratios of energy/temperature for each specie.

Mixing of burned gases: Described by complete turbulent diffusion equations.

NO_x model: Extended Zeldovich mechanism, but omitting the N+OH reaction in lean regions. The oxygen atom and OH,H concentrations are taken from a table of equilibrium values.

Heat transfer: No wall heat transfer included. Energy transport within the gas described by conservation equation.

LIMITATIONS

(1) Does not include intake, exhaust flow through valves or turbocharger operation; deals with closed cylinder processes only.

(2) Heat transfer to the walls is not included in a realistic manner.

(3) Turbulence model is overly simple for this powerful type of computer model.

(4) Chemical reaction rate for combustion is an unnecessary feature since combustion is thought to be mixing controlled.

(5) Large computer time required.

DATA INPUT REQUIREMENTS

Geometrical and Design Parameters:
- Bore
- Stroke
- Connecting rod length
- Chamber volume
- Valve areas vs. time
- Chamber shape (piston and head)

Operating Parameters:
- Load (fueling rate)
- Speed
- Injection timing
- Intake manifold temperature
- Intake manifold pressure
- EGR or residual fraction (scavenging efficiency)
- Injection rate
- Fuel orifice size and number
- Swirl level; Initial charge velocity distribution.
- Initial fuel spray dropsize and velocity distribution.

Computational Parameters:
- Grid size (25x25 is typical)
- Turbulent eddy diffusivity coefficient
- Reaction rate coefficient
- Ignition delay
- Average droplet size
- Spray angle

ADVANTAGES

- Can predict development of flow field as affected by piston shape and compression.
- Can predict spatial flame propagation along spray and transition from premixed to diffusion mode.
- Can predict spatial temperature profiles which are quite important for heat transfer calculations.
- Can predict locations of peak NO_x formation.

VALIDATION	Engine description (hypothetical engine): stratified charge 98 mm bore, 95 mm stroke CR = 10 cup in piston 1600 rpm, low swirl n-octane fuel overall equivalence ratios $\phi = .95$ and $\phi = .50$ Variables tested; model agreement: Model not validated against experiments because flame traverses are not available for stratified charge or diesel engines.
COMPUTING REQUIREMENTS	Not specified
COST OF OPERATION	Estimated to be 10-100 minutes ($600-6000) per run on a large computer.
FUTURE POTENTIAL	(1) Need better turbulence model which includes both small scale diffusion and large scale "wrinkling" of the flame. Non-isotropic effects should be included. (2) Important processes occur on a sub-grid scale and, therefore, new sub-grid models are needed. (3) Need to add flame radiation and conductive heat flux to the wall, including boundary layer effects. (4) May need to add local peak temperature to get accurate NO_x predictions. (5) Need to add ignition delay model.
AVAILABILITY	Presumably available since DOE sponsored, unless military classified.

TITLE	Hybrid (Analog) Computer Simulation of the Sampled-Data Model for Compression Ignition Engines
DATE	1970
AUTHORS	C.R. Burrows, P.W. VanEetvelt, G.P. Windett
ORGANIZATION	University of Sussex
SPONSOR	None stated
TRANSPORTATION MODE	All
APPLICATIONS	Military or civilian
OBJECTIVE	To study the effects of non-linearities in fuel injection components and engine load. Output: - Engine speed as a function of non-linear fuel rack motion.
REFERENCES	International Journal of Control, 1971, vol. 14, no. 4.
RELATIONSHIP TO OTHER MODELS	This investigation built upon the pioneering work of Welbourn (1959), Bowns (1971) and Hazell and Flower (1971).
HISTORY OF MODEL	Developed to prove the viability of sampled-data theory to model fuel injection on compression ignition engines. Prior to this investigation, linear continuous control theory had been applied.
OPERATIONAL CAPABILITIES	Examination of the influences of non-linear or repetitive changes in fuel rack position on engine speed under quasi-steady state conditions.
ASSUMPTIONS	Relationship between fuel rack position and engine speed is a constant function for any given load.

LIMITATIONS	• Program only considers the grossest of effects of fuel rack position on engine speed. • Torque delay and other data must be empirically determined for each engine. • Constant Load. • Does not deal in <u>any</u> fundamental principals. Purely empirically based.
DATA INPUT REQUIREMENTS	• Number of cylinders. • Phase relationship and angle between fuel pulse and engine torque pulse. • Engine speed, at a constant load as a function of fuel rack position. Accuracy - Authors will explore an alternate model (pulse-width simulation) in pursuit of improved accuracy. Data Base - One for each engine at every load of interest.
ADVANTAGES	Simple
VALIDATION	Poor, but better than other, contemporary models.
COMPUTING REQUIREMENTS	Not stated; certainly antiquated.
COST OF OPERATION	Unknown.
FUTURE POTENTIAL	Superseded by newer models with better performance.
AVAILABILITY	Presumably available.

TITLE	Diesel Fuel Injection System Simulation and Experimental Correlation
DATE	1970-1973
AUTHORS	J.P. Bolt, M.F. El-Erian, E.F. Wylie
ORGANIZATION	University of Michigan, Ann Arbor
SPONSOR	U.S. Environmental Protection Agency
TRANSPORTATION MODE	Highway, predominantly
APPLICATION	Military and civilian
OBJECTIVE	To study the fuel flow and mechanical characteristics of jerk pump injection systems to understand and eliminate the cause of after-injection (needle bounce). Output - As a function of pump cam angle: - needle lift - pumping chamber pressure - delivery chamber pressure - pipe end pressure - upper nozzle pressure - injection chamber pressure
REFERENCES	EPA Report EPA-460/3-74-001 (NTIS No. PB 237 208) (contains SAE Papers 710569, 730661, 730662).
RELATIONSHIP TO OTHER MODELS	None stated.
HISTORY OF MODEL	One of the earliest significant contributions relative to fuel injection systems is due to Davis and Giffen. Their discussion includes mention of many of the significant variables involved in the system: fluid compressibility, elastic deformation, pressure wave propagation, fluid friction, and pump and nozzle characteristics, including secondary injection. L. Juhasz used graphical water hammer concepts to provide an analysis of a linear model of typical simplified injection systems, including the elements of the pipeline, pump, nozzle, and a fluid volume.

Giffen and Row theoretically solve the equations representing the injection system, taking into account the effect of pressure waves in the delivery pipe and the capacity effects of the volumes concentrated in the pump and nozzle system. They handled the differential equations by placing them in finite difference form and finding an algebraic expression for the solution. This method of solution was limited to simple injection models because of the time required for mathematical solutions.

Knight introduced a model for viscous friction and cavitation in the delivery pipe, and used the same model for the pump and nozzle system described in Giffen and Row. His calculations were performed on a digital computer.

Becchi used a model which comprised a detailed representation of the injector and the pump, but he neglected friction in the delivery pipe and had no provision for possible occurrence of vapor cavities. He solved the system of differential equations by an iterative method after writing them in finite difference form.

Brown and McCallion combined Becchi's detailed representation of the pump and injector with a model that included viscous friction and possible cavitation in the delivery pipe. They also considered a detailed modeling of the delivery valve as described by Stone, and solved the system of equations by another iterative method.

The work of Walwijk, Van der Graaf, and Jansen is also to be noted. Their experimental apparatus enabled them actually to measure the motion of the delivery valve and injector needle, as well as the pressure in various locations in the system. Particular attention was devoted to the motion of the delivery valve in their simulation on a digital computer. A good correlation was achieved between experimental and computed results.

All of the investigators discuss some of the factors that are likely to affect the accuracy of the model. The value of the delivery pipeline base pressure is important for a meaningful comparison between the model and experimental results. A treatment of vapor pressure in the delivery pipeline is also needed for a complete model. Kreith and Eisentadt, and Lichtarowicz, Duggins and Markland presented experimental results of the variation of the coefficient of discharge over a wide range of Reynolds number and length-to-diameter ratio. Giffen and Row cautioned of the danger of using coefficients of discharge from the literature. They preferred to use experimentally determined values for the particular nozzle under consideration. The data of Gelalles in which he tested different nozzle configurations showed that the coefficient of discharge, besides depending on length-over-diameter ratio and Reynold's number, is also greatly dependent on the configuration of the reservoir leading to the nozzle holes.

Recent investigators also give considerable attention to the stability and convergence of their solutions. Henrici discusses three different methods of numerical solution of a system of differential equations; the iterative solution of simultaneous algebraic equations, the expansion methods (Taylor's method or Runge Kutta method), and the numerical integration methods. The third method includes the predictor-corrector method which offers the advantage of an adjustable time increment, dependent upon a given error bound. This particular advantage is of great value especially for reducing computation time. The first and second methods require the use of very small time steps and a prior knowledge of the size of the time step.

OPERATIONAL CAPABILITIES

Influence of geometric and mechanical design changes on jerk pump injection system performance can be ascertained.

ASSUMPTIONS

- "Method of Characteristics," used
- Fluid compressibility described by bulk modules of elasticity which in turn varies with pressure.

- Elastic deformation of solid (metallic) system components is ignored.
- Flow in fuel lines described by one dimensional model.
- Frictional effects during unsteady flow assumed equal to steady flow losses at same velocity and fluid property, and is a function of Reynolds number.
- Vapor cavities grow and collapse in accordance with the dynamic equations and a local mass continuity balance.
- Orifice discharge coefficients based upon steady state data.
- Gravitational effects ignored.

LIMITATIONS

Wave propagation through the fluid in the pipeline is treated as the main cause of after injection, with the pump and injector bounding either end of the pipeline.

DATA INPUT REQUIREMENTS

- Base pressure
- System geometry/characteristics
  - pipe length
  - pipe diameter
  - pump characteristics
  - discharge coefficients
  - pipe cross sectional area
  - volume of fluid chamber/pump and injector
  - friction coefficient at valve or needle
  - injector spring force/stiffness
  - mass of valve or injector needle
- Fluid properties
  - bulk modules of elasticity
  - specific weight

Input Data Accuracy: None stated, although great pains were taken to assure accuracy of experimental data used to validate model.

ADVANTAGES	A predictor-corrector type solution to the model equations is used instead of the more popular Runge-Kutta method. This allows variable time step increments to be studied in fluid characteristics, improving model accuracy and economy, as small increments are examined only when necessary.
VALIDATION	Comparisons against experimental data indicate that the model has very good overall correlation with dynamic phenomena.
COMPUTING REQUIREMENTS	None stated.
COST OF OPERATION	Not stated.
FUTURE POTENTIAL	None stated.
	Potential Accuracy: Some fine tuning of flow coefficients and pressure data suggested. Quantifiable improvement potential not stated.
AVAILABILITY	From the EPA (Jose L. Boscunana, Project Officer in 1974).

TITLE	Simulation of Processes of Fuel Injection (INJEC)
DATE	1971
AUTHORS	M. Ikegami, H. Horike, F. Nagao
ORGANIZATION	Kyoto University
SPONSOR	None stated; may be Kawasaki Heavy Industries
TRANSPORTATION MODE	All
APPLICATIONS	Military and civilian
OBJECTIVE	To model the fuel flow and pressure within a diesel fuel injection system as a function of time. Output: Fuel pressure as a function of time.
REFERENCE	Bulletin of Japanese Society of Automotive Engineers, No. 5, 1973.
RELATIONSHIP TO OTHER MODELS	None
HISTORY OF MODEL	Original model
OPERATIONAL CAPABILITIES	• Presents graphical display of fuel system pressure and flow rate as function of time at a given engine speed and rack position. • Can study different fuel system volumes, injector characteristics, pump characteristics. • Steady state.
ASSUMPTIONS	• Fuel is incompressible. • Speed of sound in fluid constant. • No wave effects. • Fuel system completely rigid. • No voids form in fuel in system.

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LIMITATIONS	• Effect of cylinder pressure change during injection ignored. • Wave or resonance effects ignored. • Ignores injector needle bounce.
DATA INPUT REQUIREMENTS	• Fuel system dimensions, volumes, orifice areas and flow coefficients • Delivery valve lifts and masses. • Cam (plunger drive) characteristics. • Delivery spring rates. • Injector nozzle needle lift, spring rate, mass and flow coefficients. • Cylinder pressure during injection.
ADVANTAGES	Authors report favorable trade-off of accuracy for reduced computing time.
VALIDATION	"Reasonable accuracy" reported for validation against one Bosch pump (PE1A60B100) and injector nozzle (DN4SI-pintle type). Accuracy: Not stated.
COMPUTING REQUIREMENTS	FACOM 230-60 system.
COST OF OPERATION	12 seconds/iteration at best; 5 iterations per run.
FUTURE POTENTIAL	Not stated.
AVAILABILITY	Presumably from Kyoto University.

