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VEHICLE TESTING OF CUMMINS TURBOCOMPOUND DIESEL ENGINE

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16. Abstract

Two turbocompound diesel engines were assembled and dynamometer tested. Both engines met the 1980 California 6 gram emission limit on $BSNO_x$+HC and achieved a minimum BSFC of .313 lb/bhp-hr and a BSFC at rated conditions of .323 lb/bhp-hr. These engines were then installed in Class VIII heavy-duty vehicles to determine the fuel consumption potential and performance characteristics. One turbocompound powered vehicle was evaluated at the Cummins Pilot Center where driveability, fuel consumption, torsional vibration, and noise were evaluated. Fuel consumption testing showed a 14.8% benefit for the turbocompound engine in comparison to a production NTC-400 used as a baseline. The turbocompound engine also achieved lower noise levels, improved driveability, improved gradeability, and marginally superior engine retardation. The second turbocompound engine was placed in commercial service and accumulated 50,000 miles on a cross-country route without malfunction. Tank mileage revealed a 15.92% improvement over a production NTCC-400 which was operating on the same route.

A number of component modifications were incorporated in the turbocompound engine which resulted in fuel consumption reductions which exceeded the expected benefit from turbocompounding alone. Previous laboratory testing showed a 6% reduction in fuel consumption for a turbocompound engine over an equivalent NH engine operating along the torque curve. Using these test results, the incremental fuel consumption improvement strictly due to the turbocompounding alone was estimated at 4.2% to 5.3% for the interim turbocompound engine depending upon the terrain or mission load factor.

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FOREWORD

This technical report covers all engine and vehicle test activity necessary to fulfill the scope of work requirements of Contract DE-AC02-78CS54936 formerly Contract EM-78-C-02-4936 between the Department of Energy and Cummins Engine Company.

The government program management was conducted by the Vehicle Systems Branch of the Automotive Technology Development Division within the Office of Transportation Programs. This organization is within the auspices of the Assistant Secretary for Conservation and Solar Applications of the Department of Energy. Program officers of the Department of Energy were Mr. Saunders Kramer and Mr. Al Chesnes. Under the terms of a DOE/NASA interagency agreement, the NASA-Lewis Research Center of Cleveland, Ohio, served for D.O.E. as the technical project managers for this contract. The individuals which served as technical representatives of the NASA-Lewis organization include Mr. Murray Bailey and Mr. Robert Migra.

The requirements of NASA Policy Directive NPD 2220.4 (September 4, 1970) regarding the use of SI Units have been waived in accordance with the provisions of paragraph 5d of that Directive by the Director of Lewis Research Center.

The Cummins technical director of this program was Mr. Roy Kamo. The authors would like to acknowledge the valuable contribution in the performance of the program by the following people: S. Bishop, M. Cooper, P. F. Eakins, R. P. Fleetwood, R. L. Harrod, M. S. Lantz, J. A. Lommel, C. J. Rhoades, C. R. Riffle, and J. M. Russell. Acknowledgement is also extended to the Tampa, Florida Cummins Distributor who performed the engine installation and to Florida Refrigerated Services of Dade City, Florida, who conducted the field test.

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SUMMARY

Two turbocompound diesel engines were assembled and dynamometer tested. Both engines met the 1980 California 6 gram emission limit on BSNOx+HC and achieved a minimum BSFC of .313 lb/bhp-hr and a BSFC at rated conditions of .323 lb/bhp-hr. These engines were then installed in Class VIII heavy-duty vehicles to determine the fuel consumption potential and performance characteristics. One turbocompound powered vehicle was evaluated at the Cummins Pilot Center facility where detailed engine-transmission-vehicle tests were conducted in a controlled environment. These tests included an assessment of the driveability, fuel consumption, torsional vibration, noise, and cooling system performance. In comparison to the NTC-400 engine selected for baseline measurements, the turbocompound engine achieved a fuel consumption improvement of 14.87%. Based on fuel consumption testing performed in the laboratory for these two engines, the analytical Vehicle Mission Simulation had predicted a benefit of 14.16%. Drive-by noise tests showed a 1 to 2 dBA lower sound intensity level with the turbocompound engine. Driveability testing revealed improved throttle response characteristics in spite of a higher specific output rating. In gradeability tests, equivalent performance could be achieved with the transmission in one higher gear ratio due to the higher power rating of the engine. Engine retardation or braking was marginally superior with the turbocompound engine.

A 50,000 mile field test was conducted with the second engine without incident of equipment malfunction. Tank mileage of the turbocompound engine on a cross-country route through the southern USA averaged 5.25 mpg or a 15.9% improvement over a NTCC-400 engine which was also operating at this location. The predicted benefit through the VMS comparison for these two engines was 15.1%. Driver reaction to the engine was favorable with comments on the engine's quiet and smooth operation and on the strong performance up long grades. At the completion of the testing program, teardown and inspection of the power turbine and gear train indicated that all gears and bearings were exhibiting normal wear patterns and that more extensive testing with the current design could easily be accomplished.

A number of component modifications were incorporated in the turbocompound engine which resulted in fuel consumption reductions which exceeded the expected benefit from turbocompounding alone. Through previous laboratory testing, it was established that a benefit of 6% reduction in fuel consumption over an equivalent turbocharged and aftercooled NH engine was achieved along the engine's torque curve. Using these test results, the incremental fuel consumption improvement strictly due to the turbocompounding alone was estimated at 4.2% to 5.3% for the interim turbocompound engine depending upon the terrain or mission load factor.

INTRODUCTION

Today's heavy-duty diesel engines are limited by certain fundamental thermodynamic and mechanical considerations. The engine design process is one of trading off variables which affect performance such as bore, stroke, compression ratio, boost pressure, injection pressure, etc., against the thermal limits of the materials selected and the structural limits of the design. Today's production engines represent years of development aimed at perfecting this optimization process. The engine designer of today finds his task complicated by growing concerns relating to the sociability of the power plant, the need to improve reliability with an increasingly complex product, and the requirement to extend the useful life or durability of the engine.

Nevertheless, the diesel engine has been successful in meeting these challenges and maintains a prevalent position in the market place. But the key to the diesel's future lies in finding the correct technical solutions to reduce its exhaust emissions and to make even greater strides in improving its thermal efficiency. For as efficient as the diesel engine may presently appear, it still rejects a majority of its thermal energy in the form of waste heat to the exhaust and cooling system. Better utilization of this otherwise wasted heat is the key to a more energy conserving and sociable diesel engine.

The general approach adopted by Cummins to improve the efficiency of the engine has been to recover available exhaust heat beyond the turbocharger requirement by means of turbocompounding. Turbocompounding should thus be viewed as an essential first step in realizing improved engine efficiency. The next step currently under development consists of shifting the heat energy normally rejected to the coolant into the exhaust where it can now be recovered. This process requires insulation of the diesel's combustion chamber.

Since turbocompounding recovers available exhaust energy, the process is dependent on the amount of energy rejected to the exhaust during operation of the engine throughout its speed and load range. In addition, exhaust energy is also a function of several other variables, the primary ones being:

Specific output	- Higher horsepower engines reject more heat to the exhaust
Emissions level	- Retarded injection timing for NO_x control increases energy rejected to the exhaust
Insulation of combustion chamber	- Lower heat rejection to the engine's coolant increases the available exhaust energy

Turbocompounding a reciprocating engine is not a new concept. Investigations in the late 1930's were aimed at increasing the specific output of the engine. This led to engine designs such as the Wright R-3350 Cyclone gasoline turbocompound which achieved a 15-21% increase in power depending on operating conditions and a brake specific fuel consumption of .390 lbs/bhp-hr. Diesel turbocompounding was applied in the Napier Nomad twelve cylinder two-cycle engine of the 1950's which achieved a specific output of 205 psi brake mean effective pressure with a brake specific fuel consumption near .350 lbs/bhp-hr.

Cummins interest in turbocompounding focuses more intensely on the ability to achieve increased thermodynamic efficiencies. A development program has been underway since 1972 to perfect a turbocompounded diesel engine. This engine is a hybrid diesel reciprocator which is augmented in power from a low pressure power turbine. Turbine power generated by exhaust gas expansion is transferred to the drive train by means of mechanically gearing the power turbine to the rear of the engine crankshaft at a fixed speed ratio. A fluid coupling separates the harmful crankshaft torsionals from the high speed gearing.

The laboratory engineering development of the turbocompound engine has reached a mature stage following the evolution of three power turbine and gear train designs. The next logical system evaluation involved vehicle performance testing. Thus in September of 1978, Cummins Engine Company entered into a contract with the Department of Energy which called for a comprehensive vehicle test evaluation of the Cummins turbocompound engine in two Class VIII trucks. A four phase vehicle test program was established to ascertain the viability of Cummins' interim turbocompound diesel engine for trucks and buses of the 1980's. These four phases of activity were as follows:

- Task I - Engine Preparation and Instrumentation
- Task II - Vehicle Mission Simulation Analysis
- Task III - Cummins Pilot Center Vehicle Testing
- Task IV - Field Testing

Task I entailed the procurement of test components, fabrication and machining for engine modifications, and assembly of the interim turbocompound engines. Each engine was inspected during assembly and dynamometer tested for performance and emissions prior to installation in the test vehicles. In Task II a Vehicle Mission Simulation (VMS) program was used for selection and optimization of the drive train for the engine. The optimization process was made with respect to fuel consumption, driveability, and gradeability. Aside from its use as an application development aid, this program was used to predict engine and vehicle performance at both test locations. In this manner actual vehicle test results could be correlated with the predictive performance.

The Task III effort consisted of a comprehensive evaluation of the engine at the Cummins Pilot Center facility. Vehicle tests performed included fuel consumption, noise, driveability, gradeability, retarding capability, and torsional vibrations. This testing is a routine procedure to assess performance of a new engine design in a vehicle. In Task IV a 50,000 mile field test in a representative fleet vehicle was conducted. Fuel consumption, driveability, operator assessment, and limited reliability and durability data was generated in the course of this test.

1.0 ENGINE PREPARATION FOR VEHICLE TEST

1.1 Turbocompound Engine Description

The turbocompound engine was developed from the Cummins NTC-400. The NTC-400 engine which was used for all baseline performance tests is rated 400 brake horsepower at 2100 rpm engine speed. The bore and stroke of the NH engine is 5.5 and 6.0 inches respectively. The engine is an inline-six, four cycle of 855 cubic inch displacement. Fuel is supplied to the engine by the Cummins PT ® high pressure injection system. The NTC-400 engine as well as the turbocompound engine is both turbocharged and aftercooled.

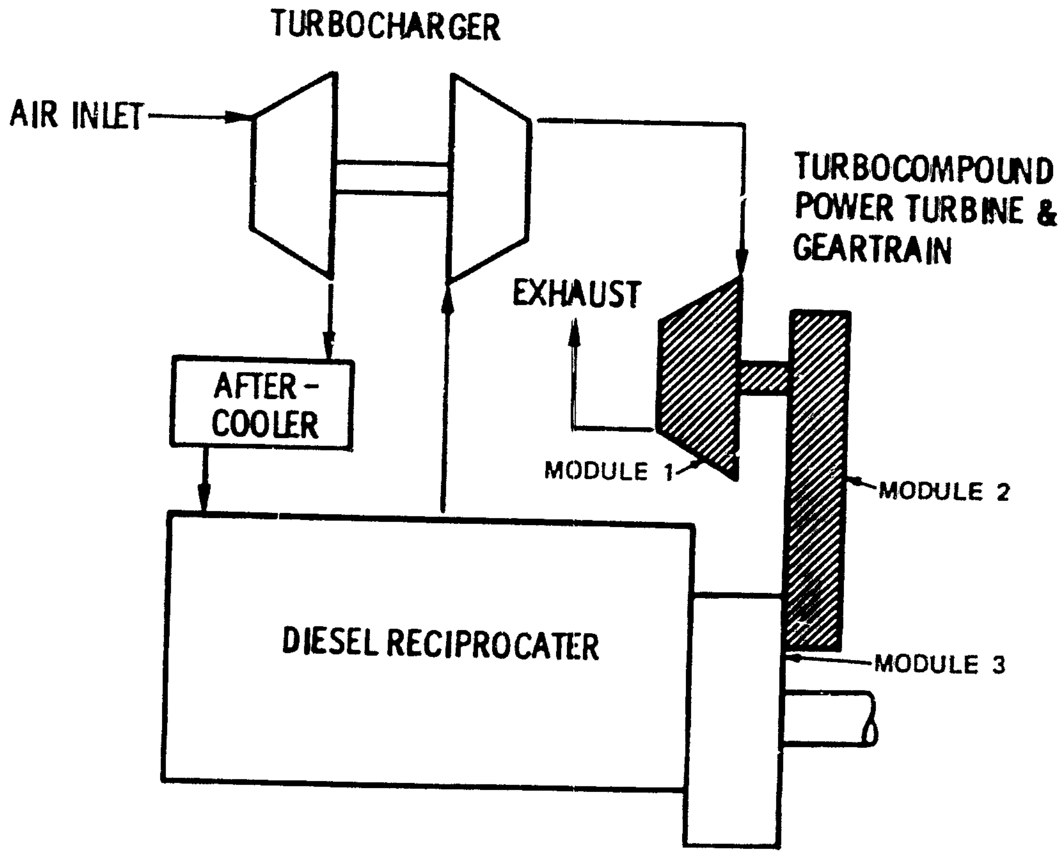
A number of component modifications of the NTC-400 have been made to improve the engine system performance under turbo-compounding conditions. These include design changes of the camshaft, valves, cylinder head exhaust ports, exhaust manifold, and turbocharger. Primarily, these modifications were initiated to reduce the blowdown energy losses during the exhaust phase of the cycle and to improve the transmission efficiency of the exhaust gas from the cylinder to the first stage turbine.

The turbocompound gear train consists of a radial inflow low pressure power turbine to recover the exhaust gas energy. This along with its bearing cartridge is one of three separate modules. The modular concept was selected to provide for ease of assembly and maintenance. The second module consists of the high speed gearbox. Here, involute spur gearing is used to achieve part of the necessary speed reduction from the power turbine to the crankshaft. Lubrication is provided by the engine oil system and directed by internal oil drillings. The third module is the low speed gearbox which completes the speed reduction required. A fluid coupling is an integral part of this module which performs the function of separating the high speed gearing from the crankshaft torsionals. The flywheel housing is a S.A.E. No. 1 housing constructed of cast iron to support the weight of the gear train. The overall increase in engine length is one inch and the entire system is designed such that it may be installed in most high horsepower engine applications. The design provides for 50% overspeed capability and 100% overspeed burst containment. A schematic of the Cummins turbocompound diesel engine is shown in Figure 1 while the actual assembled Phase III turbocompound engine is shown in Figure 2.

The turbocompound engine was rated 450 brake horsepower at 1900 rpm engine speed with 15% torque rise to 1440 lb-ft at 1300 rpm. The lower operating speed rating was selected to take advantage of the low speed torque characteristics of a turbocompound engine. The increase in power rating at a lower engine speed was achieved without increasing the thermal or structural loading of the reciprocator.

The engine was also equipped with a two-loop cooling system to achieve lower charge air temperatures. This improved the thermal efficiency of the engine and reduced nitric oxide exhaust emissions.

FIGURE 1.- SCHEMATIC OF CUMMINS TURBOCOMPOUND DIESEL ENGINE



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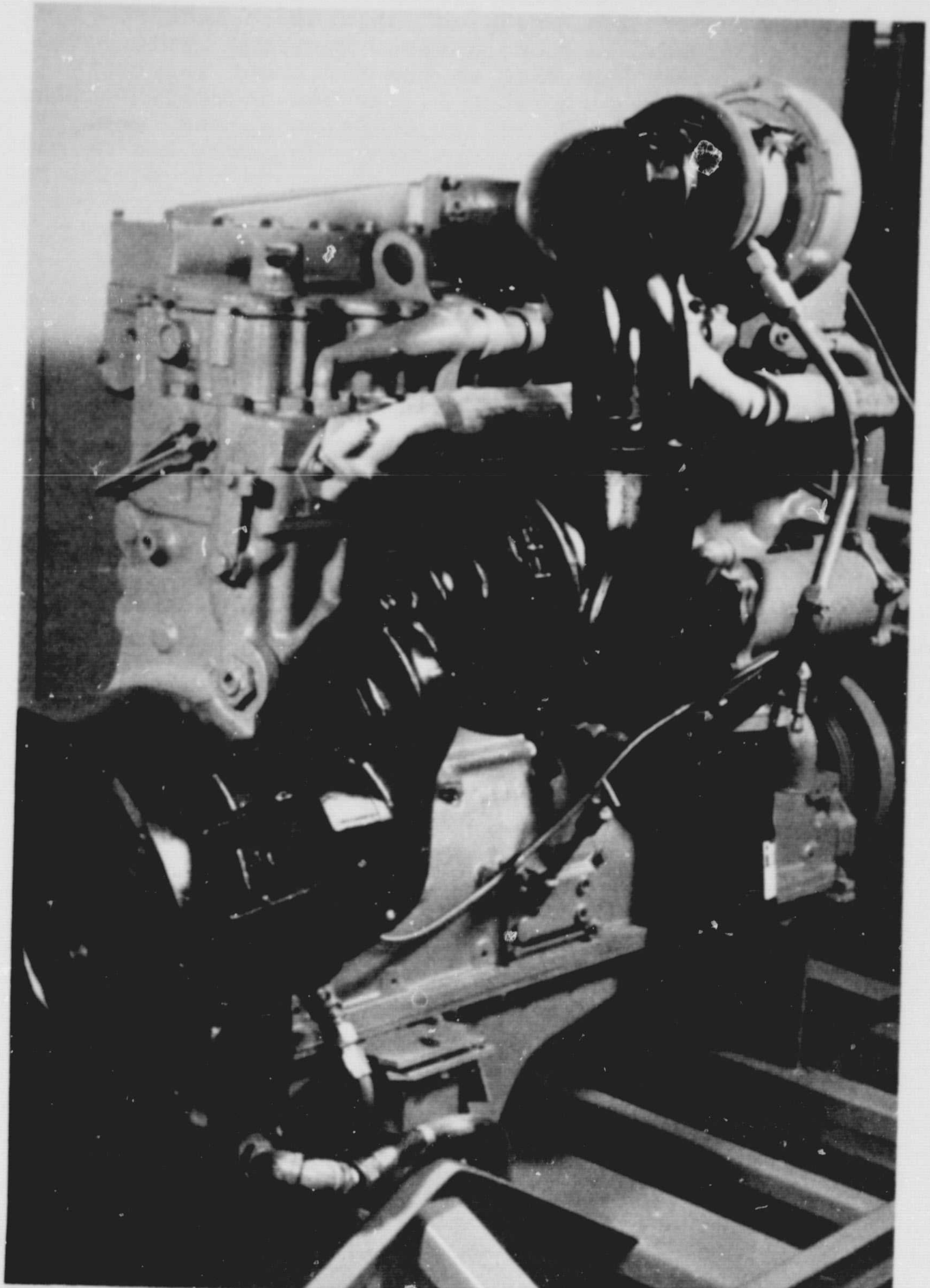


FIGURE 2.- PHASE III TURBOCOMPOUND DIESEL ENGINE

1.2 Dynamometer Testing Results

Upon completion of assembly, each engine was instrumented and placed in a test cell for dynamometer testing. Following engine break-in, testing began to determine the injection timing required to conform to the 1980 California emissions standard of 6 grams combined nitric oxide and unburned hydrocarbons as measured on the federal 13-mode gaseous emission cycle. The levels of $BSNO_X$, BSHC, and BSFC at the different injection timings tested are shown in Table 1. As the injection timing is retarded to achieve lower nitric oxide emissions, the acceleration smoke increases in opacity. Variable timing can be employed to reduce smoke levels by advancing the timing during light load operation of the engine. In addition, lower emissions are achieved with this device since the light load (modes 1, 2, 7, 12, and 13) unburned hydrocarbons are also reduced by advancing the timing. Figure 3 shows the results of the emission testing, both with and without the use of variable injection timing for light load advance. This illustrates the benefit, if not the necessity, for variable injection timing on this engine at combined emissions levels below six grams. In the final calibration, the dynamic injection timing at rated power was retarded to 16 degrees before top center (BTC) to achieve a combined emissions level of 5.78 gm/bhp-hr on the 13-mode gaseous emission cycle.

Following emissions testing, the acceleration smoke testing was performed with the federal smoke cycle. The Cummins PT® fuel pump was equipped with an air-fuel control (AFC) which served as an aneroid to limit the fuel flow to the injectors to an amount compatible with the boost air supplied from the turbocharger during accelerations. Thus, the AFC provided a smooth proportional fuel pressure transition between the zero boost level or "no air" intake manifold pressure and full boost pressure. The turbocompound engine is able to achieve full boost pressure at a faster rate due to the more rapid turbocharger response. This results from the more favorable turbocharger match the turbocompound engine provides. In general, as the output of an engine is increased, it is necessary to increase the turbine volute area schedule to prohibit overboosting the engine at high speeds. A wastegate device or variable area turbocharger would circumvent this requirement but both provide a reduction in thermal efficiency. With the turbocompound engine, this compromise in turbocharger response is not required. As the low pressure power turbine enables the selection of a geometrically smaller turbocharger turbine inlet area schedule, boost pressures and induction air flows are generated in a more timely fashion which accentuates the response of the engine. This results in a lower smoke opacity on the federal acceleration smoke cycle at the same AFC setting normally used on the turbocharged and aftercooled engine. As mentioned previously, variable timing allows the injection timing to be advanced at light loads which reduces the acceleration smoke emissions. These improvements were traded off for increased clutch engagement torque in

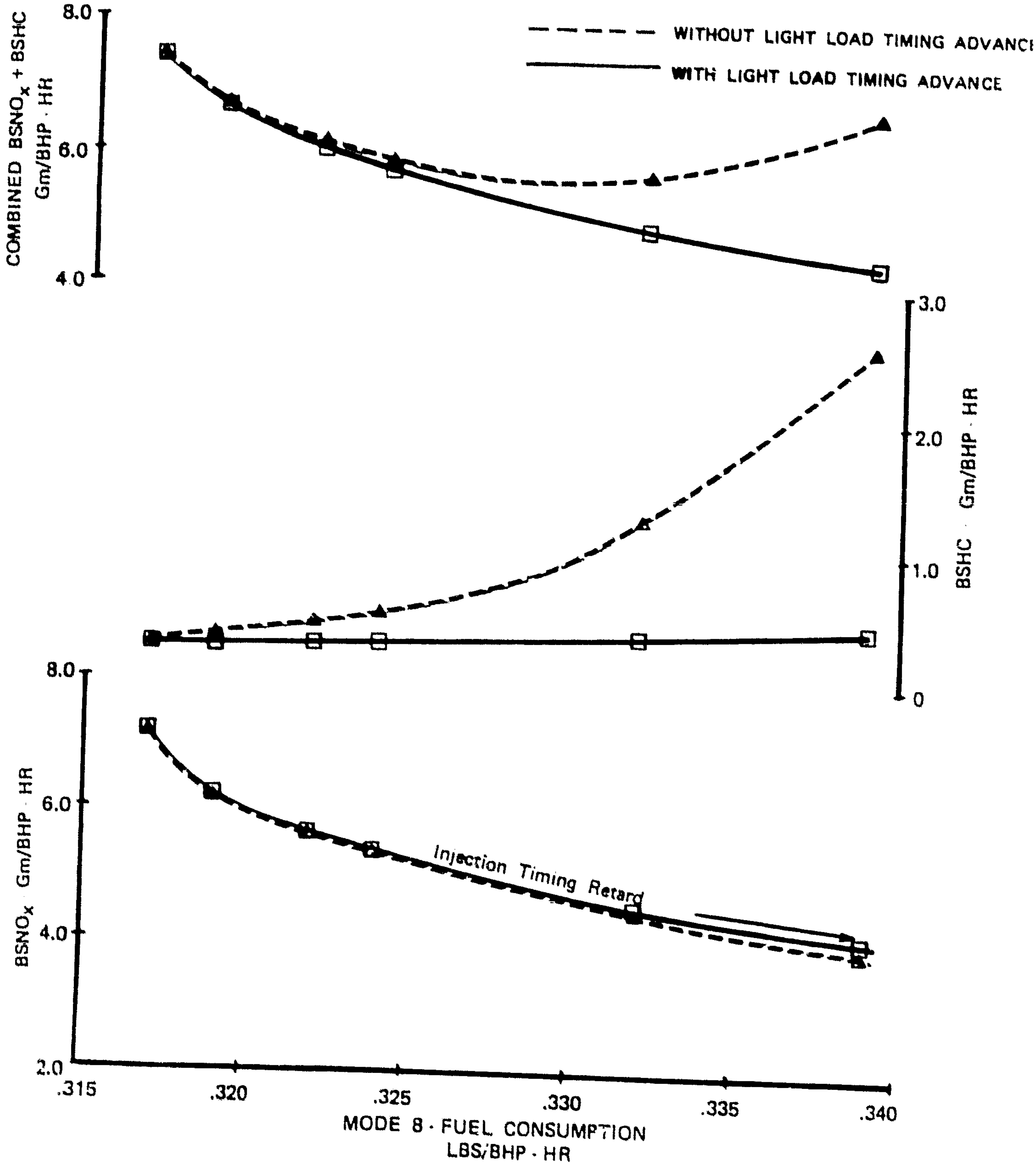
TABLE I. - FEDERAL 13-MODE GASEOUS EMISSIONS TEST RESULTS
TURBOCOMPOUND - 450 ENGINE

Dynamic Injection Timing At Rated Power	Fixed Timing (Gm/BHP-HR)			Variable Timing* (Gm BHP-HR)			Rated Power BSFC (Lb BHP-HR)	Torque Peak BSFC (Lb BHP HR)
	$BSNO_x$	BSHC	$BSNO_x$ + BSHC	$BSNO_x$	BSHC	$BSNO_x$ + BSHC		
20.0° BTDC	7.21	.250	7.45	7.21	.250	7.45	.317	.315
19.0° BTDC	6.25	.320	6.58	6.281	.250	6.531	.319	.315
17.0° BTDC	5.74	.430	6.17	5.759	.270	6.029	.322	.315
16.0° BTDC	5.45	.510	5.96	5.482	.296	5.778	.324	.315
13.5° BTDC	4.53	1.25	5.78	4.553	.339	4.892	.332	.320
11.5° BTDC	3.96	2.67	6.63	4.015	.393	4.408	.339	323

* Injection timing advanced to 20° BTDC at rated in modes 1, 2, 7, 12 & 13.

FIGURE 3. FEDERAL 13 MODE EMISSIONS TESTING RESULTS

TURBOCOMPOUND 450 BHP ENGINE



the fuel pump calibration. This was achieved by increasing the fueling to the engine while under full aneroid control. Thus, the clutch engagement or "no-air" torque of the turbocompound engine was increased while remaining in compliance with federal smoke emission standards. A matrix of smoke levels versus AFC spring rates and no-air torque levels is shown in Table 2. The AFC was assembled with a 200#/inch spring and the "no-air" torque was set at 650 lb-ft.