TITLE	Characterization and Simulation of a Unit Injector
DATE	1975
AUTHORS	N.A. Henein, T. Singh, J. Rozanski
ORGANIZATION	Wayne State University
SPONSOR	U.S. Army Automotive Tank Command
TRANSPORTATION MODE	Highway, marine
APPLICATION	Military or civilian
OBJECTIVE	To simulate the fuel pressure histories within a unit injector as a function of cam angle. Output: - Pressure vs. camangle - Fuel flow vs. camangle
REFERENCE	SAE paper 750773.
RELATIONSHIP TO OTHER MODELS	None.
HISTORY OF MODEL	None mentioned.
OPERATIONAL CAPABILITIES	Steady fuel pressure and flow as a function of camshaft angle for a variety of speed and rack positions once the pressure history is known for at least one condition.
ASSUMPTIONS	• There are no wave effects or voids in the system due to short path lengths. • Leakage, flow coefficients, and backpressure on needle assembly constant under all conditions.
LIMITATIONS	• Limited to unit injector. • Empirically calibrated • Applications to non DDA injectors questioned.

DATA INPUT REQUIREMENTS

- Injector system masses
- Spring constants
- Volume of injector chamber
- Fuel bulk modulus
- Discharge coefficients
- Flow areas
- Pressure and flow vs. camangle for one condition

Data Base: Fairly extensive instrumentation needed to get calibration data. However, program done for U.S. government. Data may be available from TACOM.

ADVANTAGES

Fairly simple model.

VALIDATION

"Fairly good," although pressure oscillations not predicted.

COMPUTING REQUIREMENTS

Not stated.

COST OF OPERATION

Low = small programs.

FUTURE POTENTIAL

Could perhaps be better "tuned."

Potential Accuracy: Needs to incorporate wave phenomena.

AVAILABILITY

Presumably available (U.S. government contract).

TITLE	Computer Model of the Electronic Control System (ECS) for Diesel Fuel Injection Timing
DATE	1982.
AUTHORS	M.J. Pipho, D.B. Kittelson.
ORGANIZATION	University of Minnesota.
SPONSOR	Optimizer Control Corporation.
TRANSPORTATION MODE	All
APPLICATION	Military and civilian.
OBJECTIVE	To simulate the performance of the ECS control and engine system and to determine the effects of ECS changes on system response and performance. Output: See list under Operational Capabilities.
REFERENCE	Closed Loop Digital Electronic Control of Diesel Engine Timing, SAE paper 830579.
RELATIONSHIP TO OTHER MODELS	None.
HISTORY OF MODEL	None stated.
OPERATIONAL CAPABILITIES	Explore response with respect to time of injection timing and engine: - Speed - Emissions - BSFC - Smoke (Bosch) - Power as a result of changes in - ECS characteristics - Load - Engine speed

ASSUMPTIONS	• Steady state engine maps valid for transient operation. • Engine can be modeled as a simple inertia system.
LIMITATIONS	• Model focuses on ECS made by Optimizer Control Corp., probably not relevant to other control systems. • 2000 rpm maximum right now due to validation limitations (Model not limited, ECS is limited).
DATA INPUT REQUIREMENTS	Engine: - Initial and off set point conditions - Inertia - Fuel maps - Emission maps - Smoke maps - Speed/power/timing maps ECS Characteristics: - Signal pulses/revolution - Phase delay - Response time characteristics - "Dither" amplitude - "Dither" frequency - Bias from MBT - Correction amplitude - Open loop yes or no - Proportional yes or no - Gain Availavility of Data Base: Engine maps not available from this source.
ADVANTAGES	Provides complete engine response to an optimization control system.
VALIDATION	Good correlation observed at low engine speeds range where ECS is functional and stable. Accuracy: Not stated.

COMPUTING REQUIREMENTS	Not stated.
COST OF OPERATION	Not stated.
FUTURE POTENTIAL	ECS system being improved.
AVAILABILITY	Probably not, work done is relevant only to the ECS which is a product of the sponsor.

TITLE	PROCES
DATE	1975
AUTHOR	H. Valland
ORGANIZATION	Norwegian Institute of Technology
SPONSOR	Unknown
TRANSPORTATION MODE	Marine and pipeline
APPLICATION	Military and civilian
OBJECTIVE	Computing the power output of a single cylinder, two or four cycle direct injected diesel. Output: - Combustion chamber wall temperatures - Gas temperatures - Mass flow - BSFC - Power - Engine energy balance
REFERENCE	Model briefly described in: "A theoretical analysis of thermal barriers in diesel engine cylinders," by H. Valland in Norwegian Maritime Research, No. 2, 1982.
RELATIONSHIP TO OTHER MODELS	Unknown.
HISTORY OF MODEL	Unknown.
OPERATIONAL CAPABILITIES	• Steady state • Variable heat release patterns • Variable heat transfer • Altered engine geometry

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ASSUMPTIONS

- Homogeneous, stochiometric gas mixture
- Perfectly mixed charge
- Surface temperatures constant throughout cycle
- Coolant temperature is average of inlet and outlet temperatures
- Inlet port, combustion chamber, and exhaust port are three separate control volumes coupled by mass flow and heat

LIMITATIONS

- Steady state
- Single cylinder
- Direct injection
- No cycle analysis

DATA INPUT REQUIREMENTS

- Rate of heat release
- Speed
- Cylinder configuration and dimensions
- Intake and exhaust port configuration
- Fuel feed rate
- Mechanical efficiency
- Coolant temperature
- Cylinder wall thermal characteristics
- Ambient conditions

ADVANTAGES

- Probably a very simple, basic model which is fast and easy to use.

(Note: model not very well described in reference document. Users manual is reportedly in Norwegian.)

VALIDATION — Not stated.

COMPUTING REQUIREMENTS — Not stated.

COST OF OPERATION — Not stated.

FUTURE POTENTIAL — Most likely very limited.

AVAILABILITY — Presumably available.

TITLE	Computer Programs to Determine the Relationship Between Pressure Flow, Heat Release, and Thermal Load in Diesel Engines
DATE	1964
AUTHOR	Gerhard Woschini
ORGANIZATION	MAN
SPONSOR	MAN
TRANSPORTATION MODE	Pipeline, Marine, Rail
APPLICATION	Military and civilian
OBJECTIVES	1. Determine the rate of heat release from the pressure history diagram. 2. Determine pressure and temperature flow from the heat release diagram. Output: - Peak pressure - Peak temperature - Indicated efficiency - Exhaust temperature - Parts of heat transfer to head, piston, cylinder walls.
REFERENCE	SAE Paper 650450
RELATIONSHIP TO OTHER MODELS	Heat transfer is based upon the determination of the heat transfer coefficient using the method of Pflaum ("Der Warmeubergang bei Dieselmaschine mit und ohne Aufladang," 1960).
HISTORY OF MODEL	None given
OPERATIONAL CAPABILITIES	Method of determining rate of heat release has been superceded by GM method. Heat transfer (thermal flow) is calculated independently for head, piston, and cylinder walls. Heat transfer is determined from a given heat release diagram.

ASSUMPTIONS	- Chamber wall temperature is constant - No blow-by - No heat transfer during scavenging
LIMITATIONS	- Can not determine influence of heat transfer on rate of pressure rise. - Heat transfer coefficient calculation not accurate. Must be used with known pressure or heat release data: not extrapolatable
DATA INPUT REQUIREMENTS	- Pressure vs. crankangle or - Heat release diagram - Equivalence ratio - Fuel composition - Engine dimensions
ADVANTAGES	Heat transfer through each of the major components calculated separately.
VALIDATION	Not validated.
COMPUTING REQUIREMENTS	IBM 1060 Fortran II
COST OF OPERATION	Eight minutes of machine time per run.
FUTURE POTENTIAL	Efforts to improve the determination of heat transfer coefficient underway.
AVAILABILITY	Presented in the paper in sufficient detail to use.

TITLE	Mirrlees Heat Transfer Program, "DIESHT"
DATE	1983
AUTHORS	R.T. Green, K. Jambunathan, S.D. Probert
ORGANIZATION	Mirrlees Blackstone Ltd., with Trent Polytechnic and Cranfield Institute
SPONSORS	Science and Engineering Research Council
TRANSPORTATION MODE	Diesel engines used in highway, rail, pipeline and marine transportation.
APPLICATION	Civil and Government
OBJECTIVE	To provide an easy-to-use, CAD-compatible, specialized software package for predicting (for a medium-speed diesel engine): (1) the steady-state rate of heat transfer through the cylinder liner (or other axisymmetric components). (2) the surface temperature of the liner, which critically affects both lubricant breakdown and corrosion.

REFERENCES

C.F. Taylor and T.Y. Toong, "Heat Transfer in Internal Combustion Engines," ASME paper No.57-HT-17, 1957.

J.F. Alcock, "Evaporative Cooling for Internal Combustion Engines," Trans.I.Mar.I., 62(10) (1950) pp. 327-38.

J.R. Metz and A. Steiger, "Contribution to the Investigation of the Diesel Cycle with the Aid of Digital Computers," Proc. I. Mech.E., 182 (Pt.3C) (1967-68), pp. 79-90.

W.J. Seale and D.H.C. Taylor, "Spatial Variation of Heat Transfer to Pistons and Liners of Some Medium-Speed Diesel Engines," Proc. I. Mech. E., 182 (Pt.1) (1970-71), pp. 203-15.

RELATIONSHIP TO OTHER MODELS/HISTORY OF MODEL

The model incorporates several "well tried and tested" empirical and semi-empirical relationships for gas-side heat transfer and a finite-element analysis to describe the rate of heat transfer through the cylinder liner. Emphasis is on developing a code that is compatible with a CAD system and easy to use interactively by engineers in the design phase.

OPERATIONAL CAPABILITIES

Output of Simulation - For Direct and Indirect Injection Engines:

- Heat transfer to cylinder liner
- Graphical temperature field in liner wall

Structure; List of submodels or processes included - Definitions of liner geometry and engine parameters:

- Calculation of gas properties
- Generation of mesh size
- Finite element analysis
- Graphical outputs

ASSUMPTIONS

Gas properties: Property tables are used to express viscosity, density, thermal conductivity and specific heat as polynomial functions of temperature.

Heat transfer:

(1) Hot gas side: treating convection only, this model uses a time-averaged correlation between the Nusselt and Reynolds number developed by Taylor and Toong (1957) and Annand (1963).

(2) Coolant side: uses a correlation for forced heat transfer to water in an annulus space developed by Alcock (1950), and by Seale and Taylor (1970-71).

(3) Through liner: finite element analysis of the steady-state heat conduction equation for an axisymmetric solid with gradients in the axial and radial directions.

LIMITATIONS

(1) Temperature of the hot gases must be input.

(2) Empirical relation for convective heat transfer from hot gases includes neither (a) gas motion effects nor (b) radiation effects and is not accurate at low engine speed (as recognized by authors)

(3) Temperature gradients in the gas, including boundary layer effects, are not modelled.

DATA INPUT REQUIREMENTS

Geometrical and Design Parameters:
- Cartesian coordinates describing the geometry of the cylinder liner (can be obtained from a CAD system)

- Material identifier; thermal conductivity of liner

Operating Parameters:
- Coolant velocity

- Charge air mass flow rate

- Temperatures of charge air, hot gases and coolant

Computational Parameters:
- Number of quadrilaterial regions describing the geometry

- Options for plotting temperature contours or temperature at each mesh

ADVANTAGES

Easy to use by design engineers without needing computer specialists. Can readily investigate the consequences of changing the liner wall thickness, coolant velocity, inner conductivity, etc.

VALIDATION

Engine description: 6-cylinder, 537 kW, 50 and 110% of design load, 750 RPM, 222 mm bore.

<u>Variables tested; model agreement</u>: At high load, the predicted temperature profiles were within a few percent of measurements, while at low load, they differed by up to, roughly, 15%.

<u>Assessment of accuracy</u>: Model predictions depend on the input value of the hot gas temperature and its associated uncertainty; otherwise, computational accuracy is good to about a few percent for fine mesh sizes (>100 elements).

COMPUTING REQUIREMENTS

FORTRAN

COST OF OPERATION

Unavailable, estimated at $5-20 per run.

FUTURE POTENTIAL

(1) Refinement of the gas-side heat transfer correlation to account for radiation, gas motion, and boundary layer effects. (This need is recognized by the authors.)

(2) Integration with other models that describe the combustion processes and thermal stress so that an interactive computerized tool can be made available to the designer.

AVAILABILITY

With the prior permission of Mirrlees Blackstone (Stamford) Ltd., copies of the computer program can be obtained from the authors.