After completion of the final fuel pump and injection timing calibrations, steady-state dynamometer performance mapping of the engine was conducted. Figure 4 shows the isofuel consumption islands as a function of engine power and speed. In Figure 5 the same data is plotted to indicate constant fuel rate as a function of engine load and speed. As can be seen, rated power brake specific fuel consumption was .323 lbs/bhp-hr decreasing to .315 lbs/bhp-hr at peak torque. Minimum brake specific fuel consumption of .313 lbs/bhp-hr occurred at 1500 rpm engine speed.

At this point in the program a company funded 1000 hour endurance test was performed on a similar turbocompound engine. The engine was cycled two minutes at rated power followed by one minute at high idle. This test was a routine precaution to monitor engine and turbocompound system durability and reliability prior to vehicle testing. Following completion of this test, the gear train was disassembled and inspected. Inspection revealed all gears, bearings, shafts, and the fluid coupling to be in good condition with normal wear patterns. It was determined that no design changes would be required prior to initiation of the vehicle tests. The only significant problem encountered during the test was that of excessive carbon deposits in the power turbine shaft bearing housing. This was due to exhaust gas leakage past the turbine shaft piston ring seal. This design deficiency can be corrected by the addition of another piston ring seal; however, it was decided that for limited testing duration planned, the leakage problem would not be a detrimental factor affecting test results. Shown in Figure 6 are some results from the 1000 hour endurance test.

2.0 VEHICLE MISSION SIMULATION

After completion of the dynamometer engine testing, Cummins' Vehicle Mission Simulation (VMS) computer program was used as an aid in the optimization and selection of the drive train for the turbocompound engine. This optimization process is made with respect to fuel consumption, driveability, and gradeability.

Selection of the best drive train involves an evaluation of the tradeoffs between fuel consumption and driveability. Fuel consumption at road speeds of 55-60 miles-per-hour can be optimized by gearing the engine to operate near its peak torque speed. This approach, however, would impair the gradeability of the vehicle as little margin in operating speed range is

TABLE II.- ACCELERATION SMOKE TESTING SUMMARY
TCPD-450 WITH MECHANICAL VARIABLE TIMING
6 GRAM COMBINED EMISSIONS ($BSNO_x$ + BSHC)

AFC SPRING RATE		NO AIR TORQUE SETTING			
		550 Ft. Lbs.	600 Ft. Lbs.	650 Ft. Lbs.	700 Ft. Lbs.
180#/In.	A	11.01 % OPACITY	12.88	14.64	15.93
	B	2.07	2.51	2.59	2.19
	C	22.66	24.7	26.67	27.86
200#/In.	A	N/A	10.13	12.32	14.57
	B	N/A	3.11	2.37	2.87
	C	N/A	20.84	23.86	25.60

KEY:

A = Average of 15 - ½ sec. smoke peaks from first two accelerations

B = Average of 5 - ½ sec. smoke peaks from lug down

C = Average of 3 - ½ sec. smoke peaks

FIGURE 4 TURBOCOMPOUND 450 PERFORMANCE MAP
WITH LINES OF CONSTANT BSFC

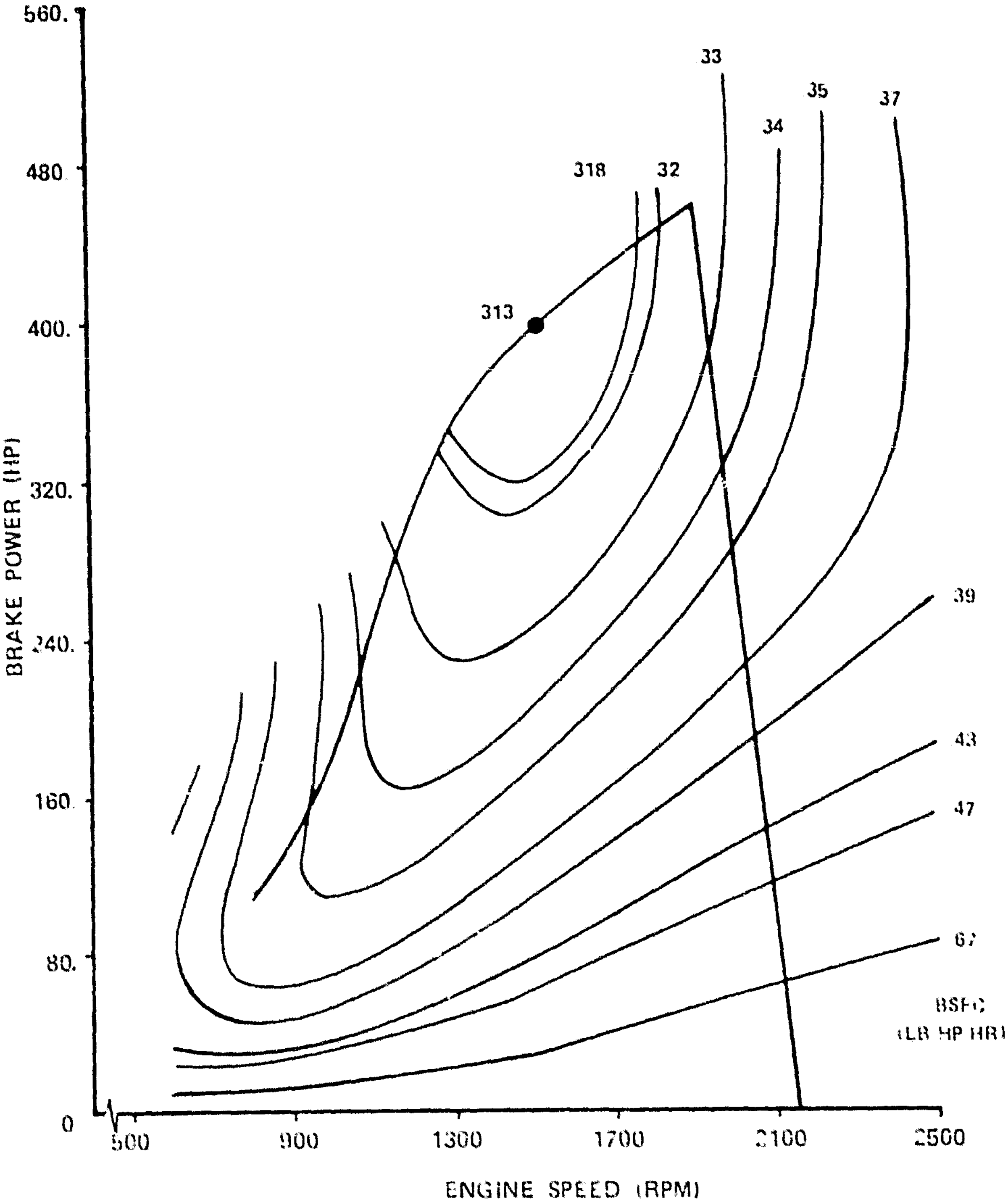


FIGURE 5. TURBOCOMPOUND 450 PERFORMANCE MAP WITH LINES OF CONSTANT FUEL RATE

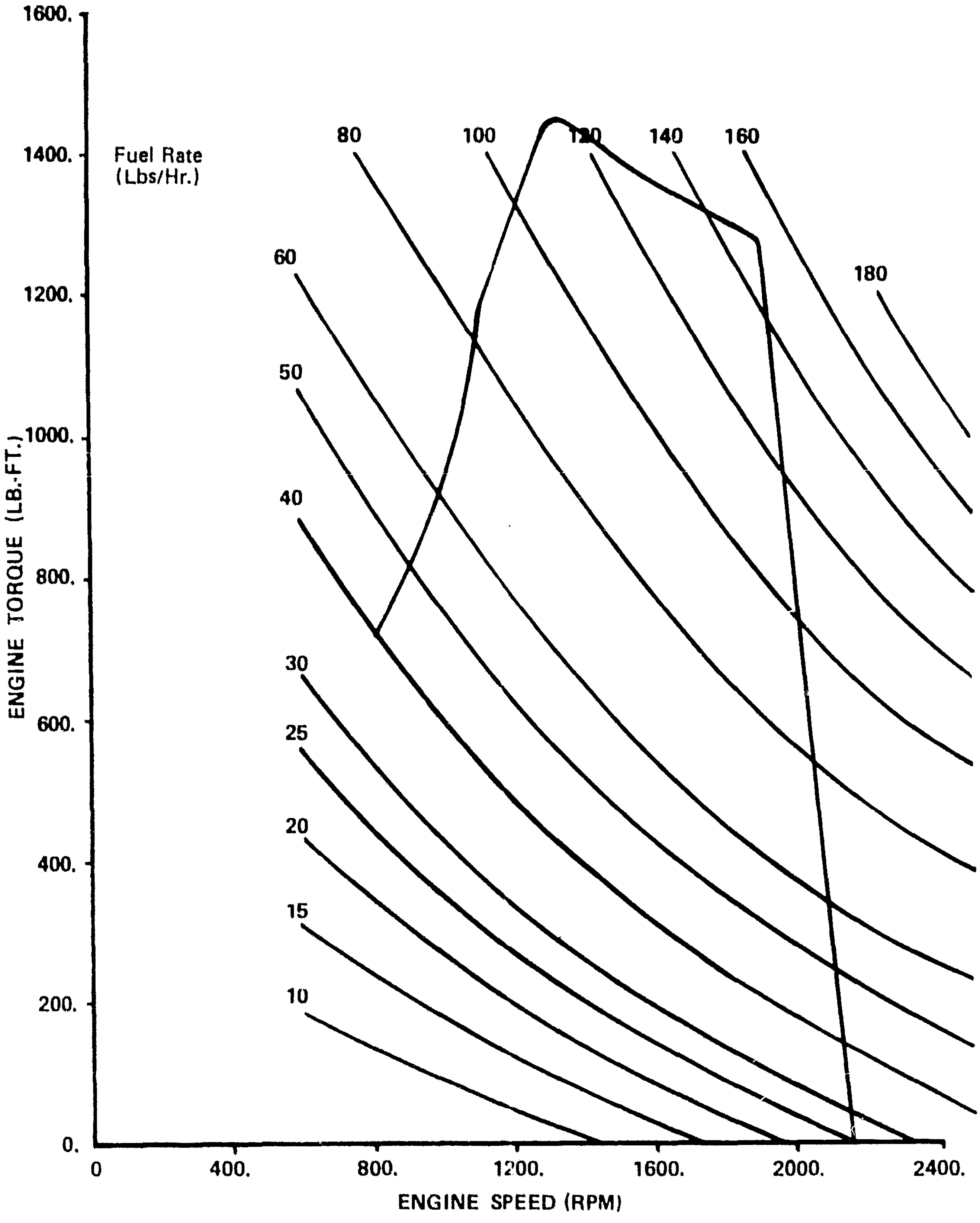
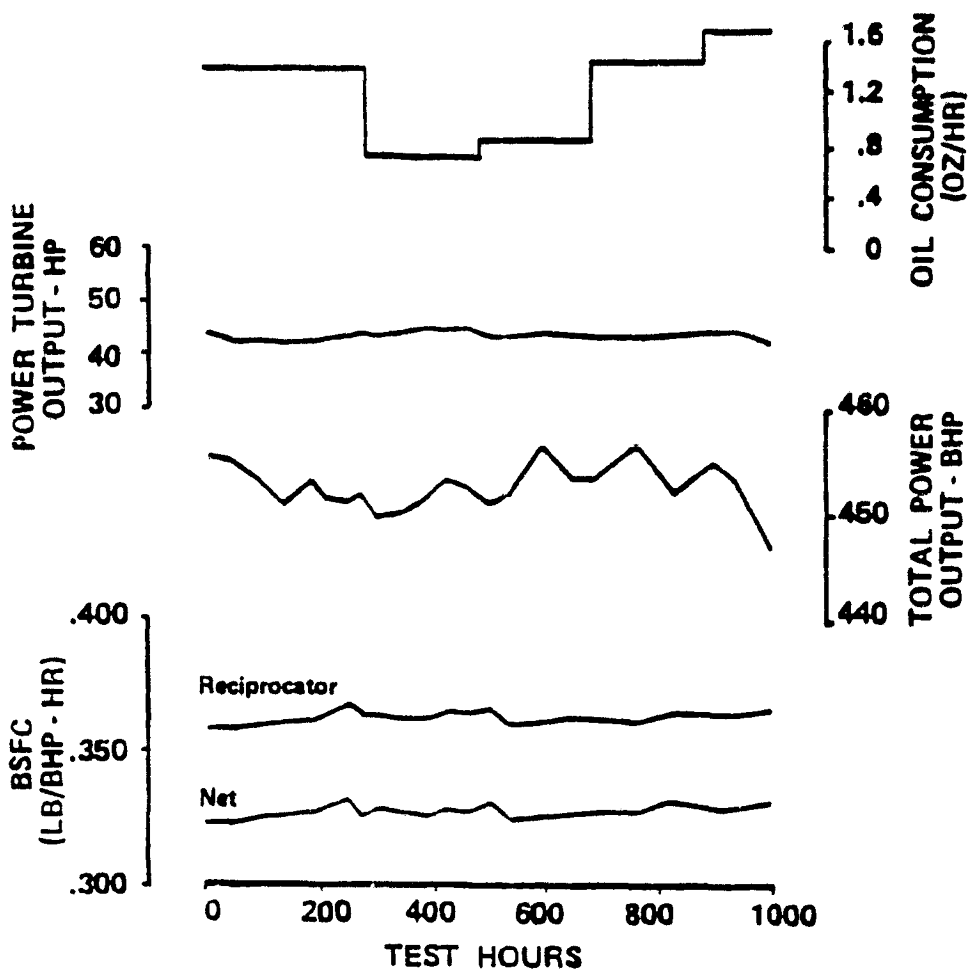


FIGURE 6. - TURBOCOMPOUND PERFORMANCE
1000 HOUR ENDURANCE TEST
TCPD-450 LOW PRESSURE POWER TURBINE
PHASE III GEAR TRAIN



available before the operator would have to downshift when approaching a grade. This, in turn, would mean more gear shifting, more drive train wear, and increased driver fatigue. At the other extreme, the drive train with the best gradeability would operate the engine at or beyond the rated speed of the power plant for a given road speed. This would provide the driver with the widest operating speed range but would also result in the highest fuel consumption. Gearing the turbocompound engine to cruise in the 55-60 mile-per-hour range at the engine's most efficient speed range of 1450 to 1650 rpm results in the best tradeoff between fuel consumption and gradeability.

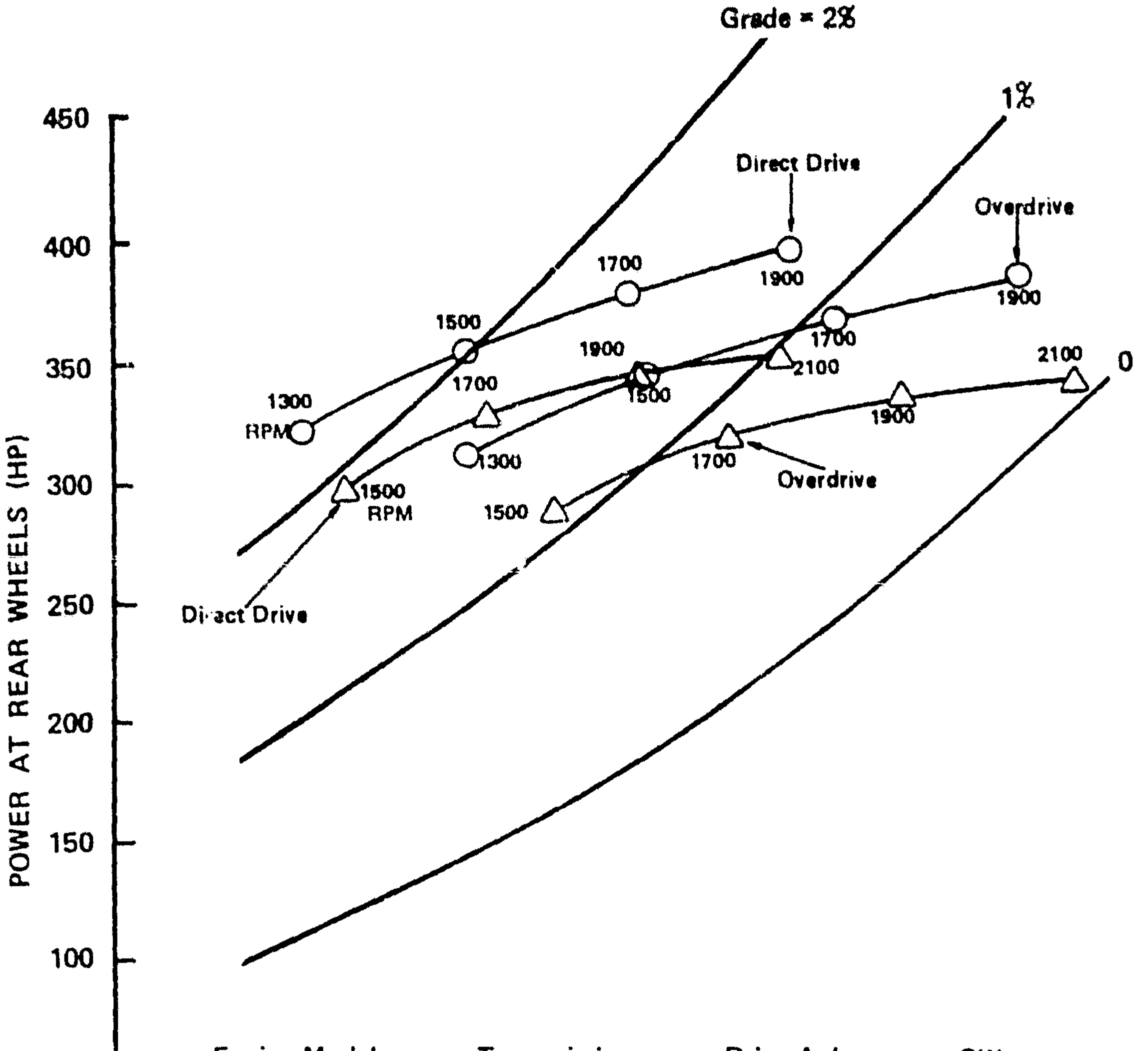
In Figure 7 the predicted gradeability performance of the turbocompound engine and the baseline NTC-400 engine used for comparison purposes is shown. The drive train selected for the turbocompound engine consists of a Fuller RTO-12513 transmission with a 3.7:1 drive axle ratio. The NTC-400 engine used the same transmission, but a 4.11:1 axle ratio since the operating speed range of the engine was higher. In this figure it can be seen that the turbocompound engine had the same predicted gradeability performance as the NTC-400 engine with the transmission placed in one higher gear due to the higher power rating. This allowed a gain in fuel consumption with the turbocompound engine since it would operate at lower, more efficient engine speeds at the same gradeability as the NTC-400 engine.

Aside from its use as an application development aid, the VMS program is capable of modeling the performance of a tractor-trailer combination over a preprogrammed route. Over 100,000 miles of U.S. route profile has been entered into the data bank of this program. Each route is a mile-by-mile description of road grades, speed limits, and directional changes. This analytical model represents a series of engineering calculations which predict commercial vehicle performance under a wide variety of road and engine conditions.

The program input requirement consists of a detailed description of the vehicle and selection of a route. The model is capable of adjusting to varying ambient operating conditions such as temperature plus prevailing wind velocity and direction. The VMS can predict both steady-state performance as well as transient engine behavior. Output data under steady-state operating conditions includes startability, gradeability, and vehicle performance in all the transmission gears. The route simulation summary includes trip time, average speed, fuel consumption, gear shifts, time spent at full throttle, and average engine load factor.

The engine performance maps of the turbocompound NH engine and the baseline NTC-400 were input for the VMS program to predict the fuel consumption of the engines on a tank mileage basis over the Pilot Center fuel economy route. A comparison

FIGURE 7. GRADEABILITY POWER AVAILABLE VERSUS POWER REQUIRED



Engine Model	Transmission	Drive Axle	GW
△ NTC - 400	RTO12513	4.111	80,000 LBS.
○ TCPD - 450	RTO12513	3.700	80,000 LBS.

of the fuel consumption for these engines as a function of percent rated speed is shown in Figure 8. The fuel map of a Cummins NTCC-400 engine which has been certified for the 1980 California emission standards was also input for a tank mileage comparison with the turbocompound engine over the field test route. The results of these predictions are presented with the actual fuel economy results in later sections of this report.

3.0 VEHICLE TESTING AT CUMMINS PILOT CENTER

3.1 Vehicle Test Installation

For vehicle testing the turbocompound engine was installed in a Kenworth conventional W925 with a Fuller RTO-12513 transmission at the Cummins Pilot Center. The engine mounting position remained identical to that of the NTC-400 engine. Shown in Figure 9 is the right side or exhaust side of the turbocompound engine. It illustrates how the high speed gearbox is positioned between the engine block and frame rails. The turbocompound engine does add one inch to the overall length and in this installation, the driveshaft was shortened and fitted with an integral torque meter to provide on-highway power output measurements. Auxiliaries added to the engine from its test cell configuration include the cooling fan, air-conditioning unit, power steering pump, aftercooler water pump, air compressor, and an electric starter.

One unique feature of this installation included a two-circuit cooling system with separate heat exchanger, water pump, and thermostat for the aftercooler circuit. The purpose of the independent coolant flow paths was to provide reduced coolant temperatures in the aftercooler circuit to achieve lower intake manifold air charge temperatures. Reduced charge air temperatures are beneficial in the reduction of nitric oxide exhaust emissions and improve engine fuel consumption. The aftercooler core was a prototype four-pass cross flow design, which permitted high effectiveness to be achieved at reduced water flow rates. The low aftercooler water flow rates were desired to reduce the heat exchanger (radiator) size and fan horsepower requirements.

Following the installation and instrumentation of the engine, the tractor was chassis dynamometer tested for evaluation of engine and cooling system performance. The cooling system tests indicated it was necessary to add an auxiliary coolant tank for increased drawdown capacity and that additional venting of the top tank in the aftercooler circuit for better deaeration was required. No modifications were required to the engine and oil cooling circuit. The necessary changes were made and subsequent tests verified that all manufacturer specifications were reached or exceeded.

Engine performance tests were conducted with the driveline torque meter installed at the transmission output shaft. This was useful in checking the various parasitic losses of the

FIGURE 8. TURBOCOMPOUND 450 VS. BASELINE NTC-400 PERFORMANCE OPERATING SPEED AND LOAD RANGE

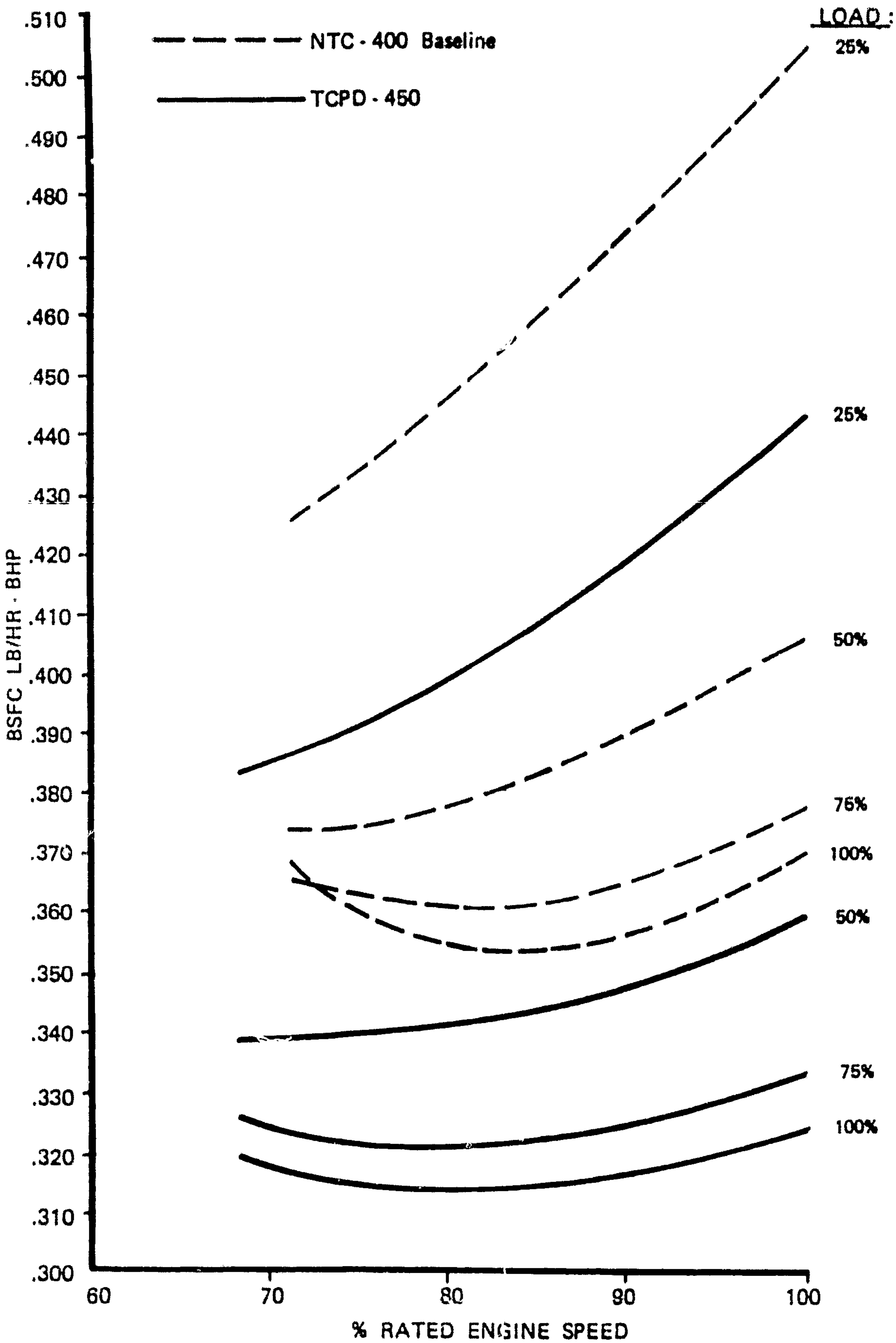
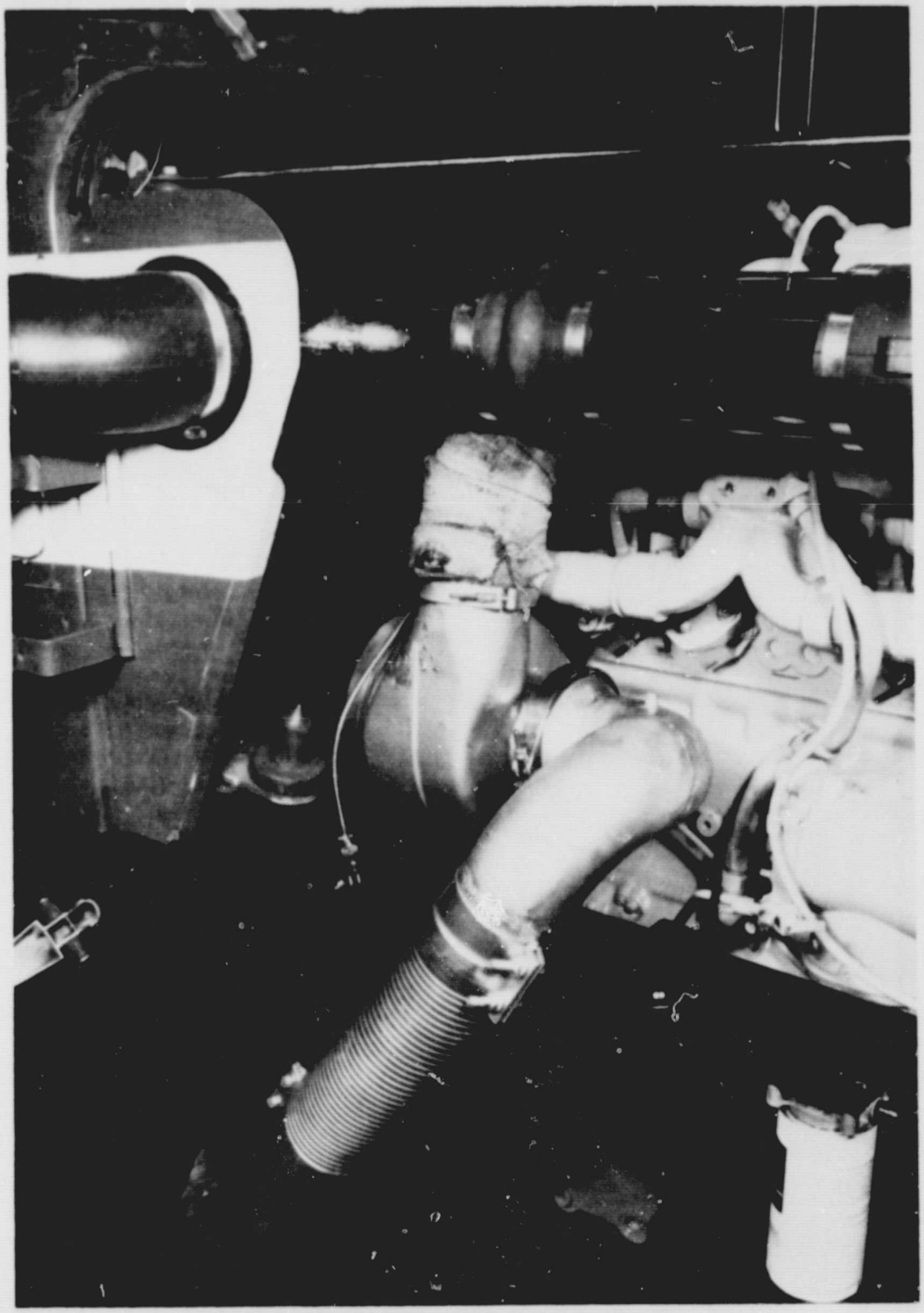