TITLE	Prediction of the Exchange Processes in a Single Cylinder Internal Combustion Engine
DATE	1978
AUTHORS	P.A. Lakshminarayanan, P.A. Janakiraman, M.K. Gajendra Babu, B.S. Murthy
ORGANIZATION	Each author is a member of faculty of different universities; they are, respectively: - University of Technology, Loughborough, England; - Indian Institute of Technology, Madras, India; - Indian Institute of Technology, Delhi, India; - University of Santa Clara, Santa Clara, California.
SPONSORS	None stated
TRANSPORTATION MODE	All
APPLICATION	Military or civilian

OBJECTIVE	To model gas flow in the intake and exhaust systems of a single cylinder engine, including valve and end effects, in a simpler manner than other models.
	
	Output:
	- Manifold pressure
	  - intake
	  - exhaust
	- Gas bulk velocity both as a function of crankangle, plus bulk mass flow rate.

REFERENCES	SAE paper 790359.
RELATIONSHIP TO OTHER MODELS	None.
HISTORY OF MODEL	None stated.
OPERATIONAL CAPABILITIES	Study the influence of manifold length and end conditions on gas pressure, velocity as a function of crankangle, as well as bulk mass flow rate.

ASSUMPTIONS

- Manifolds are divided into a number of cells, each containing uniform gas properties.
- Constant pipe friction.
- No pipe bend effects.

LIMITATIONS

- No pipe junction or cylinder-to-cylinder interference effects.
- No combustion or cycle analysis.
- Naturally aspirated engines only.

DATA INPUT REQUIREMENTS

- Piston movement
- Manifold length and diameter (intake and exhaust)
- End condition
  - nozzle type
  - area ratio
  - valve opening WRT piston positioning
- Cylinder pressure and temperature as a function of crankangle or piston position.
- Ambient gas conditions.
- Friction coefficient along manifold.
- Rate of heat transfer to or from manifold gas.
- Gas physical properties.

ADVANTAGES

- Accuracy above first order effects is claimed.
- Simpler (cheaper?) calculation procedure.

VALIDATION

Compared to "method of characteristics" techniques and also against single cylinder diesel tests. Model is claimed to be "accurate." Data displayed shows general trends can be predicted, but excursions from the general trend are missed under firing conditions. Motoring condition predictions appear to have good correlation with experiment.

Accuracy: Not stated.

Input Data Accuracy: Not stated.

COMPUTING REQUIREMENTS	Not stated.
COST OF OPERATION	Not stated, but allegedly less than other models.
FUTURE POTENTIAL	Not stated.
AVAILABILITY	Unknown.

TITLE	Computer Aided Design of the Exhaust of a Turbocharged Diesel Engine
DATE	1968-1974
AUTHOR	J.D. Ledger
ORGANIZATION	University of Manchester, Institute of Science and Technology
SPONSOR	None apparent
TRANSPORTATION MODE	All
APPLICATION	Military and civilian

OBJECTIVE	Interactive study of the compressible gas flows in the exhaust pipe of a turbocharged (single cylinder as model reported) diesel engine. Use as a CAD tool to assess performance impact of different pipe designs.
	
	Output:
	- Exhaust pipe
	  - pressure (entry or exit)
	  - gas velocity (entry or exit)
	  - cylinder mass flow
	  - cylinder pressure
	  as a function of crank angle.

REFERENCE	"European Computing Conferences, Interactive Systems," London, United Kingdom. ISBN 0903796066, September 1975.
RELATIONSHIP TO OTHER MODELS	Based somewhat on the work of Benson and his "characteristics" methodology.
HISTORY OF MODEL	Development of model started in 1968 when only hybrid-analog/digital computer systems were available which would handle the centered-difference method Ledger started out with. Model was converted to all digital, interactive with graphic displays as reported. Model is reportedly being upgraded to employ Method of Characteristics.

OPERATIONAL CAPABILITIES

Exhaust manifold inlet and outlet (nozzle) characteristics such as

- exhaust valve timing,
- exhaust valve and port geometry
- turbocharger effective nozzle area

as well as manifold dimensions can be studied to determine their influences on cylinder blow-down under steady state operation.

Program is designed in a modular manner to facilitate easy alteration of design parameter and operating conditions.

ASSUMPTIONS

- One dimensional, unsteady isentropic flow of compressible gas
- No pipe bending effect (straight pipe)
- Cylinder expansion : pv 1.3 = constant

LIMITATIONS

- Simple cylinder
- No multi-pipe effects
- Single cylinder blowdown process
- No scanning effects
- Old model: superceded by newer ones which used this as a starting point.

DATA INPUT REQUIREMENTS

- Cylinder bore and stroke
- Connecting rod length
- Compression ratio (nominal)
- Exhaust pipe length and cross sectional area
- Exhaust and intake valve timing
- Valve opening and closing rates
- Supercharge (boost) pressure and temperature
- Exhaust nozzle open area ratio
- Engine speed
- Cylinder release pressure and temperature
- Estimates for exhaust pipe inlet pressure, temperature, and velocity
- Number of crank angles studied

ADVANTAGES

- Fairly rapid
- Graphical display
- Modular configuration allows easy modification

VALIDATION

None mentioned.

FUTURE POTENTIAL

- Multi-pipe configuration under development
- Method of characteristics to be further incorporated

COMPUTING REQUIREMENTS

- DEC PDP10 with graphics terminals
- Interactive in English

AVAILABILITY

Presumably available.

TITLE	Computer Aided Design Package for Engine Manifold System
DATE	1980
AUTHORS	S.C. Low, R.S. Benson, and D.E. Winterbone
ORGANIZATION	University of Manchester, Institute of Science and Technology
SPONSOR	Unknown
TRANSPORTATION MODE	All
APPLICATION	Civilian
OBJECTIVE	Interactive program for predicting the performance of a total engine system capable of incorporating manifold and valve design changes easily. This allows basic design processes to be accelerated and allows for a shorter data debugging time.

Output - Primary (graphical form):
- Pressure/crankangle diagrams for each end and middle of all manifold pipes.
- Pressure/crankangle diagrams for each cylinder, including pressure at manifold inlet/outlet.
- Mass flows and trapped mass for each cylinder.

Secondary:
- Pressure/crankangle diagrams for each cylinder, including peak pressure and rate of rise assessment.
- Cumulative work/crankangle:
  - IMEP
  - Power/cylinder
  - Trapped pressure and temperature
- Temperature/crankangle for each cylinder.
- Valve area/crankangle.
- Manufacturability of valve gear assessment.
- Adequacy of valve sizing/lift profile.

REFERENCE	Computer Aided Design Package for Diesel Manifold System SAE 790277.

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RELATIONSHIP TO OTHER MODELS	None, directly, although it is tied in philosophy to the University of Manchester MK 12 model.
HISTORY OF MODEL	One of the first programs based on the "method of characteristics." Probably <u>the</u> first program to combine the design and performance prediction processes.
OPERATIONAL CAPABILITIES	Engine treated as several modules under steady-state conditions. - Power (in-cylinder calculations) - Valve Gear (design only) - Manifolds, including turbine nozzle. Graphics - for plotting results only. <u>Power Module Model</u> is based on simple heat release diagram which must be supplied, a polytropic compression and expansion, perfect gas laws, and first law of thermodynamics. <u>Manifold Module Model</u> is a comprehensive wave model using non homentropic theory. Virtually any manifold design and its impact on engine performance can be assessed within program limitations. Cylinder to cylinder variations are determined.
ASSUMPTIONS	See description of power and manifold modules.
LIMITATIONS	Primarily a manifold and VALVE/VALVE GEAR assessment tool with a simple "power" or combustion model. Limited for minimal computer space to: - Four cylinders/manifold - Five valve gear arrangements; three push rods and two overhead cams. - Various rocker arm ratios

- Five cam definitions
  - three arc cam
  - constant acceleration cam
  - parabolic acceleration cam
  - sinusoidal acceleration cam
  - polynominal cam

- Orifice nozzle simulation of turbocharger turbine.

- Simple compressor model to assess turbocharger balance.

- Crude heat loss model.

- Simplified coefficients in internal energy.

DATA INPUT REQUIREMENTS

- Cylinder size
- Power
- Engine speed
- Fuel type
- Air fuel ratio
- Heat release diagram
- Combustion timing
- Firing order
- Manifold dimensions
- Inlet or cylinder exhaust conditions (calculated)
- Valves and valve gear geometry
- Camshaft profile

ADVANTAGES

- Program is interactive allowing for rapid incorporation of data changes. May be used by designers who need not understand the detailed workings of program.

- Assess design influences on engine performance.

- Predicts cylinder to cylinder variations due to manifold design.

- Provides manufacturability assessment of valve gear.

VALIDATION

Validation has been by comparison with the UMIST Mk. 12 non-homentropic I.C. Engine formulation program which has been extensively checked against experimental data.

Pressure and mass parameters are in reasonable agreement with UMIST Mk. 12 output. Acceptable correlation between trends for all cylinders. Temperatures vary up to 6 percent between programs and there is poor correlation of values across cylinders.

COMPUTING REQUIREMENTS

- ANSI Fortran IV
- Control Data Corporation CYBER 72
- Digital Computer; Tectronics 4010
- VDU's for graphics

COST OF OPERATION

Not stated.

FUTURE POTENTIAL

- May provide dynamic stress analysis of valve gear.
- Further reduction in data requirements by use of automatic mesh length generation.
- Extension of program to accept more cylinders and different configurations.
- Further refinement of the power module to increase accuracy without loss of speed.

AVAILABILITY

Probably available.

TITLE	A Generalized Computer Aided Design Package for I.C. Engine Manifold System
DATE	1980
AUTHORS	S.C. Low, P.C. Baruah
ORGANIZATION	University of Manchester, Institute of Science and Technology (UMIST)
SPONSOR	None apparent
TRANSPORTATION MODE	All
APPLICATION	Military and civilian
OBJECTIVE	To interactively predict the performance impact of the manifolding systems design on a multi-cylinder reciprocating engine. Output - As a function of crankangle: - cylinder pressure - cylinder mass flow - cylinder to cylinder variation in pressure and mass flow. - IMEP
REFERENCE	SAE paper 810498.
RELATIONSHIP TO OTHER MODELS	Based upon "A Computer Aided Design Package for Diesel Engine Manifold Systems," SAE paper 790277 (E-0022-IE).
HISTORY OF MODEL	A "better" version of E-0022-IE which had a similar objective.
OPERATIONAL CAPABILITIES	• Assess impact of different intake and exhaust manifold systems on cylinder pressures and mass flows as well as IMEP (estimated). • Steady state. • Study virtually any manifold configuration and dimensions.

ASSUMPTIONS

- Heat release unaffected by mainfolding.
- Polytropic compression and expansion.
- Perfect gas law.
- Gas is non-homentropic.

LIMITATIONS

- 10 cylinder
- No cycle analysis
- Steady speed

DATA INPUT REQUIREMENTS

- Power
- Number of cylinders
- Air-fuel ratio
- Bore and stroke
- Connecting rod length
- Ambient temperature and pressure
- Lower heating valve of fuel
- Cylinder heat loss (percent of total)
- Combustion timing
- Heat release curve
- Cam type and characteristics
- Valve lift (intake and exhaust)
- Valve diameter to cylinder bore ratio (intake and exhaust)
- Valve timing
- Compression ratio
- Engine speed
- Rocker arm ratio
- Exhaust back pressure
- Manifold dimensions (intake and exhaust) each pipe
- Manifold configuration (drawn on VDU)
- Outlet (exhaust) nozzle area to pipe area ratio
- Throttle setting

Input Data Accuracy: Manifold configuration need only be roughly sketched on VDU. Dimensions must be separately stated. No accuracy requirements stated.

ADVANTAGES

- Very rapid.
- Minimal input data needed.
- Interactive.
- Spark ignition (throttled) as well as diesel (unthrottled).

VALIDATION	With one engine in addition to E-0022-IE. Generally good agreement.
COMPUTING REQUIREMENTS	Not stated.
COST OF OPERATION	Not stated.
FUTURE POTENTIAL	Could incorpotate cycle analysis to become powerful total engine model.
AVAILABILITY	Presumably available from UMIST.