FIGURE 9. - INSTALLATION PHOTO OF PHASE III TURBOCOMPOUND ENGINE - EXHAUST OR RIGHT SIDE VIEW



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cooling fan, power steering pump, air compressor, and transmission. As shown in Table 3, torque measurements at the transmission output shaft were in agreement with calculated values within the accuracy of the instrumentation.

Having achieved confidence that steady-state vehicle performance of the turbocompound engine was predictable and in agreement with earlier laboratory dynamometer test results, the Pilot Center vehicle testing program was launched. This phase of testing was intended to compare the turbocompound engine against the vehicle test results previously completed with the baseline NTC-400 engine in the same test vehicle. The NTC-400 engine was selected as the baseline power plant as it most closely approached the output rating of the turbocompound engine within the current production NH family of engines. The NTC-400 engine was rated 400 brake horsepower at 2100 rpm and conformed to the federal emission standard of 10 grams combined $BSNO_X$ + BSHC. The turbocompound engine was developed from the NTC-400; however, it was rated 450 brake horsepower at 1900 rpm. The turbocompound engine complied with the 1980 California emission standard of 6 grams combined emissions. As previously mentioned, the turbocompound engine incorporated a number of design revisions intended to enhance its performance under turbocompounding conditions. These differences along with the different power and operating speed ratings often do not allow a direct comparison in vehicle test results. Care must, therefore, be exercised in data interpretation and comparison. These effects will be discussed as the results are presented.

3.2 Fuel Consumption

The fuel economy test route consists of public roads forming a loop which begins at the Cummins Technical Center (CTC) in Columbus, Indiana. From here, it goes south through Louisville, turns east to Cincinnati, and returns to Columbus. The route is divided into four legs and a profile description is shown in Table 4. The total mileage for the complete route is 260.17 miles. Landmarks are used to identify change points in the route terrain. The fuel economy testing requires that the test vehicle be accompanied by another base vehicle in order to adjust for the day-to-day changes which are observed in fuel consumption due to changes in ambient, road, and traffic conditions.

Vehicle test tank mileage results were based on the fuel readings taken at the CTC at the end of each test run. In addition, both vehicles were equipped with an on-board fuel consumption meter so that mileage results could be ascertained in various categories of the route description such as city, two-lane highway, urban expressway, interstate, etc.

TABLE III. - TURBOCOMPOUND CHASSIS DYNO TORQ'JE MEASUREMENTS

Engine Speed (RPM)	Calculated Engine BHP	Calculated Accessory Losses (HP)	Installed Engine Torque (Lb-Ft)	Calculated Transmissio Efficiency %	Gear Ratio	Calculated Transmission Torque Output (Lb-Ft)	Measured Transmission Torque Output (Lb · Ft)	% VMS Error	F ad Speed (MPH)	Chassis Dyno (HP)
1900	455	26.0	1186	99.05	1.00	1175	1155	1.7	54	374
1600	407	19.45	1272	99.15	1.00	1261	1260	.1	45	350
1300	344	12.0	1341	99.3	1.00	1332	1325	.5	37	302
1900	455	26.0	1186	97.05	1.35	1554	1564	- .6	40	383
1600	407	19.4	1272	97.15	1.35	1668	1696	-1.7	33	352
1300	344	12.0	1341	97.3	1.35	1761	1790	-1.6	26	301
1900	455	26.0	1186	97.05	1.81	2083	2075	.3	29	387
1600	407	19.4	1272	97.15	1.81	2237	2250	.6	24	353
1300	344	12.0	1341	97.3	1.81	2362	2380	.8	19	299

$$\text{VMS ERROR} = \frac{\text{VMS TORQUE} - \text{TORQUE METER TORQUE}}{\text{TORQUE METER TORQUE}}$$

TRUCK = UNIT 30
TRANSMISSION = RTO 12513
CHASSIS DYNO - 9 6-79

TABLE IV.- CUMMINS FUEL ECONOMY ROUTE DEFINITION

Route	Location	Mileage						Total
		City	Enter Exit Interstate	Two Lane	Urban Expressway	Level Rolling Interstate	Hilly Interstate	
1	CTC to Cementville, Ind.	4.53	1.97	--	---	58.05	--	64.55
2	Cementville, Ind. to Glencoe, Ky.	--	3.28	--	12.82	5.57	49.88	71.35
3	Glencoe, Ky. to Newpoint, Ind.	--	3.59	--	29.48	20.07	33.78	86.92
4	Newpoint, Ind. to CTC	8.01	--	29.34	---	--	--	37.35
		12.54	8.84	29.34	42.10	83.69	83.66	260.17

Based on the completion of four test runs, the average fuel consumption of the turbocompound engine was 5.346 miles-per-gallon of diesel fuel. This represented a .692 mile-per-gallon or 14.87% improvement over the NTC-400 engine which averaged 4.654. Complete test results are shown in Table 5. As expected, the turbocompound engine showed the largest improvement on the interstate highway segments of the course where vehicle speeds and corresponding engine load factors are highest. A summary of the VMS calculations shown in Table 6 shows a predicted fuel consumption of 5.40 miles-per-gallon for the turbocompound engine, while the NTC-400 prediction was 4.73. Thus, VMS predicted an improvement of 14.16% for the turbocompound engine over the NTC-400 in this installation and road course. If the predicted benefit is used in conjunction with the actual NTC-400 mileage results, the predicted fuel consumption for the turbocompound unit is 5.31 miles-per-gallon for an error of only .6% in comparison to actual results.

These fuel consumption results exceeded the expected benefit of turbocompounding alone. The incremental fuel consumption gain of turbocompounding a turbocharged and aftercooled NH engine (TCA-450) has been determined in previous company funded laboratory dynamometer testing. Here, back-to-back comparisons have been conducted based on equivalent power and operating speed ratings. The engine performance map comparison is shown in Figure 10. A maximum benefit of 6% was achieved along the engine's torque curve by means of turbocompounding alone. At reduced speeds and load, this benefit diminishes as the available exhaust gas energy is reduced. Fuel consumption advantages remain positive, however, above 50 psi brake mean effective pressure.

Using these laboratory test results, the incremental fuel consumption improvement strictly due to turbocompounding alone on a tank mileage basis was estimated. The route selected for analysis was the Pilot Center fuel economy route previously described. In this analysis, the turbocompound and turbocharged engines are identical in all respects (power, torque rise, operating speed range, etc.) with the exception of measured fuel consumption differences. The vehicle and drive train selected for analysis were also identical. The VMS calculations presented in Table 7 show a predicted fuel consumption of 5.16 miles-per-gallon for the turbocharged engine and 5.40 miles-per-gallon for the turbocompound engine. This represents an improvement of 4.6% with the turbocompound engine on this route which is 77% of the maximum benefit achieved along the engine's torque curve. The complete VMS route summaries for the TCPD-450, the baseline NTC-400, and the equivalent TCA-450 are shown in Appendix A.

3.3 Noise Testing

The drive-by noise testing was performed at the Cummins Walesboro noise test facility according to S.A.E. Standard J-366b. The test results are as follows:

TABLE V.- TURBOCOMPOUND FUEL ECONOMY TEST

TEST ENGINE: TCPD - 450 | BASELINE ENGINE: NTC - 400

Categories	11/16/79		11/19/79		11/26/79		11/27/79		Average	
	Test	Base	Test	Base	Test	Base	Test	Base	Test	Base
1. Total Fuel Used (Gal.)	48.62	53.93	46.45	54.70	50.15	58.60	49.45	56.40	48.67	55.91
2. Total Miles Per Gallon	5.351	4.824	5.601	4.756	5.188	4.440	5.261	4.613	5.346	4.654
3. Percent Advantage :										
A. City	10.78		9.25		16.44		13.43		12.73	
B. Enter/Exit Interstate	6.13		9.00		19.00		7.26		10.19	
C. Two Lane	6.19		13.07		15.65		12.61		11.79	
D. Urban Expressway	13.25		23.73		15.05		15.34		16.86	
E. Level/Rolling Interstate	11.57		18.53		18.72		13.17		15.60	
F. Hilly Interstate	11.40		18.54		15.75		15.18		15.24	
G. Overall	10.93		17.76		16.85		14.05		14.87	
4. Weather (Noon CTC)										
A. Temperature (Degrees F.)	44		56		47		55.3		50.5	
B. Wind Direction (Degrees)	283		205		208		180		219	
C. Wind Speed (MPH)	1		11		8		17		9.2	
D. Barometric Pressure (In. Hg)	29.588		29.397		29.008		29.207		29.300	

TABLE VI. - VMS PREDICTION FOR
CUMMINS FUEL ECONOMY ROUTE
TCPD - 450 VS. NTC-400

Engine Model	TCPD - 450	NTC - 400
Test Vehicle	Unit No. 30 Kenworth Conventional	Unit No. 32 Ford C.O. E.
Fuel Used (Gallons)	48.2	55.0
Fuel Mileage (MPG)	5.40	4.73
Average Speed (MPH)	43.3	42.8
Driving Time (Hrs.)	6.01	6.07
Idle Time (Min. - Sec.)	14-22	14 - 22
Time at Full Throttle (%)	16.0	26.2
Engine Load Factor	38.0	43.0
Gear Shifts	536	672

ASSUMPTIONS: GW (Lbs.) 73,000
CRUISE SPEED (MPH) 55
WIND SPEED (MPH) 9
WIND DIRECTION (DEG.) ... 219
TEMPERATURE (DEG. F.) .. 51

FIGURE 10. - PERCENT IMPROVEMENT IN FUEL CONSUMPTION
EQUIVALENT TCA-450
VS.
INTERIM TURBOCOMPOUND NH ENGINE
6 GRAM EMISSION LEVEL

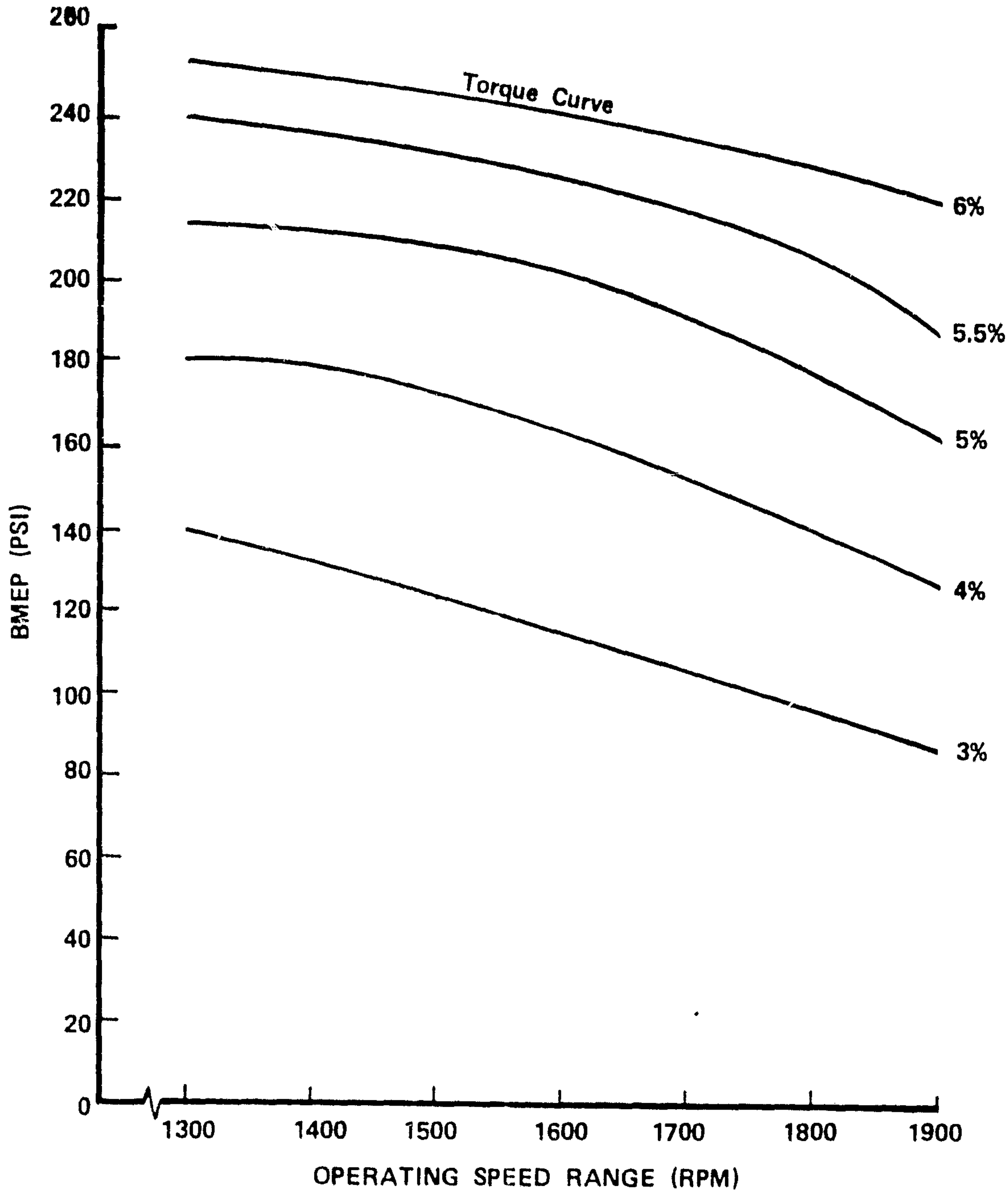

TABLE VII. VMS PREDICTION FOR CUMMINS FUEL ECONOMY ROUTE TCPD 450 VS. EQUIVALENT TCA 450

Engine Model	TCPD - 450	TCA - 450
Test Vehicle	Unit No. 30 Kenworth Conventional	Unit No. 30 Kenworth Conventional
Fuel Used (Gallons)	48.2	50.4
Fuel Mileage (MPG)	5.40	5.16
Average Speed (MPH)	43.3	43.3
Driving Time (Hrs.)	6.01	6.01
Idle Time (Min. - Sec.)	14 - 22	14 - 22
Time at Full Throttle (%)	16.0	16.2
Engine Load Factor	38.0	38.0
Gear Shifts	536	537

ASSUMPTIONS:

GW (Lbs.) 73,000
CRUISE SPEED (MPH)........... 55
WIND SPEED (MPH)............ 9
WIND DIRECTION (DEG.) 219
TEMPERATURE (DEG. F.)........ 51

Drive-By Noise Test (J-366b)

Engine	Left Side (dBA)	Right Side (dBA)
NTC-400 (Baseline)	83.5	83.6
TCPD-450 (Turbocompound)	82.5	81.6

The noise tests were performed with the vehicle in the same configuration. The measurements with the NTC-400 were obtained prior to the installation of the turbocompound engine. In both tests the engines were not equipped with sound attenuant devices. The current legislative requirement effective since January 1, 1978, is 83 dBA.

The turbocompound engine was one to two decibels lower than the NTC-400. Although further interpretation of these results is subjective without additional measurements, it is believed that the lower sound intensity of the turbocompound engine was due to three reasons: First, the turbocompound engine injection timing was retarded due to the higher specific output and to achieve lower nitric oxide exhaust emissions. Retarded injection timing reduced the ignition delay period which resulted in a lower rate of combustion pressure rise in the cylinder. This resulted in a corresponding reduction in combustion related noise. Second, a reduction in the exhaust gas contributed noise was likely in that the fluid is expanded in two stages with the turbocompound engine. Since the same muffler was used in both tests, a reduction in exhaust noise would be expected. Third, the turbocompound operating speed range was lower than that of the NTC-400 engine. As the noise test procedure consists of a vehicle accelerating along the test pad, the lower engine speed rating was beneficial in reducing the noise emission. The noise tests did confirm that the expected additional mechanical noise of the turbocompound gear train was of limited importance and not great enough to offset the favorable characteristics of the engine just described.

3.4 Engine Retarding Capability

The engine retarding test is designed to determine the engine braking effect on negative grades at closed throttle. This is an important performance test for heavy-duty vehicles due to the high inertia of the 73,000 to 80,000 lb gross weight. The test is conducted on hilly terrain on I-74 west of Cincinnati. The test procedure calls for the vehicle to approach the test section at 55 mph. When the first test marker is reached, the throttle is closed. When the vehicle speed drops to 40 mph, the throttle is advanced to full throttle until vehicle speed again reaches 55 mph. This procedure is repeated until the test is completed 3.68 miles later. Test results are shown in Table 8.

TABLE VIII. - ENGINE RETARDATION TEST

	First Mile		Second Mile		Third Mile		Fourth Mile	
	Base	TCPD	Base	TCPD	Base	TCPD	Base	TCPD
MPH @ Start	56	57	58	56	46	53	54	54
Maximum MPH Attained	60	58	58	56	54	54	60	59
Minimum MPH Attained	56	56	45	40	40	39	54	54
MPH @ Finish	58	56	46	53	54	54	56	55
Time @ WOT (Sec.)	0	0	0	18	32	27.4	2.6	2.1
Time (Sec.)	60.5	63	74.4	72.8	80	77.8	42.4	43.2
Distance (Miles)	1	1	1	1	1	1	.68	.68

Test Vehicle : Cummins Unit 30
Gear : Direct (12th)

To remove the effect of different engine acceleration rates, the best comparison was made during the first mile and the final .68 mile segment of the course. During the first mile in both tests, the vehicle was operative only at closed throttle. The road terrain in this first mile was not a constant grade which explains the variation in vehicle speed during this segment. The time required to travel this mile section was 63.0 seconds for the turbocompound engine and 60.5 seconds for the NTC-400, or an improvement of 4%. In the final .68 mile segment of the course, both engines again entered the test section at equivalent vehicle speeds. Again, the time interval required to traverse the test section was favorably longer for the turbocompound engine. This indicated that the retarding capability of the turbocompound engine was marginally superior to that of the NTC-400.

This difference in retarding capability can be explained by the higher exhaust gas pressure imposed on the engine under turbocompound conditions due to the smaller volute area or area-radius ratio of the turbocharger turbine housing. This was offset by the higher inertia of the turbocompound engine due to the power turbine and recovery gear train. This factor would tend to diminish engine retarding capability.

3.5 Engine Driveability

During this investigation, five independent tests were performed to assess the throttle response characteristics of the power plant. These tests included throttle delay, passing acceleration, throttle interrupt, upgrade power recovery, and low -to-high idle. These tests are structured to duplicate five different, but very typical acceleration modes.

In the throttle delay test, the vehicle decelerates with the transmission in one of the lower gears until the engine low idle speed or approximately 600 rpm is reached. At this point, full throttle is applied and the time recorded until the engine reaches rated speed. This test provides a measure of the low speed throttle response characteristics of the engine. The test results are shown in Table 9. The shorter the time interval, the better the throttle response is of the engine. The NTC-400 averages approximately 33% longer time duration to achieve rated speed.

To test passing acceleration capability, the transmission is placed in twelfth or direct gear. The vehicle is then allowed to coast down to a speed of 40 mph. At this point, full throttle is applied and the time required to reach 55 mph vehicle speed is recorded. The test results are shown in Table 10. Passing acceleration of the turbocompound engine was superior to that of the NTC-400 engine which required 15% more time to attain 55 mph.

TABLE IX. - THROTTLE DELAY TEST

Engine Model	2nd Gear (6.12:1)		3rd Gear (4.56:1)		4th Gear (3.38:1)	
	Idle Speed (RPM)	Time to Rated RPM (Sec.)	Idle Speed (RPM)	Time to Rated RPM (Sec.)	Idle Speed (RPM)	Time to Rated RPM (Sec.)
Test Engine TCPD - 450	560	3.86	560	5.67	560	7.97
Baseline NTC - 400	600	4.9	575	7.5	575	11.0

TABLE X. - PASSING ACCELERATION TEST

Engine Model	Engine RPM At Start Of Test	Time to Achieve 55 MPH (Sec.)	Ambient Temp. (^oF)	Wind Speed (MPH)	Wind Direction
Test Engine TCPD - 450	1347	28.8	53^o	2	Left - Front
Baseline NTC - 400	1388	33.0	54^o	8	Right - Rear

3!

The throttle interrupt test is structured to be representative of a vehicle grade performance in congested traffic. In the test the vehicle climbs a 3% grade at wide-open throttle with the transmission in direct gear. The throttle is closed for three seconds and then reapplied. The time interval to reach the torque curve rail pressure is then recorded. Results are shown in Table 11; and as can be seen, the throttle response was 38% faster for the turbocompound engine.

The fourth test in this series is the upgrade power recovery test. Here, the vehicle is allowed to coast down a one-mile hill with closed throttle in direct gear. At the bottom of the hill, the throttle is snapped to the full throttle position and the vehicle climbs a one-mile long, two-percent grade. The results of the upgrade power recovery test are shown in Table 12.

The low-to-high idle test was used to determine the time it takes for the engine to accelerate from low idle to high idle and decelerate from high idle to low idle with the transmission in neutral. With the engine operating at normal temperatures and at low idle, the throttle is snapped fully open and held until high idle speed is reached; then the throttle is fully released. The transmission is in neutral with the clutch engaged. This procedure is repeated several times and results averaged. The results are shown below:

Engine	Low Idle (RPM)	High Idle (RPM)	Time (Sec.)	
			Low to High	High to Low
TCPD-450	550	2160	1.6	6.8
NTC-350	600	2060	1.0	3.9

As data was not available for the NTC-400, comparison was made to the NTC-350 engine. The turbocompound engine rate of deceleration was slower than the NTC-350. This will increase the time required to shift gears; however, operators of the engine were unaware of any differences in transmission shift durations. Therefore, this increase in shift time did not appear to be objectionable.

In summary of the tests results examined, the driveability of the turbocompound engine was equal to, if not better, than the baseline engine. In general, as the specific output of an engine is increased, the driveability characteristics suffer. This is due to the fact that turbocharger response is the key to providing rapid throttle response. There are many factors which contribute to the turbocharger acceleration rate; but from engine idle conditions, the turbine area schedule is dominant. As mentioned previously, the favorable turbocharger match available with the turbocompound engine accentuates the response and, hence, the driveability of the vehicle.

TABLE XI. - THROTTLE INTERRUPT TEST

Engine Model	Engine RPM - Start	Time To Torque Curve Rail Pressure (Sec.)	Maximum Rail Pressure (PSI)	Ambient Temp. (°F)	Wind Speed (MPH)	Wind Direction
Test Engine TCPD - 450	1680	2.6	118.0	42	2	Left Rear
Baseline NTC - 400	1690	3.9	130.0	62	6	Left Rear

TABLE XII. - UPGRADE POWER RECOVERY

Engine Model	Engine RPM At Start of Full Throttle Upgrade	Time to Run Course (Sec.)	Speed (MPH)	
			Start	Finish
TCPD - 450	1800	48.55	52.1	53.1
NTC - 400	1800	55.8	53	44
TCPD - 450	1700	49.48	50.6	52.1
NTC - 400	1700	58.00	50.0	44
TCPD - 450	1600	52.61	48.2	50.1
NTC - 400	1600	60.4	48	43
TCPD - 450	1500	53.98	44.7	48.9
NTC - 400	1500	64.8	44	42

3.6 Engine Gradeability

Two tests were conducted to quantify the vehicle grade performance. The first test determines how the vehicle performs on an extended grade under typical driving conditions, while the second test determines the startability of the vehicle with a 72,000 G.W. on an 8% grade.

For the first test, the course is located just east of Bloomington, Indiana, on a section of Indiana 46. It is an 8% grade and .49 miles in length. The test vehicle enters the test section at approximately 50 mph in direct gear (1:1 gear ratio). The operator is instructed to drive as he normally would up-shifting and/or downshifting at his own discretion. The time to complete the course, the number of shifts required, and the ease of shifting are monitored to evaluate the engine performance. The results of this test are shown in Table 13. The turbocompound engine was able to achieve the same gradeability as the baseline engine with the transmission in one higher gear ratio and at a terminal vehicle speed 3 mph faster. Since the transmissions and rear axle ratios were identical, the basis for these results was the fact that the turbocompound engine had more power available due to the higher rating.