TITLE	Characteristics of Exhaust Gas Pulsation of Constant Pressure Turbo-Charged Diesel Engines
DATE	1979
AUTHORS	T. Azuma, Y. Tokunaga, T. Yura
ORGANIZATION	Kawasaki Heavy Industries
SPONSOR	Ship Building Research Association of Japan
TRANSPORTATION MODE	Marine
APPLICATION	Military or civilian
OBJECTIVE	Clarify the characteristics of exhaust gas pulsations of constant pressure turbocharged diesel engines. Output: Pressure in various exhaust pipe ducts as a function of crankangle.
REFERENCE	Journal of Engineering for Power, October 1980, Vol. 102, Transactions of the ASME.
RELATIONSHIP TO OTHER MODELS	Uses the "method of characteristics."
HISTORY OF MODEL	This model is claimed as a first (work such as reported in E-0052 preceded it, however, even though that was not a model).
OPERATIONAL CAPABILITIES	Can examine exhaust gas pulsations in turbocharged diesels under steady state operating conditions. Use as a design tool to optimize cylinder interactions and exhaust gas energy delivery to turbocharger turbine.
ASSUMPTIONS	• One dimensional flow. • Perfect or ideal gas. • No heat loss from exhaust system. • Non-isentropic, adiabatic system.

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- Any exhaust system can be modeled as a combination of:
  - flow in straight pipe
  - branch flow
  - nozzle flow
  - flowless volume
  - orifice flow (throttled)

LIMITATIONS	• Turbocharged engine • Steady state • Exhaust gasses only, no engine performance analysis
DATA INPUT REQUIREMENTS	• Exhaust system characteristics. • Engine firing order. • Number of engine cycles (two or four). • Engine speed. • Scavenge air pressure and temperature. • Cylinder pressure and temperature at exhaust valve opening. • Cylinder bore and stroke. • Number of cylinders.
ADVANTAGES	Fairly unique model in that this is perhaps the first one to model exhaust pulsations and gas flow interactions.
VALIDATION	Generally excellent agreement obtained when compared to a physical air-only model of diesel engines and a diesel exhaust system.
COMPUTING REQUIREMENTS	Not stated.
COST OF OPERATION	Not stated.
FUTURE POTENTIAL	Authors intent to "marry" this model with an engine simulation model in order to use it to assess performance effects of pulsations on turbochargers and hence engines.
AVAILABILITY	Unlikely.

TITLE	Computer Program to Predict the Gas Exchange Process of a Diesel Engine
DATE	1974
AUTHORS	A.J. Hallam, S. Cottam
ORGANIZATION	Ruston Paxman Diesel Std.
SPONSOR	Ruston Paxman Diesel Std.
TRANSPORTATION MODE	Marine (pipeline)
APPLICATION	Military or civilian.

OBJECTIVE	To predict the influence of design changes of a diesel engine's working fluid handling systems on engine performance. Specific components covered include:
	- Turbocharger
	- Intake manifold
	- Intake and exhaust valves
	- Exhaust manifold
	
	Output:
	- Pressure versus crankangle for
	  - manifold
	  - cylinder
	- Turbocharger performance map
	  - pressure ratio vs air flow
	- BSFC
	- Boost pressure
	- Air/fuel ratio
	  - trapped
	  - overall
	- Exhaust gas temperature
	- Heat input/cylinder
	- Heat transferred to
	  - piston
	  - liner
	  - cylinder
	  - valves

REFERENCE	<u>Computer Aided Design</u>, Volume 7, Number 2, April 1975, pp. 83-88.

RELATIONSHIP TO OTHER MODELS	None specifically. Uses "emptying and filling" concepts.
HISTORY OF MODEL	Developed as an easy to use model capable of handling virtually any configuration diesel engine. It was developed to replace a highly complex model with applications limited to existing engines.
OPERATIONAL CAPABILITIES	Examine impact of: - Bore and stroke - Manifold flow areas - Nozzle or orifice characteristics - Valve opening profiles - Number of valves - Manifold junctions - Turbocharger performance as well as ambient conditions on engine performance. Also provides gas side heat transfer coefficients and mean gas temperature in the locus of valves, pistons, cylinder liner, and cylinder head as well as the amount of heat transfer.
ASSUMPTIONS	• Gases are treated as being thermodynamically perfect. • Atmospheric conditions remain constant, separate values are given at the inlet to and exit from the system. • A single value is used for gas constant R irrespective of gas composition and temperature. • At any instant the gas conditions are uniform within any one volume. • Gas entering the volume through the junctions mixes perfectly with the gas already present. • The cycle is taken as a series of finite intervals. The size of the interval remains constant. Energy and mass flow rate are constant throughout each interval as are the gas conditions in each volume.

- Fuel may be burned in any volume. Its mass is added at the same instant as the heat energy is released by combustion.
- To calculate heat transferred from the surface of a fixed volume a mean heat transfer coefficient is used throughout the cycle.
- To calculate heat transferred from the surface of a working volume, the surface is taken in sections, using a mean wall temperature for each one. The heat transfer coefficient is calculated for each step and can be varied for each section.
- Combustion characteristics are influenced only by fuel/air ratio, and presumably modeled only by P.V. characteristics.

LIMITATIONS

- Combustion process not modeled.
- A junction will be one of the following types:
  (a) fixed area orifice
  (b) variable area orifice
  (c) compressor
  (d) turbine
  (e) simplified compressor, having fixed air flow
  (f) simplified turbine, consisting of a swallowing capacity curve.
- A turbine junction has one exit volume and up to four entry volumes. All other junctions have one exit volume and one entry volume.
- There can be only one junction between a pair of volumes.
- The capacity of a working volume is controlled by a conventional piston motion. Alternatively, a capacity curve can be supplied. Both two-stroke and four-stroke cycles are permitted.
- There must be at least one working volume.

- Each working volume must be an entry volume to a variable area orifice junction and an exit volume from another variable area orifice junction.

- Any shaft delivering power out of the system must have a fixed speed.

- Any fixed-speed shaft that is not itself an output shaft must be connected to one that is.

- Variable-speed shafts cannot be linked to any other shaft.

- Each working volume is connected to a fixed-speed shaft and hence torque is output from the engine either directly or by transmission to another shaft.

- Each active junction (types (c)-(f)) is on a shaft.

DATA INPUT REQUIREMENTS

- Working fluid system
  - dimensions
  - flow coefficients
  - valve timing
  - valve lift profile
- Turbocharger characteristics
- Initial values of gas conditions
- Speed
- Load
- Heat release curve

ADVANTAGES

- Reportedly is very flexible and user friendly.

- Provides heat transfer information to cylinder components to assist in thermal design problems.

- Not limited to specific configurations of engines (within limits of combustion assumptions which are not stated).

VALIDATION	Very good agreement reported with both previous validated engine models and measured performance on a Ruston diesel.
COMPUTING REQUIREMENTS	Not stated.
COST OF OPERATION	Not stated.
FUTURE POTENTIAL	None stated. Could be combined with more rigorous combustion model to become very powerful modeling tool. Potential Accuracy: "Errors" blamed on measurement shortcomings as opposed to model deficiencies.
AVAILABILITY	Proprietary model.

TITLE	Breathing Cycle of the Four-Stroke Automotive Engine
DATE	1979
AUTHOR	T.J. Trella
ORGANIZATION	U.S. Department of Transportation/Transportation Systems Center
SPONSORS	U.S. Department of Transportation, National Highway Traffic Safety Administration
TRANSPORTATION MODE	All
APPLICATION	Military and civilian.
OBJECTIVE	To model the intake system of a four-cycle open chamber engine (DI diesel or spark ignited engine) and determine the influence of design parameters on engine performance. Output: - Volumetric efficiency - Trapped residual fraction - Air flow rate (Intake Manifold) all as a function of engine speed or intake manifold vacuum.
REFERENCES	Article of same title in unknown publication.
RELATIONSHIP TO OTHER MODELS	None.
HISTORY OF MODEL	Much has been written about increased breathing and torque output. Particular emphasis has been placed on the design of the inlet manifold, carburetor-inlet throttling, and exhaust system. Recently, study reports have begun to appear on the use of variable inlet/exhaust valve timing as a means of reducing nitrous oxide and hydrocarbon exhaust emissions in spark-ignition engines at wide open and partial-throttle conditions. Such studies show that valve overlap, when properly applied over the load/speed range, has an appreciable effect on reducing these emissions. In addition, engines

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whose valves are timed for maximum power at high speeds can be modified with variable valve timing to exhibit increased torque at low speeds, thus providing better overall vehicle performance.

The simulation model described in this paper was designed to predict engine breathing performance.

The analytical methods used to perform the simulations are based on extensions of a nonconventional unsteady-fluid dynamic model which makes use of a sequence of stationary but finite fluid-control volumes to predict the dynamic behavior of the gas in an inlet track. The gas dynamics of the exhaust system are not simulated in the present model.

OPERATIONAL CAPABILITIES

Engine performance (air consumption) and residual trapped fraction are modeled as a function of inlet track, camshaft, valve, part, and throttle design dimensions as well as valve timing, lift and engine speed.

The model is designed for steady speed engine operation.

ASSUMPTIONS

- Working fluid is air only.
- Working fluid behaves as idled gas.
- Blumberg fuel burning rate assumed for SI, Triangular heat release rate assumed for CI.
- Gas properties uniformly distributed throughout combustion chamber.
- Quasi-steady state orifice theory is fundamental approach to gas flow calculations.

LIMITATIONS

- Does not calculate exhaust flow. Must be gathered empirically.

- Require empirical data obtained from specific engine under study.

DATA INPUT REQUIREMENTS

- Design data on:
  - Inlet track
  - Valve mechanism
  - Combustion chamber
  - Crank/read mechanism
- Engine valve lift speed.
- Engine control parameters.
- Manifold temperature and pressure.
- Valve part discharge coefficients.
- Combustion chamber and inlet manifold wall temperature.
- Empirical data on:
  - Exhaust back pressure
  - Inlet restrictions

Availability of Data Base:
None required, but input data publicly available from DOT/TSC.

ADVANTAGES

Uses novel approach to gas flow calculations, eliminating the time consuming "method of characteristics."

VALIDATION

Six engine study. "Reasonable" correlation achieved (up to 20 percent error in some reported comparisons).

COMPUTING REQUIREMENTS

Not stated

COST OF OPERATION

Not stated

FUTURE POTENTIAL

May include prechamber effects in future work.

AVAILABILITY

Available from U.S. DOT/TSC.

TITLE	Development of a Real-Time Digital Computer Simulation of a Turbocharged Diesel Engine
DATE	1979
AUTHOR	S.S. Shamsi
ORGANIZATION	Pakistan State Oil Company Ltd.
SPONSOR	UMIST
TRANSPORTATION MODE	All
APPLICATION	Military and civilian.
OBJECTIVE	To model the response of a turbocharged diesel engine to changes in shaft load. Output: - Engine speed as a function of time. - Engine power - Exhaust temperature - Turbocharger speed - Fuel rack position - Manifold pressure - Air flow - Smoke
REFERENCE	SAE Paper 800521
RELATIONSHIP TO OTHER MODELS	None stated.
HISTORY OF MODEL	None given.
OPERATING CAPABILITIES	Evaluate the influence of alternative governor/fuel pump and/or turbocharger characteristics on a given engine's transient response to changes in shaft load.
ASSUMPTIONS	• Transient response consists of a series of steady-state air flow conditions. • Mechanical accelerations governed by Newton's second law.

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- Steady-state maps valid during transient operation.
- Scavenge mass flow = constant percentage of trapped mass flow rate.
- Compression efficiency is constant at 70 percent.
- During transients there is a 5 percent reduction in engine IMEP and turbine inlet temperature from steady-state values.

LIMITATIONS

- Depends on the existence of steady-state maps.
- Examines influence of turbocharger and governor/fuel pump characteristics only.

DATA INPUT REQUIREMENTS

Steady-state maps
- Engine performance
- Turbocharger characteristics
- Governor characteristics
- Engine friction

ADVANTAGES

- Only digital engine response model in existence (1980).
- Claimed to be very economical to run.

VALIDATION

"Good agreement" between test bed and model performance achieved except for short duration (1 second) spikes in test bed performance.

Validation only on one engine.

COMPUTING REQUIREMENTS

PDP-10 Digital machine.

COST OF OPERATION

Not stated except that it is "very economical."

DATA BASE	Not required.
FUTURE POTENTIAL	Incorporate study of means to improve turbocharger response.
AVAILABILITY	Unknown.

TITLE	A Combustion Correlation for Diesel Engine Simulation
DATE	1979
AUTHORS	N. Watson, A.D. Pilley, M. Marzouk
ORGANIZATION	Imperial College of Science and Technology
SPONSOR	None apparent.
TRANSPORTATION MODE	Highway, possibly others.
APPLICATION	Military and civilian.
OBJECTIVE	To provide a means for correlating the Apparent Heat Rate Release (AHRR) with engine configuration and operating conditions in order to improve the accuracy of engine models which do not incorporate combustion models. Output: Apparent heat release rate at engine operating points not actually tested.
REFERENCE	SAE Paper 800029.
RELATIONSHIP TO OTHER MODELS	None, but could be incorporated into a number of models such as E-0051-OP or E-0055-IE.
HISTORY OF MODEL	Work by Shipinski as well as Woschini and Anisits tried to obtain correlation between engine configuration and operating parameters using a Wiebe function. The subject method incorporates a Wiebe function methodology but also considers parameters influencing the fuel burning rate and incorporates them into "shape factors" (Apparent Fuel Burning Rate (AFBR) vs. crankangle). It also considers premixing as well as the effects of diffusion limited and combustion kinetic limited burning.