For the startability test, the turbocompound test tractor coupled to the performance load trailer is parked on a 100 yard long 8% grade at the loading dock area of the Cummins' Walesboro Component Plant. With the engine idling and at operating temperature, the trailer brakes are released, the clutch engaged, and the vehicle proceeds up the grade, upshifting when required. Grade starts were attempted in 1L (8.35:1), 2L (6.12:1), and 3L (4.56:1).

The results of this test are shown in Table 14. It should again be noted in this comparison that the NTC-400 was rated at 2100 rpm while the turbocompound engine was rated at 1900 rpm. For this reason, an additional column was added which established the time to reach 1900 rpm for the baseline engine. The turbocompound engine had significantly reduced clutch slippage durations and improved acceleration rates in reaching rated speed compared to the NTC-400. It should also be noted that the turbocompound engine was able to start in third gear on this grade while the NTC-400 was not. This had also been previously predicted through use of VMS.

Grade startability is a function of three variables; namely, clutch engagement torque, transient response of the engine, and available horsepower. The clutch engagement torque of the turbocompound engine was approximately 20% higher than that of the NTC-400. The turbocompound engine also had faster throttle response as evidenced in tests previously discussed. As boost pressures are generated faster during acceleration modes, the

TABLE XIII. - TURBOCOMPOUND GRADE PERFORMANCE

Engine Model	Course Start		Course Finish		Number Of Shifts	Time (Secs.)
	Speed (MPH)	Gear Ratio	Speed (MPH)	Gear Ratio		
Test Engine TCPD - 450	54	1.1 (4th Direct)	28	1.81:1 (2nd Direct)	2	48.8
Baseline NTC - 400	53	1:1 (4th Direct)	25	2.47:1 (1st Direct)	3	51.8

TABLE XIV. - GRADE STARTABILITY TEST

TCPD - 450

Engine Model	Starting Gear Ratio	Clutch Slippage (Sec.)	Max. Rail in Starting Gear (PSI)	Max. Eng. Torque in Starting Gear (Lb-Ft)	Time to Rated RPM in Starting Gear (Sec.)*	Time to 1900 RPM in Starting Gear (Sec.)*
Test Engine TCPD - 450	8.35:1 (1L)	2.6	75	609	5.2	5.2
Baseline NTC - 400	8.35:1 (1L)	4.2	96	N.A.	10.0	9.6
Test Engine TCPD - 450	6.12:1 (2L)	3.0	112	855	9.3	9.3
Baseline NTC - 400	6.12:1 (2L)	5.5	152	N.A.	16.0	15.4
Test Engine TCPD - 450	4.56:1 (3L)	6.6	126	1078	22.2	22.2
Baseline NTC - 400	4.56:1 (3L)	No Start	—	—	—	—

* Note: TCPD - 450 is a 1900 RPM rating and the NTC - 400 is a 2100 RPM rating

engine fueling can also be increased. Therefore, the turbocompound engine also had more instantaneous horsepower than was available with the NTC-400. Finally, the turbocompound engine was rated at higher power with more torque availability at lower engine speeds. The turbocompound had a peak torque rating of 1440 lbs-ft at 1300 rpm, while the NTC-400 value was 1150 lbs-ft at 1500 rpm. Thus, not only did the turbocompound engine have more torque to start the vehicle moving and faster throttle response, but also more torque was available throughout the operating speed range of the engine.

3.7 Engine Torsional Vibration

The purpose of the torsional testing is to determine if there are any excessive drive train torsional vibrations present within the operating speed range of the turbocompound engine. Torsional vibrations are measured at the vibration damper, the flywheel, and at the transmission output shaft via a torsiograph pick-up. A real time analyzer is used to reduce the data recorded on a FM tape recorder. Shown in Table 15 are the maximum amplitudes of vibration at each of the three measurement locations for both engines. At the damper and flywheel location, the maximum amplitudes occurred at the same rotational speed. At the transmission output shaft, the maximum amplitude for the NTC-400 occurred at a different speed.

Torsional vibrations of less than 1.0 degrees peak-to-peak are not considered excessive. The turbocompound engine did not exceed this level. Overall, however, the turbocompound engine did have slightly higher vibration amplitudes than the baseline engine. One would expect third order torsional vibrations under loaded conditions to be slightly higher for the turbocompound engine since amplitudes are closely related to the specific output or mean effective pressure rating of the engine. In conclusion, the turbocompound engine had higher torsional vibrations, but they were within acceptable vibration limits.

4.0 50,000 MILE FIELD TEST

A 50,000 mile field test of the turbocompound engine was conducted with Florida Refrigerated Services located in Dade City, Florida. The engine was placed in the Kenworth conventional truck shown in Figure 11. This truck was equipped with a Fuller RTO-12513 transmission and 3.70 drive axle ratio which was the optimum drive train match for the turbocompound engine. The company was also testing a Cummins NTCC-400 engine which met the 1980 California emission requirement. This engine had accumulated over 120,000 miles of operation and provided a yardstick for comparison purposes.

Florida Refrigerated Services transports citrus fruit from Florida to California and returns with fruit or vegetable produce. This route enabled the turbocompound engine to accumulate 6000 miles per round trip and complete the 50,000 miles of testing

TABLE XV. - TORSIONAL VIBRATION TEST
TCPD - 450 VS. BASELINE NTC - 400

Location	Engine	Order	Maximum Amplitude (Deg. Peak to Peak)	Gear Ratio	Engine RPM
Damper	Test Engine TCPD - 450	3	.660	1.57:1	2500
	Baseline NTC - 400	3	.430	1.57:1	2500
Flywheel	Test Engine TCPD - 450	3	.425	1:1	1400
	Baseline NTC - 400	3	.280	1:1	1400
Transmission Output	Test Engine TCPD - 450	1.5	.470	1.57:1	2500
	Baseline NTC - 400	1.5	.150	1.57:1	2500
	Baseline NTC - 400	1.5	.410	1:1	2100

FIGURE 11. KENWORTH CONVENTIONAL FLORIDA REFRIGERATED SERVICES
50,000 MILE FIELD TEST VEHICLE

C-80-2165

in 17 weeks. The southern route across the United States includes I-75, I-10, I-20, and I-8. This is shown in Figure 12. The route provides a variety of terrains including plains, rolling hills, and mountainous grades. Over 90% of this route is in the VMS data file which allowed operational results to be compared to the program predictions.

The turbocompound engine began commercial service on October 24, 1979. Operational data recorded throughout the field test included fuel consumption, mileage, oil consumption, gross weight, and general comments on the performance of the engine. The test was completed on February 21, 1980, after completing 51,539 miles. The entire test was completed without any unscheduled downtime. Tank mileage throughout the test averaged 5.25 mpg which represented a 15.9% improvement over the NTCC-400 engine operating at this location. The fuel economy results are summarized in Table 16. A summary of the VMS calculations shown in Table 17 show a turbocompound engine predicted benefit of 15.1% over the NTCC-400 and 3.8% improvement over a comparable engine but without the turbocompounding system. This benefit would increase to 16.6% and 4.2%, respectively, with a five mph increase in operating speed. If the predicted benefit of 15.1% is used in conjunction with the actual NTCC-400 mileage results, the predicted fuel consumption for the turbocompound vehicle is 5.21 mpg for an error of only .7% in comparison to the actual results.

The field test driver's comments of the turbocompound engine were very positive and encouraging. Specificially mentioned was the smooth engine operation between 1600 and 1800 rpm. Good throttle response was noted and performance on grades was sensed to be equivalent to a 525 horsepower engine. The higher power rating in comparison to the NTC-400 power plant was instrumental in reducing driver fatigue as less gear shifts were required. As each pair of drivers in this operation typically makes 42 trips to California per year, this characteristic is of high value to both the driver and owner of the vehicle.

Following completion of the field test, the engine was removed and returned to the Cummins Technical Center for teardown and inspection. Inspection of the turbocompound system revealed all gears, bearings, shafts, and the fluid coupling to be in good condition exhibiting normal and expected wear patterns. It is recognized that comprehensive reliability and durability data cannot be ascertained from a single 50,000 mile field test. However, the condition of the free power turbine and gear train components did suggest that more extensive testing with the current design could easily be accomplished.

A high degree of confidence in the predictive accuracy of the VMS model was achieved by comparing the vehicle test results with the calculated results of VMS. Therefore, accuracy of

FIGURE 12.- TURBOCOMPOUND FIELD TEST ROUTE

Test Route

OPERATOR - Florida Refrigerated Services
GVW- 72,000 Lbs.
FREIGHT - Fruit & Produce

TABLE XVI. - TURBOCOMPOUND FIELD TEST DATA

Trip	Return Date	Miles	Average Trip GW	Fuel Consumed	Average Trip MPG
1	10 - 29	5444	73,500	996	5.47
2	11 - 10	6155	70,000	1124	5.48
3	11 - 22	5858	72,500	1131	5.18
4	12 - 03	5112	71,500	1011	5.06
5	12 - 19	6439	71,875	1173	5.49
6	1 - 07	4934	70,000	951	5.19
7	1 - 26	6410	74,250	1302	4.92
8	2 - 12	5988	73,000	1162	5.15
9	2 - 21	5199	72,250	967	5.38

Engine Model	Operational Results		VMS Prediction	
	Average Trip Fuel Consumption	TCPD-450 Benefit (%)	Average Trip Fuel Consumption	TCPD-450 Benefit (%)
Test Engine TCPD - 450	5.251	15.93	5.79	15.11
Baseline NTC - 400	4.529		5.03	

TABLE XVII. - SUMMARY OF VMS PREDICTED FIELD TEST DATA

Engine	Maximum Cruise Speed	Fuel Used (Gal.)	Fuel Mileage (MPG)	% Improvement TCPD - 450	Average Engine Speed (RPM)	Average Fuel Rate Lb/Hr.	Average Vehicle Speed (MPH)
TCPD - 450	60	470	5.79		1490	69.9	57.0
*TCA - 450	60	487	5.58	3.76	1490	72.5	57.0
NTCC - 400	60	541	5.03	15.11	1741	80.3	56.9
TCPD - 450	65	503	5.41		1582	79.5	60.6
*TCA - 450	65	524	5.19	4.24	1582	82.8	60.6
NTCC - 400	65	586	4.64	16.59	1848	92.4	60.3

Truck Specifications:

TCPD-450 Geared Speed = 74.4 @ 1900 RPM - 19.0 HP Fan

*TCA - 450 Geared Speed = 74.4 @ 1900 RPM - 19.0 HP Fan

NTCC-400 Geared Speed = 70.3 @ 2100 RPM - 20.0 HP Fan

* Comparable turbocharged - aftercooled engine
(improvement represents turbocompound only difference)

Input Conditions:

GW = 73,000 Lb.
Radial Ply Tires
Still Air
Ambient Temperature = 85°F
Kenworth Conventional Truck
Accessories: Air Conditioning and Locked Fan
Routes Simulated from Tampa, Florida to Los Angeles, California

this program can be assured in predicting performance gains of the turbocompound engine over other route profiles. A VMS data summary for five route profiles is presented in Table 18 for the turbocompound engine, the comparable and equivalent turbocharged engine, and the baseline NTC-400 engine. In this simulation, all vehicles are geared to achieve the same maximum vehicle speed. Here, it can be seen the turbocompound benefit over the comparable engine without turbocompounding is proportional to the load factor or time speed at full throttle increasing from 4.2% on a level interstate to 5.3% on a mountainous route. This, of course, is due to the fact that turbocompound engine fuel consumption advantages improve as engine load factors increase.

5.0 DISCUSSION OF RESULTS

A series of tests have been performed to better understand the viability and performance characteristics of a turbocompound diesel engine in an automotive heavy-duty vehicle. This is the first known application of a turbocompound engine in this type of vehicle. Earlier applications of the turbocompound engine have been made in the military and aviation fields. Primarily, the thrust of these earlier endeavors was to achieve higher specific outputs from a given displacement engine. The primary objective in the engine design described in this study was to achieve improved fuel consumption, although the power rating of the base engine was also increased 12.5% from 400 to 450 brake horsepower.

The turbocompound engine offers improvement in specific fuel consumption. There is a progressive improvement in fuel consumption as a function of engine load with the maximum benefit occurring along the engine's torque curve. As the automotive heavy-duty vehicles typically operate at high load factors, they are particularly suited to the performance gains available by means of turbocompounding.

On the subject of fuel consumption, the objective of this vehicle test study was to validate the fuel consumption gains which were achieved earlier in the laboratory during the development of this engine. The validation procedure consisted of entering the fuel map of the engine into a program which simulates the operating conditions of the engine in a vehicle over a road course. If agreement can be achieved with actual vehicle test results, then vehicle fuel consumption predictions on a mile-per-gallon basis can be made for various road terrains with a high degree of confidence knowing the fuel consumption map of the engine. In the course of this study, a strong correlation between predicted and actual results was obtained. This is particularly true when the relative or incremental improvement in turbocompounding is highlighted. Therefore, it was with some degree of confidence that other road terrains and engine types could be analyzed to assess performance.