OPERATIONAL CAPABILITIES	Uses limited empirical data on effects of equivalence ratio, ignition timing, speed, load and cylinder pressure vs. crankangle to predict combustion AHRR over a very wide range of engine speeds and loads.
ASSUMPTIONS	Combustion always takes place in the same step-by-step manner regardless of engine speed and load.
LIMITATIONS	Based on empirical data measured for each engine of interest.
DATA INPUT REQUIREMENTS	- Cylinder pressure diagram (motoring and running) - Injection timing and duration - Needle lift diagrams - Equivalence ratio as f. of crankangle - Engine speed Potential Accuracy: Very much a function of a number of initial data points. Input Data Accuracy: Desired to be better than the accuracy claimed for cylinder pressure measurement, a key input.
A VANTAGES	Expands the accuracy of other models which use a fixed rate of heat release for all engine conditions.
VALIDATION	Performed on three engines with varying degrees of success.
COMPUTING REQUIREMENTS	Not stated.
COST OF OPERATION	Not stated.
FUTURE POTENTIAL	None stated.
AVAILABILITY	Presumably.

TITLE	Model title unknown: explained in detail in: Free Piston Gasifier Studies: Development of a Hybrid Simulation, Rueter, F.; Swiderski, A.; NRC, DME Mechanical Engineering Report ME-230, National Research Council of Canada.
DATE	1968-1969
AUTHORS	F. Rueter, A. Swiderski
ORGANIZATION	National Research Council of Canada
SPONSORS	Unknown
TRANSPORTATION MODE	Pipeline
APPLICATION	Civilian
OBJECTIVE	Investigate the operation and performance of a turbocharged, two cycle free piston diesel engine and to develop the engine to an optimum configuration. Also to predict the effects of various design assumptions on engine performance and operation. Output: - Power - Specific fuel consumption - Piston frequency - Diesel compression pressure - Maximum diesel combustion temperature - Maximum bounce pressure - Hydraulic piston stroke - Diesel piston stroke
REFERENCE	Hybrid Computer Study of a Free Piston Engine with a Hydraulic Pump; F. Rueter, A. Swiderski, and J. Samolewicz, National Research Council of Canada, Mechanical Engineering Report ME-236.
RELATIONSHIP TO OTHER MODELS	None.
HISTORY OF MODEL	Not given.

OPERATIONAL CAPABILITIES	Investigate the influence of various design parameters - Bounce cylinder diameter - Diesel exhaust port position - Bounce cylinder effective clearance length - Hydraulic cylinder diameter - Mechanical spring rate - Mechanical spring preload - Bounce port position - Component masses - Boost pressure - Cylinder bore (power and hydraulic) - Engine friction - Combustion efficiency - Ambient conditions All can be evaluated under steady state conditions, but include a start-up phase.

ASSUMPTIONS	• Mechanical and combustion efficiencies
	• Combustion
	  - Constant volume heat release up to 2500 psi
	  - Constant pressure heat release over 2500 psi
	  - Minimum A/F ratio = 18
	  - Combustion efficiency = 98 percent
	• Isentropic expansion/compression
	• No leakage in diesel cylinder (i.e., No Blow By)
	• Desired boost pressure always available

LIMITATIONS	• Free piston, 2 cycle turbocharged diesel • Single combustion model • Steady state • Hydraulic power extraction • Needs hybrid analog/digital computer
DATA INPUT REQUIREMENTS	• Engine dimensions and reciprocating component masses, spring rate • Fuel injection system throttle setting • Fuel properties • Boost pressure • Engine friction • Combustion and thermal/mechanical efficiencies

ADVANTAGES	• One of the few free piston models. • Includes some cycle analysis.
VALIDATION	None done with this model, but approach is said to have been validated in other models.
COMPUTING REQUIREMENTS	Electronic Associates Model 690 hybrid computer (Model 680 analogue and 640 digital). Fortran IV language for digital portion.
COST OF OPERATION	Not stated.
FUTURE POTENTIAL	None stated. Potential Accuracy: Assumptions can be fine tuned to improve accuracy after an engine is built and run for comparison.
AVAILABILITY	Presumably available from NRC.

TITLE	Application Engineering Techniques Related to High Performance, Medium Speed Diesel Engines
DATE	Undated: probably mid 1970s.
AUTHORS	R. Greenhalgh, P. Tooth, I.I. Bickley.
ORGANIZATION	Mirrlees Blackstone, Limited
SPONSOR	Mirrlees Blackstone, Limited
TRANSPORTATION MODE	Marine, pipeline
APPLICATION	Military or civilian.
OBJECTIVE	To determine the response of an engine to changes in: - Load - Ambient pressure and temperature and evaluate alternative systems or installations to cope with these changes. Output: - Engine - Speed - Power - Compressor Pressure Ratio - Air Manifold Temperature - Air Flow - Exhaust Temperature
REFERENCES	Article of same title printed in unlabeled reference.
RELATIONSHIP TO OTHER MODELS	None mentioned.
HISTORY OF MODEL	Developed from hand calculation procedure used by Mirrlees Blackstone.

OPERATIONAL CAPABILITIES	Predict behavior of engine: - Speed) - Turbocharger) - as a function of time - Governor) in response to changes in load, which can be either a step change or a ramp change. Also, predict engine power and speed capabilities at varying altitudes and ambient temperature. Predict the influence of various accessories: - Turbocharging (single or dual) - Intercooling - Aftercooling - Alternate cooling systems on engine performance under non-standard ambient conditions.

DATA INPUT REQUIREMENTS	• Ambient Conditions
	• Load
	• Empirically derived performance data (or maps) for engine.
	  - cylinders
	  - boost devices
	  - air cooling systems
	
	• Potential Accuracy
	  - Will improve and have expanded predictive range as the data base is expanded through experience.
	
	• Input Data Accuracy
	  - Highly influential to output accuracy.

ASSUMPTIONS	Not stated. However, this model is <u>highly</u> empirical, based on the assumption that laboratory experiments correlate with field performance.
LIMITATIONS	• Exclusively empirical. • Requires performance "map" for each system component under study.

- Probably most applicable only to the Mirrlees Blackstone or similar large bore medium speed diesels.

ADVANTAGES

- Accurate, quick, predictions of engine performance under conditions not yet experienced (good application engineering tool).
- Model transient response of engine under actual operating conditions.

VALIDATION — Close agreement with in field measurements.

COMPUTING REQUIREMENTS — Computer type not mentioned: language is ICLJEAN.

COST OF OPERATION — Not stated.

FUTURE POTENTIAL — Continue to work, apparently on refining empirical data base, in order to improve range of conditions which can be modeled.

AVAILABILITY — Not stated, most likely not available.

TITLE	Development of P.C. Engine Simulation Program.
DATE	1971-1974
AUTHORS	K. Shiraishi, K. Murakami, M. Mizushima, and T. Nakayama.
ORGANIZATION	Nippon Kokan (Japanese licensee for Pielstick-SEMT Engines).
SPONSOR	Nippon Kokan
TRANSPORTATION MODE	Marine
APPLICATION	Military and civilian.
REFERENCE	Nippon Kokan Technical Report - Overseas July 1975.
OBJECTIVE	To model the NKK (Pielstick) 3PC2-5L test engine in order to make performance predictions. Output - As a function of horsepower: - Fuel rate - Speed (RAM) - Air flow - Turbocharger speed - Supercharger speed - Peak combustion pressure - Manifold temperatures
RELATIONSHIP TO OTHER MODELS	Based on the 1971 modeling work of 130th Research Panel of Shipbuilding Association of Japan.
HISTORY OF MODEL	Not stated.
OPERATIONAL CAPABILITIES	Predicts the power output of the NKK-Pielstick 3PC2-5L engine over its entire operating range.
ASSUMPTIONS	• Semi-perfect gas. • Combustion rate solely a function of crank position. • Heat transfer rate governed by Eicherberg's empirical formulae.

LIMITATIONS	• Steady-state performance only. • Applicable only to subject engine. • Empirical coefficients used to tune theoretical formulae. • Even firing, single pipe exhaust systems.
DATA INPUT REQUIREMENTS	• Engine dimensional data. • Supercharger/turbocharger characteristic curves. • Gas temperature: pressure at various points in manifolds. • Combustion start angle. • Combustion duration. • Heat release index. • Various flow coefficients for the engine under study. Availability of Data Base: Required empirical correlations inherent in model.
VALIDATION	Validated against subject engine with agreement within 5 percent steady-state.
COMPUTING REQUIREMENTS	Not stated
COST OF OPERATION	Not stated
FUTURE POTENTIAL	• Will expand capabilities to uneven firing, multiple pipe exhaust manifolds. • Improving turbine modeling system to get better correlation.
AVAILABILITY	Highly unlikely

TITLE	Wholly Dynamic Model of a Turbocharged Diesel Engine for Transfer Function Evaluation
DATE	1976
AUTHORS	Winterbone, Thiruarooran and Wellstead
ORGANIZATION	University of Manchester, Institute of Science and Technology (UMIST)
SPONSORS	Not stated.
TRANSPORTATION MODE	All
APPLICATION	Military and civilian.
OBJECTIVE	To describe the response of an engine to changes in shaft load with emphasis on an accurate description of the intake and exhaust systems coupled with a turbocharger. Output: - Exhaust temperature - Turbocharger speed - Engine speed - Fuel rack position All as a function of time.
REFERENCE	SAE Paper 770124.
RELATIONSHIP TO OTHER MODELS	Not stated.
HISTORY OF MODEL	The model discussed in this paper attempts to overcome many of the shortcomings of the quasi-steady case by adopting a more fundamental approach. It is based on the 'filling-and- emptying' technique for evaluating turbocharged engine performance. Some empirical factors have been implied, these were assessed from steady-state results. It is felt that this model is the best compromise between the simple quasi-steady models and the complex wave-active based simulations. The program consists of two main sections, the gas flow section,

in which the filling of the cylinders is matched to the turbine and compressor characteristics, and the power section, in which the power output of the engine is evaluated by a modified simple cycle analysis. The final model consists of 30 simultaneous non-linear differential equations which are integrated on a step by step basis.

OPERATIONAL CAPABILITIES

Determine the influence of turbocharger, intake, and exhaust manifold on engine response to a change in shaft load.

ASSUMPTIONS

- Turbine and compressor are adequately represented by steady-state characteristics.
- Cycle-to-cycle variations neglected.
- Exhaust manifold heat losses are a constant percentage of manifold input enthalpy.

LIMITATIONS

- Many of its fundamental equations are oversimplified and model is hence "tuned" with coefficients which may have to be empirically determined from one engine to the next.
- Model not generally applicable from one engine to the next without empirical "tuning" data.
- Actual determination of heat losses totally ignored.

DATA INPUT REQUIREMENTS

- Turbocharger characteristics
- Governor characteristics
- Engine characteristics
  - Manifold systems details
  - Rotating component moment of inertia etc: (paper not legible).

ADVANTAGES	Claimed to be more fundamentally based than some models, hence requiring less empirical data: However, the "tuning" coefficients used are empirically derived and may not be universally applicable.
VALIDATION	Validated only to the extent that "tuning" coefficients determined on one engine.
COMPUTING REQUIREMENTS	Fortran IV: uses CDC 7600 or PDP-10 computers.
COST OF OPERATION	CPU/Engine rpm = 600 for PDP-10 CPU/Engine rpm = 20 for CDC-7600
FUTURE POTENTIAL	Better validation work and more fine tuning is underway. Potential Accuracy: Improvements being sought. Universally applicable accuracy improvement doubtful.
AVAILABILITY	Presumably from UMIST.

TITLE	Simulation of a Turbocharged Diesel Engine to Predict the Transient Response
DATE	1977
AUTHOR	M.R. Goyal
ORGANIZATION	John Deere
SPONSOR	John Deere
TRANSPORTATION MODE	Highway, perhaps others.
APPLICATION	Military and civilian.
OBJECTIVE	To predict engine performance (speed, A/F ratio, pump rack position, turbocharger speed, intake manifold pressure during speed and load transients. Output: As a function of time: - Shaft speed - Turbocharger speed - Fuel rack position - Intake manifold pressure Fuel and AM flow Power Turbine inlet temp
REFERENCE	ASME paper 78-DGP-11
RELATIONSHIP TO OTHER MODELS	Based upon work of Borman and McAuley.
HISTORY OF MODEL	None given.
OPERATIONAL CAPABILITIES	Uses quasi-steady state analysis to determine engine response to changes in operator input (throttle position) or shaft load. Effect of changes in control, operations, and design can be studied.

ASSUMPTIONS	• Engine and turbocharger pass through a series of quasi-steady states during transient.
	• Heat transfer coefficients based on Annand's work.
	• Each cylinder component has a constant, uniform surface temperature.
	• Fuel mass heat release rate described by Wiebe's semi-empirical dimensionless equation.
	• Burning schedule described by Benson.
	• Engine friction estimated by method of Chen and Flynn.
LIMITATIONS	• Must be empirically tuned to engine under study.
	• Simplified combustion model.
DATA INPUT REQUIREMENTS	- Steady-state Compressor Performance Charts - Steady-state Turbine Performance Charts - Mechanical Component Polar Moments of Inertia - Engine Load Profile - Governor and Pump descriptive equations - Engine Dimensions
	Data Base: Steady-state engine data needed on engine of interest.
VALIDATION	Good correlation achieved with turbocharged as well as turbocharged and intercooled engines (2 engines, 12 operating points total published).
COMPUTING REQUIREMENTS	Not stated.
COST OF OPERATION	Not stated.
FUTURE POTENTIAL	Not discussed.
AVAILABILITY	Unlikely.

TITLE	Boiler Analysis Program (BAP)
DATE	1970 (modification through 1982)
AUTHORS	J. Gerstman, with recent modifications by I.P. Krepchin.
ORGANIZATION	Foster-Miller
SPONSOR	Private
TRANSPORTATION MODE	Highway
APPLICATION	Both military and civilian.
OBJECTIVE	This model was developed for the design and analysis of once-through boilers, both fired and waste heat. The configuration assumed in the model is a patented conical helix. Output - The major outputs of this model are: - Steam flow for given gas conditions and desired steam temperature and pressure, or - Gas flow for given water flow and desired steam temperature and pressure. - Boiler efficiency. - Steam and gas side pressure drops. - Temperature distributions of the steam, wall and gas.
REFERENCES	Demler, R.L., "Design and Development of an Automotive Propulsion System Utilizing a Rankine Cycle Engine (Water Based Fluid)," for U.S. ERDA, EY-76-C-02-2701 A001, September 1977.
RELATIONSHIP TO OTHER MODELS	The BAP model can be used in conjunction with steam expander model to simulate bottoming cycle systems.

HISTORY OF MODEL

Over the years since 1970, the model has been modified to accommodate: alternate fuels, split-fin tubing, interactive design use. The capability to model waste heat boilers and to converge faster are also recent additional capabilities.

OPERATIONAL CAPABILITIES

This model includes the following range of capabilities.

- Steady-state calculations, some information available for transient behavior.

- Complete parametric capabilities.

Limited to 10 water/steam passes - Any tube and fin sites and any coil diameter.

ASSUMPTIONS

The major assumptions are:
- Uniform gas flow distribution.
- Constant steam pressure.

LIMITATIONS

None identified.

DATA INPUT REQUIREMENTS

The data that are required as input to the model are:
- Boiler geometry.
- Water inlet and outlet temperature and pressure.
- Water flow or gas flow.
- Gas temperature or fuel and fuel-air ratio for fired boilers.

ADVANTAGES

None identified.

VALIDATION

This model has been validated by experiment and prototype performance. Validation described in Demler, R.L., "Demonstration of a Steam Powered Face Haulage Vehicle," FMA/DOE ET-75-C-01-0916, July 1979.

COMPUTING REQUIREMENTS	The model code written in Fortran and used on CYBER 170 series and VAX 11/780.
COST OF OPERATION	The average cost per run of operating this model on the current hardware described above is $.20/run.
FUTURE POTENTIAL	No current plans.
AVAILABILITY	This program is not for sale, however, it can be used for a fee.

TITLE	Rankine Cycle, Waste Heat Recovery Engine (part-load and full-load) Performance Model
DATE	1974
AUTHORS	DiBella, F.A., and Wang, C.
ORGANIZATION	Thermo Electron Corporation, Waltham, Massachusetts
SPONSOR	Thermo Electron Corporation (TECO) Internal R&D funding
TRANSPORTATION MODE	All modes
APPLICATION	This model is applicable to military and civilian use.
OBJECTIVE	This program is used to determine the full and part-load performance of a Rankine Cycle system using specified heat exchanger and turbine components. It will calculate the performance of a Rankine Cycle System with a minimum of input data; and with either a water cooler or air cooled condenser cooling system specified. An indirect heating or cooling sub-system can also be accommodated for Solar Rankine Cycle System Analysis, for example. Radiator fan cooling curves are also available for accurate power consumption versus cooling performance evaluations. The model also permits the working fluid to be changed in order to evaluate the Rankine Cycle Performance for various working fluids. Output: The major output parameters are the Rankine Cycle System's net power output, component (fan, pump, etc.) parasitic losses as well as heat exchanger and turbine operating efficiencies for operating point at full or part-load conditions.
REFERENCES	Not identified. However, Thermo Electron maintains all of the necessary program documentation and/or manuals.

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RELATIONSHIP TO OTHER MODELS

This computer model is the "Main" program for which several sub-programs have been written in order to separately evaluate any of the principle Rankine Cycle Components. This main model does not require the sub-programs to function however, the sub-programs will only identify the performance that can be expected of an individual component. By observing each individual component's performance taken separately; the engineer can identify and make improvements to that component before it is used in the main program.

In this sense, this computer program is the main program of a family of shorter computer models.

HISTORY OF MODEL

This Rankine Cycle System performance model was developed by Thermo Electron Corporation to support its development work in the design, assembly and testing of Organic Rankine Cycle Systems.

This model has been used to predict the full and part-load performance characteristics of TECO's systems ranging in size from 35 kW to 450 kW. It can be used for systems with any power output provided the necessary heat exchanger size and turbine design point performance is known and input into the computer program.

The model has been updated with regards to turbine aerodynamics and/or heat exchanger heat transfer coefficients as testing of the developed systems have been performed and test results confirmed.

OPERATIONAL CAPABILITIES

The model is essentially a steady-state model of the Rankine Cycle's full and part-load performance. It can identify its operational characteristics with only a minimum of essential inputs; for example, heat energy temperature and flowrate and ambient temperature. The sizes of any of the heat exchangers or the pumping curve characteristics or the turbine's aerodynamic design point character-istics can be readily changed; particularly if the system is used with a computer that has a time share capability.

ASSUMPTIONS

The computer model does not require any assumptions to be made concerning the Rankine Cycle System performance. Each component of the Rankine Cycle System model used either TECO tested results or manufacturers performance guarantees (i.e., pump and fan curves, heat exchanger performance data).

LIMITATIONS

The computer model may be limited in modeling a Rankine Cycle System below 30 percent of its Rated-Design Point power output.

DATA INPUT REQUIREMENTS

Input data for the Rankine Cycle System computer model includes heat energy inlet temperature and flowrate and the ambient or "Heat Sink" temperature. The system's component sizes and turbine size and Design Point operating characteristics are also required. However, these component descriptions are input only once, at the start of the program, and are used to determine the part-load performance of the Rankine Cycle System when part-load heat energy conditions are identified to the model.

Input Data Accuracy: The input data can be to only one decimal place.

Cost of Data Base: The cost for the data base varies with the type of heat source, the amount of part-load data, and the degree of fluctuation of this data. A specific cost for the data base is, therefore, not readily determined without a description of the size of the data to be run.

ADVANTAGES

It is thought that this Rankine Cycle System model is very versatile for use with various energy recovery scenarios. For example, the heat source can be a solar heated heat transfer fluid or a fuel oil or coal-fired heat exchange. The heat source may involve waste heat energy recovery from diesel or gas turbine engines. The "cold sink" may also involve a simple air-cooled or water-cooled condenser or involve the more complicated, indirect heat transfer cooling system. For example, a radiator and cooling fan assembly to reject heat from a water-cooled condenser.

VALIDATION	The computer model has been used to verify the performance of a 35 kW, 75 kW, 100 kW, and 450 kW Organic Rankine Cycle System with success. The operation of the 35 and 100 kW units are documented in several DOE and internal reports, respectively.
COMPUTING REQUIREMENTS	The computer model is currently used with a Xerox computer and is written in Fortran IV language.
COST OF OPERATION	TECO's cost to operate this program is not representative because of TECO's access to an inexpensive time share service. The actual running time for the program is typically measurable in seconds and not minutes.
FUTURE POTENTIAL	The computer model continues to be updated whenever methods are found to perform the system calculations quicker, with fewer iterations. Modifications of the turbine aerodynamic models are made to reflect current state-of-the-art. Potential Accuracy: The performance accuracy is very much dependent upon manufacturers heat exchanger, pump and/or fan data as well as on the extent of the working fluid properties available for the program's computations. It is necessary to have friction as well as heat transfer versus flowrate data for each heat exchanger in the system. The plumbing diameters and the number of 90° and 180° returns in the plumbing is also necessary for an accurate pressure drop calculation. The amount and location of insulation used with the components is also required.
AVAILABILITY	The model presently unavailable to external organizations. Rankine Cycle modeling can be contracted from the Thermo Electron Corporation or adapted for use by NASA/Lewis provided contractual arrangements are made.

TITLE	DRC Modelling (Rankine Bottoming Cycle Engines)
DATE	1980-1983
AUTHORS	Various
ORGANIZATION	Mechanical Technologies, Inc. (MTI)
SPONSORS	Various including DOE and MTI
TRANSPORTATION MODE	Has been applied to pipeline and marine applications.
APPLICATION	Civilian
OBJECTIVE	Optimum sizir . performance and cost trade-offs including thermodynamic inputs as well as financial DCF analyses.
REFERENCES	Model results have been incorporated in numerous articles, papers and reports published by MTI. There is no formal documentation of the models themselves.
RELATIONSHIP TO OTHER MODELS	This model is a stand alone model. Models covering the use of steam Rankine bottoming and topping cycles draw upon the same economic subroutines.
HISTORY OF MODEL	The current model is the latest version of a series of models developed by MTI since 1975. These include inputs from studies funded by various governmental and commercial customers and MTI.
OPERATIONAL CAPABILITIES	It provides thermodynamic and mechanical design and performance, estimated costing and economic analyses. It is a steady state model. Transient operation in stationary applications is not relevant.
ASSUMPTIONS	Not identified.

LIMITATIONS	The model is for steady state operation and does not explicitely incorporate the performance characteristics of the diesel engine in order to obtain an engine system performance map. The characteristics of the diesel engine are accounted for by input as external data, the steady state temperatures, and flow rates of the diesel engine waste heat streams.
DATA INPUT REQUIREMENTS	Heat flows and temperatures for input stream, cooling water temperatures, energy economic parameters.
OUTPUT PARAMETERS	Performance, design parameters, costs, and DCF.
ADVANTAGES	The analyses and cost data have been verified by actual tests and fabrications.
VALIDATION	The model has been validated. No publication has been prepared.
COMPUTING REQUIREMENTS	The model is written in a Fortran language which can be run on IBM compatible equipment. Input data needs include operating temperature levels, input heat flows, and energy economic parameters.
COST OF OPERATION	Not identified.
FUTURE POTENTIAL	The performance and cost data are updated periodically to incorporate the most recent data.
AVAILABILITY	The model can be applied by MTI for funded studies.

TITLE	Brayton Bottoming System (BBS) Evaluation
DATE	This model is an evolution of an existing model that has been developed and modified over the past five years.
AUTHORS	Gene Wilmot, et al., Hamilton Standard Division (HSD). Adapted to Diesel Engine Application by T.N. Obee, United Technologies Research Center (UTRC).
ORGANIZATION	HSD of United Technologies Corporation and United Technologies Research Center (UTRC).
SPONSOR	UTC
TRANSPORTATION MODE	Any diesel engine-powered mode.
APPLICATIONS	Mostly civilian.
OBJECTIVE	To perform design and performance calculations of Brayton-cycle waste heat recovery systems under both design and off-design conditions.
REFERENCES	Proprietary manuals.
RELATIONSHIP TO OTHER MODELS	This is a self-contained model that combines the design and performance characteristics of compact heat exchangers with those of turbomachines. The heat exchanger part of this model can be accessed separately for heat exchanger design and sizing purposes.
HISTORY OF MODEL	This model represents an adaptation to BBS of a sophisticated aircraft environmental control air-cycle system model which has been in use at HSD for many years.
OPERATIONAL CAPABILITIES	This model can be used both for design and heat exchanger sizing calculations and for off-design performance calculations of the entire system. Design factors of interest can be varied easily.
ASSUMPTIONS	Validity of compact heat exchanger maps such as those given in Kays & London, and validity of turbomachinery similarity and scaling laws.

LIMITATION	The model assumes that only air will flow through turbomachines. Also, only uniform fouling of heat exchanger surfaces can be accounted for.
DATA INPUT REQUIREMENTS	Design Mode: Cold and hot side flow rates and inlet/outlet temperatures; pressure levels and allowable pressure drops; heat exchanger configuration and fin geometry (Stanton Number and friction factor maps are stored in computer library for a wide variety of finned surfaces). Performance Mode: Characteristics of heat exchangers and turbomachines (e.g., performance maps or data) and external conditions such as diesel exhaust temperature, pressure and flow rate at a given speed, ambient conditions and heat exchanger fouling factors.
ADVANTAGES	Fast simulation of complex systems consisting of several heat exchangers and several turbomachines and connecting conduits, both for design and off-design calculations.
VALIDATION	The original version of the model has been successfully used for designing air-cycle aircraft cabin cooling systems, e.g., the HSD-designed and built system used on the F-16 Falcon.
COMPUTING REQUIREMENTS	The model is written in Fortran and usually ran on an IBM 3380.
COST OF OPERATION	Less than $1 per run.
FUTURE POTENTIAL	Extending the simulations to fluids other than air, and an improved model for heat exchanger fouling.
AVAILABILITY	The model is proprietary to UTRC. Can be used only by UTC Divisions. Indirectly available to NASA through contracts to UTRC or HSD.

TITLE	Rankine Bottoming Cycle Performance Code
DATE	June 1981
AUTHORS	Korazinski, J.L. and Ash, J.E., were the people primarily involved inthe code development.
ORGANIZATION	Argonne National Laboratory
SPONSOR	Initially: DOE - Office of Industrial Programs; Currently: DOE - Office of Vehicle and Engine R&D.
TRANSPORTATION MODE	The initial application was for stationary systems in the size range of 600-2400 kW.
APPLICATIONS	Program can, however, estimate organic Rankine engine performance in quasi steady state applications associated marine or pipeline applications.
OBJECTIVE	To calculate the performance (efficiency, power output, etc.) and cost of Rankine bottoming cycle systems as a function of working fluid and operating parameters.
REFERENCES	1. Manciniak, T.J., et al, "Comparison of Rankine-Cycle Power Systems: Effects of SEven Working Fluids," Argonne National Laboratory Report ANL/CNSV-TM-87 (June 1981). 2. Ash, J.E., "Analytical Expressions for Thermodynamic Properties of Rankine Bottoming Cycle Organic Working Fluids," (draft), (June 1982).
RELATIONSHIP TO OTHER MODELS	The current model is not a submodel or part of a family of models. The current model can be used as a separate entity. It could, however, be adopted for use as a subroutine to estimate the performance of combined diesel engine/RBC systems.
HISTORY OF MODEL	The current ANL model is based upon the model described in the report ANL/CNSV-TM-87. The major modifications involved the inclusion of equations into the code for the calculation of fluid properties.

OPERATIONAL CAPABILITIES

- The performance calculations are independent of the size or type of the heat source. The cost data presently in the code applies to systems in the range of 600-2400 kW.
- Steady-state or quasi-steady-state.
- Gross factors (heat source flow rate and temperature, cooling water temperature, turbine efficiency, etc.) can be readily changed for parametric studies.

ASSUMPTIONS

The model inputs specific assumptions relative to heat transfer coefficients, working fluid properties, and component performance characteristics. As such, it is valid only under the specific design conditions where these design point conditions apply.

LIMITATION

The model was not set up to do a detailed design analysis of a specific bottoming cycle system. It is intended for scoping studies to assess the impact of the working fluid on the system performance and cost.

DATA INPUT REQUIREMENTS

The input data required include a description of the heat source (temperature, flow rate), some basic properties of the working fluid (e.g., molecular weight, boiling point), and cost data for the sizes of components of the bottoming cycles being studied.

ADVANTAGES

The model is useful for quickly and cheaply performing scoping studies to determine the effect of working fluid selection and gross operating parameters (temperatures, capacity, etc.) on RBC performance and cost. It is intended to fully document the model and make the computer code readily available to potential users. The model is useful for quickly performing scoping studies to determine the effects of changes in fluid properties on system performance and cost.

VALIDATION

Some validation of the model was done for the Sundstrand 600 kW bottoming cycle system. This validation data has not been formally published.

COMPUTING REQUIREMENTS

The code is written in Fortran. It has been run on an IBM 3033 computer.

COST OF OPERATION

The average run cost about $1.50-$2.50 depending on the number of cases run for a specific fluid, which may range from about 30 cases to about 70 cases. Each case corresponds to a different operating condition (different maximum temperature and pressure) for the fluid.

FUTURE POTENTIAL

Additional development work is planned on the fluid property subroutines. It is also intended to modify the component models and improve their flexibility. It is also planned to change the cost models to cover a size range more appropriate to bottoming cycles for heavy-duty transportation systems.

AVAILABILITY

Prior to its release, the model needs to be more thoroughly documented.

TITLE	Turbocharged Diesel Engine Simulation to Predict Steady-State and Transient Performance
DATE	1977
AUTHORS	A.S. Ghuman, M.A.Iwamuro, H.G. Weber
ORGANIZATION	Cummins Engine Company
SPONSOR	Cummins Engine Company
TRANSPORTATION MODE	Highway and other adaptations of highway engines (may be limited to direct injected engines).
APPLICATION	Military and civilian.

OBJECTIVE	• Predict relative merits of various methods used to improve transient engine response.
	• Predict steady-state and transient performance of a particular engine system at some untested operating condition.
	
	Output:
	- Engine
	  - IMEP
	  - Engine friction
	  - Pumping work
	  - Volumetric efficiency
	  - Exhaust manifold temperature
	
	- Turbocharger
	  - Speed
	  - Pressure ratio
	  - Efficiency
	  - Mass flow

REFERENCES	ASME Paper 77 DGP5
RELATIONSHIP TO OTHER MODELS	None stated.

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OPERATIONAL CAPABILITIES

- The model uses limited experimental data to develop steady-state engine performance maps.
- Steady-state engine maps are used to develop engine transient response performance.
- Various engine parameter variables (see input data) or forcing functions (such as fuel rate variation with time, engine load variation, etc.) can be varied to assess the impact on steady-state and transient performance.

ASSUMPTIONS

- Steady-state performance maps for engine and turbocharger are valid during each instant of transient operation.
- In-cylinder heat transfer rate is constant.
- Steady-state engine performance can be adequately mapped by curve fitting between a few experimentally determined points.
- The exhaust manifold metal is assumed to be divided into two layers, the inner much thinner than the outer. This allows improved modeling of the thermal responsiveness of the wall during transients.

LIMITATIONS

- "Emptying and Filling" model
- The model demands inputs which are estimated or experimentally derived. Few fundamental engine parameters are considered. For example, the effect of an insulated manifold is predicted by estimating the change in manifold gas temperature.
- Ignores "cycle analysis" completely.
- No in-cylinder time delay for gas flow.
- Will not predict manifold resonances and hence cylinder to cylinder variations.

DATA INPUT REQUIREMENTS

- Steady-State
  - Engine speed
  - Fuel rate or air/fuel ratio
  - Compressor inlet temperature and pressure
  - Turbine exit temperature
  - Coolant temperature into aftercooler
  - Aftercooler effectiveness
  - Turbocharger bearing losses
  - Intake manifold pressure and temperature
  - Exhaust manifold pressure

- Transient
  - Steady-state performance maps
    - engine speed
    - fuel rate or air/fuel ratio
    - turbocharger speed
    - compressor inlet pressure and temperature
    - turbine exit pressure
    - intake manifold pressure and temperature
    - exhaust manifold pressure and temperature
    - exhaust manifold metal temperature
  - Coolant temperature into aftercooler
  - Aftercooler effectiveness
  - Engine system inertia
  - Turbocharger inertia
  - Load on the engine
  - Exhaust manifold lead transfer area
  - Exhaust manifold inside diameter
  - Volumes of intake and exhaust manifold ports
  - Thermal properties of exhaust manifold metal
  - Valve timing

Input Data Accuracy: No special requirements listed. Obviously the more accurate and more numerous, the better.

Accuracy:
- Steady-state - generally within 5 percent claimed.

- Transient - "generally good agreement."

ADVANTAGES

Very rapid assessment of the impact of parametric changes on the performance of a four-stroke turbocharged diesel engine.

VALIDATION	Model, as reported, has been validated for transient conditions only under low load acceleration, and apparently for only one engine.
	Data published in source document.
COMPUTING REQUIREMENTS	None stated.
COST OF OPERATION	One minute of computer time.
FUTURE POTENTIAL	Authors hope to develop this into a model capable of handling two stage turbocharging. Weber indicates this model obsoleted at Cummins by one written by Watson, Imperial College, London.
	Potential Accuracy: No claims for future improvements were made.
AVAILABILITY	Not available.

TITLE	Prediction and Measurement of Two-Stroke Cycle Diesel Engine Performance and Smoke at Altitude
DATE	1977
AUTHORS	W. Schmidt, D. Venhuis, S. Hinkle
ORGANIZATION	Detroit Diesel Allison
SPONSOR	Detroit Diesel Allison
TRANSPORTATION MODE	Highway
APPLICATION	Military and Civilian
OBJECTIVE	To predict changes in two-stroke, turbocharged and blown diesel engine power output and smoke with changes in altitude. Output: - BSFC - BHP - Bosch Smoke Number
REFERENCE	ASME 77 DGP-3
RELATIONSHIP TO OTHER MODELS	None mentioned.
HISTORY OF MODEL	None given.
OPERATIONAL CAPABILITIES	Steady state performance (power ISFC, and smoke) of a two-stroke, turbocharged and blown diesel as influenced by altitude is calculated from measured baseline performance using performance characteristics of: - Turbocharger - Blower - Engine air trapping - Fuel mass flow - Air/fuel ratio Design factors can be altered by changing the baseline coefficients describing a particular engine's performance.

ASSUMPTIONS

- Turbocharger output constantly proportional to inlet air density
- Altitude has no effect upon fuel supply system and cooling system.
- Indicated power and exhaust property characteristics of the cylinders are influenced by altitude only as they influence trapped air/fuel ratio.

LIMITATIONS

- The model is empirically based.
- Limited to the influence of ambient air density (altitude) on the air side systems. Calculates smoke, BHP and BSFC with changes in altitude only, taking into account only gross air density effects.
- Different manifold configurations cannot be modeled.
- Each engine under study must be tested to determine the performance coefficients. Considers only power, BSFC, smoke.

DATA INPUT REQUIREMENTS

- Air density
- Turbocharger effectiveness
- Air box density
- Rotary blower speed
- Rotary blower displacement
- Rotary blower efficiency
- Rotary blower pressure ratio
- Engine air mass flow rate engine trapping efficiency
- Fuel flow rate
- Engine smoke characteristics
- Engine speed
- Combustion chamber and cylinder volume

Various performance coefficients for each system:
- Turbocharger
- Blower
- Cylinder
- Smoke

must be empirically determined at baseline operating conditions.

ADVANTAGES	Rapid, single calculation of engine performance as a function of altitude.
VALIDATION	"Reasonably" good correlation with test data shown.
COMPUTING REQUIREMENTS	Suitable for hand calculator.
COST OF OPERATION	Almost none.
FUTURE POTENTIAL	Apparently none. Potential Accuracy: Further refinement at this level of sophistication probably not warranted.
AVAILABILITY	Model fully described in source document.

TITLE	A Real-Time Analogue Computer Simulation of a Turbocharged Diesel Engine
DATE	1975
AUTHORS	R.S. Benson, D.E. Winterbone, S.S. Shamsi, G.D. Closs, A.G. Mortimer, P. Kenyon
ORGANIZATION	University of Manchester, Institute of Science and Technology
SPONSORS	None listed
TRANSPORTATION MODE	Highway, Marine
APPLICATION	Military and civilian
OBJECTIVE	To simulate for the purpose of analytically improving the transient response of a turbocharged diesel engine when subjected to a step change in load. Engine response is modeled as: - Engine speed - Turbocharger speed - Rack position - Compression boost - Air/fuel ratio all as a function of time. Output: - Engine speed - Turbocharger speed - Exhaust temperature - Rack position - Engine speed - Boost ratio - Engine air flow as a function of a set speed and time from a step shaft load input.
REFERENCES	IME Proceeding 1976 SAE Paper 770122 ASME 76-WA/DGP1

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RELATIONSHIP TO OTHER MODELS

Based on model developed by Ledger (see SAE Paper 710177 and 730666).

HISTORY OF MODEL

Previous work has been performed at UMIST on the modeling of a Ruston and Hornsby 6APC diesel engine. This had a 0.20 m (8 in.) bore, and produced a maximum output of 19 bar (270 $lb_f/in.^2$) bmep at 1000 rpm, with a boost pressure of 2.7 bar (80 ins mercury abs). The engine was fitted with a large valve overlap camshaft to enable it to achieve the maximum benefit from turbocharging. The computer models were based largely upon on-design steady state test results; the combustion equations were extended using off-design results obtained from a single-cylinder version of the same engine. The model predictions agreed reasonably well with empirical results, but deficiencies were noticeable in the prediction of turbocharger response, air mass flow and exhaust temperature. Furukawa extended a digital computer model of the engine to include air injection into the compressor of the turbocharger. The aim of this work was to show that assisted acceleration of the turbocharger would improve the system response when a sudden load is applied.

OPERATIONAL CAPABILITIES

- Take empirically measured steady and transient data and develop model for transient engine response.
- Turbocharger response characteristics can be altered.

ASSUMPTIONS

Many simplifying assumptions made to linearize or reduce the mathematical complexity of modeling the engine. These assumptions are inherent in the equation used and are too numerous to list here.

LIMITATIONS

- The model is based on a vast amount of empirical data for a specific engine. Hence it is not easily transferred from one engine to another.

- Air fuel ratio is deduced rather than directly measured. The deduction is based on the assumptions inherent in the methodology.
- Ignores cycle analysis completely.

DATA INPUT REQUIREMENTS

- Virtually all engine data required as output, plus friction (Willan's line format).
- Manifold pressure and temperature
- Turbine inlet pressure and temperature
- Smoke
- BMEP
- Fuel flow and pressure
- Crankangle
- Cylinder pressure
- Needle lift
- Air mass flow
- Engine torque

ADVANTAGES

The model appears to be somewhat cumbersome to use due to the need for both an analog and a digital computer, while its accuracy is about the same as less restrictive models (E-0018-TC).

VALIDATION

Engine performance is claimed to have been predicted within about 5 percent.

COMPUTING REQUIREMENTS

Unknown analog computer used: Program apparently not limited to this specific unit. But a digital (DEC PDP15 with two disc drive) used to interface between the engine and analog computer for data acquisition purposes.

COST OF OPERATION

Not stated.

FUTURE POTENTIAL

None

Potential Accuracy: Probably can't be improved.

AVAILABILITY

Model described in ASME paper. However, much empirical data needed as described in IME paper.

TITLE	A Dynamic Simulation of a Two-Stroke Turbocharged Diesel Engine
DATE	1981
AUTHORS	D.E. Winterbone, W.Y. Loo
ORGANIZATION	University of Manchester, Institute of Science and Technology (UMIST)
SPONSOR	Detroit Diesel Allison
TRANSPORTATION MODE	Highway
APPLICATION	Military or civilian
OBJECTIVE	To describe the transient (and steady-state) performance of a two-stroke turbocharged (and blown) diesel using control volume emptying and filling concepts. Output: - Load - Fuel injected (percent of full) - Compressor outlet pressure (percent of full) - Compressor outlet temperature (percent of full) - Blower outlet temperature (percent of full) - Air box pressure (percent of full) - Turbine inlet pressure (percent of full) - Turbine inlet temperature (percent of full) - Turbocharger speed - Air mass flow rate (percent of full)
REFERENCE	SAE Paper 810337
RELATIONSHIP TO OTHER MODELS	• Based upon a four stroke model reported by Winterbone, Benson, and Furukawa in SAE 730665. • Uses combustion model developed by Whitestone and May "Rate of Heat Release in Diesel Engines and its Correlation with Fuel Injection Data," IME Vol. 184, 1969-1970, a single zone rate of heat release model.
HISTORY OF MODEL	First reported in SAE 810337.

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OPERATIONAL CAPABILITIES

- Evaluate steady-state performance over a broad range of load conditions (30-100% full load).
- Predict transient performance of an engine in
  - response to step changes in load
  - "typical" operation in a truck

Design factors may be varied by altering the parameters which define the state of the working fluid as well as fundamental engine or system parameters (inertia, speed, load, swept volume, etc.)

ASSUMPTIONS

- Gas flows can be modeled by first order non-linear differential equations.
- Turbine, compressor, and blower can be represented by their steady-state characteristics.
- Cycle to cycle variations are not important.
- Gas pressure and temperature driving compression stroke modeled assuming polytropic compression.
- Combustion process in two parts:
  (1) preparation limited combustion and air
  (2) reaction limited combustion rate
- Heat transfer calculated using ANNAND expression.
- Scavenging process based on assumption that the entering fresh charge is mixed completely and immediately with the cylinder contents.
- During scavenging:
  - gas mixture contains only CO_2, H_2O, O_2 and N_2
  - gas obeys perfect gas law ($p\dot{V} = \dot{m}RT$)
  - internal gas energy is a function solely of temperature and air/fuel ratio.

LIMITATIONS

- Uses filling and emptying concepts
- Two-stroke engine only
- No emissions information
- Turbocharger speed effects ignored.
- Ignores manifold resonances which cause cylinder to cylinder variations.

DATA INPUT REQUIREMENTS

Mechanical characteristics of:
- turbocharger
- blower
- intercooler
- air receiver
- engine cylinder
- valving
- exhaust system

as they effect air flow and combustion. The model is based upon fundamental principles and hence very little empirical data is required.

ADVANTAGES

- Can be easily applied to a range of engines because little if any empirical data required.
- Applicable over a wide speed range.
- Models each component within the engine air flow and combustion system separately based on fundamentals.
- Includes simulation of engine in a truck.

VALIDATION

- Shows good steady-state correlation with engine for which model initially developed (error within 5 percent).
- Transient response appears "realistic" but not fully validated yet.

COMPUTING REQUIREMENTS	Uses ANSI Fortran IV - All equations are in paper: Runge Kutta technique (4th order) is used to solve in the computer.
COST OF OPERATION	Not specified.
FUTURE POTENTIAL	Look forward to incorporating a smoke model. Potential Accuracy: Further work promises sharpening up the model as some combustion coefficients are fine-tuned.
AVAILABILITY	Unknown: may be recreated from reference.

TITLE	A Non-Linear Digital Simulation of Turbocharged Diesel Engines Under Transient Conditions
DATE	1976
AUTHORS	Neil Watson, Maged Marzouk
ORGANIZATION	Imperial College of Science and Technology
SPONSOR	Ministry of Defense (U.K.) Military Vehicle and Engineering Establishment
TRANSPORTATION MODE	All
APPLICATIONS	Military or civilian
OBJECTIVE	To study and analyze the transient response of a turbocharged diesel engine due to a change in load or power demand (throttle position). Output: Primary output is the engine speed and exhaust characteristics (pressure, temperature) in response to load change. However, program is designed to provide diagnostic data allowing analysis of phenomena listed under "Range of Capabilities." The <u>only</u> independent variable is crankangle.
REFERENCE	SAE paper 770123
RELATIONSHIP TO OTHER MODELS	• Combustion: Kreiger, Borman, Fowell, and Marzouk • Heat transfer: Woschini • Engine power losses: Chen
HISTORY OF MODEL	There are many sources of non-linearity in diesel engines. However, linearized models (based on either continuous control or sampled-data concepts) have been used to investigate the stability of engine controllers. Sampled data models are closer to the discontinuous nature of a reciprocating engine, but a major handicap is imposed by the assumption of a constant sampling interval. Quasi-linear models, which employ steady-state characteristics of the engine, constitute a further step towards the dynamic simulation of turbocharged diesel engines. The most widely reported

simulation is that developed at UMIST, although Bowns has published a similar model. These models link steady-speed experimental data representing engine thermodynamics and gas flow with dynamic models of the mechanical components.The major disadvantage of quasi-linear models is their heavy reliance on empirically determined data; particularly at "off-design" conditions such as those which occur during transients. Furthermore, the representation of complex combustion and air flow phenomena tends to be oversimplified. By representing the air-flow characteristics of an engine as a steady-flow phenomenon, possible differences between inward and outward flow are not explicitly considered. Evidence suggests that reverse flow from cylinder to inlet manifold, significantly affects the response of highly rated engines.

The unsteady thermodynamic and gas flow processes occurring inside a turbocharged diesel engine are satisfactorily evaluated at constant engine speed by quasi-steady engine simulation programs. Since these programs calculate unsteady phenomena, regardless of engine running conditions, such techniques are potentially suitable for extension to transient operation. This forms the basis of this model. However, different formulation and solution procedure was essential, since the periodicity condition (constant engine speed) does not hold during transient operation.

OPERATIONAL CAPABILITIES

The model is rather thorough, so a number of effects can be explored including:

- Different loading rates
- Turbocharger match
- Turbocharger inertia
- Engine and load inertia
- Exhaust manifold design
- Inlet manifold design
- Valve timing
- Charge air cooling
- Variable geometry turbocharging
- Re-matching with an exhaust waste-gate valve

- Fuel-pump rack limiters
- Compression ratio
- Engine friction
- Thermal inertia of combustion chamber surfaces

All under transient <u>and</u> steady-state conditions.

ASSUMPTIONS

- Thermodynamic equilibrium at all times
- Ideal-gas behavior at all times
- All control volumes contain homogeneous mixture of air and combustion products
- Ignore property gradients and phenomena
  - non-equilibrium compositions
  - fuel vaporization before and during combustion
  - spatial variations within manifolds
- Combustion products assumed from
  - Kreiger and Borman (lean)
  - Marzouk (rich)
- Cylinder heat transfer by Woschini
- Combustion process in 2 distinct phases:
  (1) ignition delay (duration of propagation of pressure wave along the fuel line)
  (2) heat generation
    - premixed portion of burning
    - diffusion portion of burning

LIMITATIONS

- Simple combustion model.
- Model appears sensitive to small errors in describing engine characteristics such as governor response to engine speed.

DATA INPUT REQUIREMENTS

- Heat transfer area and coefficients
  - manifolds
  - combustion chamber
- Engine friction torque
- Load
- Cylinder diameter
- Internal energy
- Fuel burning rates
  - premixed
  - diffusion
- Engines polar moment of inertia
- Load polar moment of inertia

- Turbocharger polar moment of inertia
- Initial and upsetting conditions
- Ambient conditions
- Mode of fuel burning proportionality factor
- Engine speed
- Efficiency
  - turbine
  - compressor
  - turbocharger
- Engine dimensions
- Fuel injection system characteristics

Input Data Accuracy: Reportedly transient response of some engine systems, particularly turbocharger and governor is hard to measure. Present techniques appear inadequate. Improvement needed in this area.

ADVANTAGES

- This appears to be a very powerful model.
- Takes the entire power producing system into account.
- Combustion model is better than that of other similar models studied, but is still rather simple.
- Uses a minimum of empirically determined coefficients.

VALIDATION

"Excellent" agreement. Only serious discrepancies appear to be prediction of maximum cylinder pressure (to be expected) and turbine inlet temperature (attributed to thermocouple lag rather than model deficiencies).

COMPUTING REQUIREMENTS

Not stated.

COST OF OPERATION

Not stated.

FUTURE POTENTIAL

Not stated.

Potential Accuracy: Not stated; very good already.

AVAILABILITY

Unknown.

4.0 INDEXES

All of the models are indexed in two separate ways: (1) by model category, and (2) by organizational author.

Model Category Index

The model category index is organized as follows:

- Heavy Duty Transport System Models
  - (1) Highway Transport
  - (2) Marine Transport
  - (3) Rail Transport
- Heavy Duty Diesel Engine Models
  - (4) Matching Intake/Exhaust Systems to the Engine
  - (5) Fuel Efficiency
  - (6) Emissions
  - (7) Combustion Chamber Shape
  - (8) Fuel Injection System
  - (9) Heat Transfer
  - (10) Intake/Exhaust System
  - (11) Operating Performance
  - (12) Bottoming Cycle
  - (13) Turbocharger

Within each of the thirteen model categories, each model is listed in numerical order according to its access code (which merely signifies the chronological order in which the model literature was acquired by the project team).

Organizational Author Index

This index organizes all models alphabetically by the organization that authored the model.

4.1 MODEL CATEGORY INDEX

MODEL CATEGORY INDEX

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MODEL CATEGORY INDEX

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4.2 ORGANIZATIONAL AUTHOR INDEX

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