TABLE XVIII. VMS DATA SUMMARY FOR VARIOUS TERRAINS

ROUTE	ENGINE	% TIME @ FULL THROTTLE	GEAR SHIFTS	AVERAGE SPEED	TANK MILEAGE	% TCPD FUEL CONSUMPTION BENEFIT
LEVEL INTERSTATE	TCPD-450	4.2	16	53.4	6.17	
	*TCA-450	4.3	18	53.5	5.92	4.22
	NTC-400	8.8	24	53.3	5.50	12.18
ROLLING PLAINS	TCPD-450	5.1	16	53.7	6.20	
	*TCA-450	5.1	16	53.7	5.95	4.20
	NTC-400	8.8	24	53.3	5.50	12.32
.2 PERCENT UP INTERSTATE	TCPD-450	5.7	19	53.4	5.66	
	*TCA-450	5.8	18	53.4	5.43	4.24
	NTC-400	13.3	28	53.2	5.04	12.30
HILLY INTERSTATE	TCPD-450	26.3	29	53.5	5.99	
	*TCA-450	26.5	27	53.5	5.71	4.30
	NTC-400	32.6	56	52.4	5.28	13.45
MOUNTAIN PASS	TCPD-450	37.3	64	49.3	5.20	
	*TCA-450	37.3	66	49.3	4.94	5.26
	NTC-400	45.2	82	47.7	4.58	13.54

* COMPARABLE TURBOCHARGED-AFTERCOOLED ENGINE (BENEFIT REPRESENTS TURBOCOMPOUND ONLY DIFFERENCE.

ASSUMPTIONS: 18 HP ACCESSORIES, GEARED SPEED = 67 MPH, RADIAL TIRES, 73,000 LB GW, 85°F

In the course of this study, the fuel consumption of the turbocompound engine was compared to that of a NTC-400 engine. The NTC-400 was selected for comparison purposes since its power rating of 400 brake horsepower is highest in the NH series of engines which have been released and certified for production. The turbocompound engine was derived from this engine. As discussed in the text of this report, there are improvements made to the turbocompound engine which were intended to improve the engine's performance under turbocompound conditions but are beyond the scope of the addition of a power turbine and speed reduction gear train. These design changes cloud the fuel consumption findings unless the effects of these modifications can be sorted out from the comparison. This exercise was, in fact, performed in a separate company funded laboratory test.

In comparison to the NTC-400 engine, the turbocompound derivative achieved a fuel consumption improvement of 14.9%. But in the stricter sense, the benefit decreases to 4.6% which represents the improvement due to turbocompounding alone. The comparison unfortunately is not this simple. Also associated with turbocompounding are reductions in the thermal and mechanical loading of the reciprocator. In addition, the system allows a much more favorable turbocharger match to the engine which offers an additional degree of freedom in the engine speed range and torque rise rating. The combination of these effects may be traded off to further improve the fuel consumption of the engine by the selection of lower operating speeds with higher mean effective pressure ratings. These pursuits cannot be fully achieved when the engine is only turbocharged. It is for these reasons that the turbocompound engine speed range was reduced 200 rpm in comparison to the NTC-400 even though the output of the engine was increased 50 horsepower.

The noise testing results were encouraging but not of great significance. Fortunately, it was determined that the incremental additional noise of the power turbine and gear train was masked by the additional damping of exhaust noise due to the power turbine and the lower speed range of the engine. The results do indicate that little development effort needs to be expended in reducing the gear train noise and other sources from the engine remain to be of far greater importance. It should be noted that all noise reduction techniques, either now available or currently in development, will not inhibit the performance of the turbocompound engine.

The driveability of the turbocompound engine was considered to be very good. Again, these favorable characteristics in terms of clutch engagement torque, throttle response, and low speed torque are not directly attributable to the turbo-compounding but are due to the additional design latitude the turbocompounding of an engine allows. This is primarily achieved with the turbocharger match which enables the selection of a geometrically smaller turbine housing. Whereas this match would result in overboosting a turbocharged engine or the requirement for a wastegate device, under turbocompounding the expansion ratio across the power turbine at high speed and load conditions negates this requirement. The result is a more rapid turbocharger response which allows for increased fueling during acceleration modes of the engine and provides for excess air at low engine speeds. This enables higher torque rise or wider operating speed ranges. The additional inertia of the power turbine and gear train reflected to the engine's crankshaft results in longer time durations to accelerate or decelerate the engine under closed throttle conditions such as when changing transmission gears. This factor did not result in any complaints from the vehicle operators who apparently did not detect the difference.

Due to the higher power rating of the turbocompound engine and the quicker turbocharger response, the gradeability of the power plant exceeded that of the NTC-400. This factor coupled with a wider operating speed range could allow the selection of a lower number of transmission gears, although a 13-speed gearbox was used in this program. The transmission and final axle ratio selected for these tests was routine for high horsepower automotive diesel engines. The components specified were matched for the engine to operate at relatively low speeds with the transmission in overdrive at highway speeds. Ideally, had lower axle ratios been available, it would be beneficial to match the transmission to the engine in direct gear at highway speeds. In direct gear the transmission efficiency is 99%; whereas, in overdrive due to the additional gear meshes the efficiency is only 97%.

The 50,000 mile field test program was completed without experiencing any equipment malfunction or unscheduled downtime. Chassis dynamometer tests were conducted at the beginning, at mid-point, and at completion of the field test. No significant change in the engine's performance was detected. Fuel consumption results again agreed very well with the analytical predictions. In this case, the turbocompound engine was compared to the NTCC-400 which is certified for California in 1980. The operator's commentary with respect to the engine's performance was very favorable with particular mention of the driveability, gradeability, and smooth engine operation.

6.0 CONCLUSION

Two turbocompound diesel engines were assembled and dynamometer tested. Both engines met the 1980 California 6 gram emission limit on BSNOx+HC and achieved a minimum BSFC of .313 lb/bhp-hr and a BSFC at rated conditions of .323 lb/bhp-hr. These engines were then installed in Class VIII heavy-duty vehicles to determine the fuel consumption potential and performance characteristics. The first engine was evaluated at the Cummins Pilot Center facility where tests were performed in the following areas: fuel consumption, cooling system, noise, retarding capability, driveability, gradeability, torsional vibrations, and other general performance characteristics. The second engine was placed in revenue service hauling produce cross country for a planned 50,000 mile test.

As the power turbine and gear train of the turbocompound engine are fully integrated into the base turbocharged and aftercooled engine, installational modifications required are minimal. This suggests the possibility of retrofitting the existing fleet of engines with the turbocompound components without great difficulty. In this manner, more universal application of the technology could be achieved.

In comparison to the NTC-400 engine which was selected for baseline performance, the turbocompound engine achieved a fuel consumption reduction of 14.87 percent. Based upon earlier fuel consumption testing results performed in the laboratory, the predicted benefit was 14.16 percent. Thus, confirmation of both the dynamometer test results and the computer model simulation of the test route was achieved with the actual vehicle tests.

A great part of this benefit over the baseline engine is due to other improvements incorporated in the turbocompound engine. Some of these product improvements have universal applications, others are made possible because the engine is turbocompounded. For example, the turbocompound engine operating speed range was reduced 200 rpm in comparison to the baseline engine which improves the engine's efficiency due to a reduction in friction and parasitic losses. Whereas this particular technique is finding its way into many of the recent heavy-duty diesel product offerings, it is more difficult to achieve at the higher power levels primarily due to turbocharger compressor limitations. When an engine is operating in a turbocompounded configuration, the compressor speed, flow range, and pressure ratio requirements are reduced in comparison to the turbocharged counterpart, particularly during high altitude operation of the engine. In addition, the torque rise characteristics of the engine are more favorable when the power plant is turbocompounded. These characteristics enabled the selection of lower operating engine speeds and the resultant fuel consumption advantages which would not have been feasible with the turbocharged engine at this power rating. In fact, had the operating speed range of the turbocompound engine been the same as the baseline engine, the fuel consumption benefits due to turbocompounding alone would have been slightly greater, even though the overall benefit would be slightly diminished due to the frictional and parasitic losses.

Other improvements incorporated in the turbocompound engines which were tested in this program are presently in the final engineering development phase prior to production release. These engine system and component improvements will be integrated into future engine models. The exact fuel consumption benefit which can be attributed solely to the turbocompounding device added to the engine has been determined in the laboratory development of the system. In comparison to a turbocharged and aftercooled diesel engine at the same power rating and exhaust emission level, the turbocompounding feature provides a 6 percent fuel consumption advantage along the maximum torque curve of the engine. This benefit diminishes as engine load is reduced but remains positive to nearly engine idle operation. The advantage in actual vehicle service depends upon the degree of loading. For example, for level grade interstate operation the tank mileage improvement calculated is 4.2 percent increasing to 5.3 percent in mountainous terrain.

As fuel costs continue to rise in the future in real dollars, the cost effectiveness of the turbocompound device will improve. Currently, heavy-duty trucks operating on the long haul routes typically accumulate 100,000 miles or more annually and consume 20,000 gallons of diesel fuel. In these applications a 5 percent reduction in fuel consumption represents 1000 gallons of diesel fuel saved per vehicle annually which at current bulk rate prices is approximately equivalent to a $1000 annual savings in fuel expense.

In addition to substantial dollar savings for the truck owner, the benefit of turbocompounding represents a substantial savings in petroleum products for the nation. Most of the freight transported by vehicle in the U.S. is carried aboard Class VII and Class VIII diesel powered trucks (gross vehicle weight of 26,000 lbs and greater). In 1977 there were 1,418,000 trucks in use in the United States in this weight classification. Seventeen percent of these vehicles were engaged in long haul trucking operations defined as greater than 200 miles per day. With the average truck consuming 20,000 gallons of diesel fuel annually, the long haul trucking industry uses 4.82 billion gallons of diesel fuel per year. Turbocompounding each engine in this large fleet of vehicles would result in a savings of 241.1 million gallons of diesel fuel which is equivalent to 5.74 million barrels of crude oil. In July of 1980, the cost of imported crude oil was approximately $28 per barrel. The total savings is, therefore, equivalent to a reduction in the country's import requirement by 161 million dollars.

It should also be noted that while the turbocompound engine was demonstrating reduced fuel consumption, it was conforming to more stringent environmental emission standards established by the State of California in 1980. The technique commonly employed to achieve lower NO_X emissions is to retard the combustion process. This results in a degradation of the engine's thermal efficiency and increases the energy content of the exhaust gases. The turbocompounding system is better able to utilize this otherwise wasted thermal energy and thus maintains a high thermal efficiency.

In addition to improved fuel economy and reduced emissions, the turbocompound engine demonstrated excellent driveability characteristics and was well accepted by the vehicle operators. Typically, as the output of the engine is increased, the turbocharger match is compromised and driveability suffers. However, with the turbocompound engine not only is the output increased, but the response is also improved.

The turbocompound gear train tested showed excellent durability potential by completing both a 1000 hour endurance test and the 50,000 mile field test without any major malfunction.

In summation, the turbocompound engine provides an opportunity for the future by offering increased thermal efficiency, reduced exhaust emissions, and improved driveability while maintaining present standards of durability. Cummins and DOE are continuing to pursue the turbocompound development with the objective of further improvements in fuel economy. Present planning indicates that an advanced turbocompound engine will be ready for vehicle testing in 1982. The performance target for the advanced turbocompound is a 5 percent improvement in vehicle tank mileage over the 5.35 mpg demonstrated during 1979 in the fuel economy testing of the interim turbocompound engine.

7.0 APPENDIXES

A. VMS ROUTE SUMMARIES

TURBOCOMPOUND 450

VEHICLE MISSION SIMULATION

VMS USER - J. L. HUEHNE SIMULATION NO - 003 DATE - JAN 16,'80 SERIAL NO --17910

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SIMULATION SUMMARY

ROUTE 1 - PILOT CENTER TO CEMENTVILLE
ROUTE 2 - CEMENTVILLE TO TRUCKSTOP AT I71
ROUTE 3 - TRUCKSTOP AT I71 TO NEW POINT
ROUTE 4 - NEW POINT TO PILOT CENTER

	ROUTE ONE	ROUTE TWO	ROUTE THREE	ROUTE FOUR	TOTAL ROUTE
GCW OR GVW (LBS)	73000.	73000.	73000.	73000.	
CRUISE SPEED (MPH)	55	55	55	55	
WIND SPEED (MPH)	9	9	9	9	
WIND DIRECTION (DEG)	219	219	219	219	
TEMPERATURE (DEG F)	51	51	51	51	
**					
DISTANCE (MILES)	64.6	71.3	86.9	37.3	260.1
DRIVING TIME(HRS)	1.40	1.60	1.85	1.16	6.01
IDLE TIME(MIN-SEC)	1-44	6-47	1-53	3-57	14-22
AVERAGE SPEED(MPH)	46.0	44.7	47.0	32.2	43.3
FUEL USED (GAL)	12.2	12.9	16.3	6.8	48.2
FUEL MILEAGE(MPG)	5.29	5.52	5.34	5.51	5.40
TIME AT FULL THROTTLE(PCT)	8.2	20.4	22.0	10.0	16.0
AVG ENGINE SPEED (REVS/MILE)	1959	1972	1915	2443	2018
ENG LOAD FACTOR(PCT)	42	39	42	28	38
TOTAL GEAR SHIFTS	96	74	124	242	536
TIME ON BRAKES(MIN)	4.0	3.8	7.1	8.6	23.5

BASELINE NTC 400

VEHICLE MISSION SIMULATION

VEHICLE PERFORMANCE REPORT FOR DOE VEHICLE TEST PAGE NO -- 6
DATE - MAR 18,'80

VMS USER - J. L. HOEHNE SIMULATION NO - 006 SERIAL NO --19170

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SIMULATION SUMMARY

ROUTE 1 - PILOT CENTER TO CEMENTVILLE
ROUTE 2 - CEMENTVILLE TO TRUCKSTOP AT I71
ROUTE 3 - TRUCKSTOP AT I71 TO NEW POINT
ROUTE 4 - NEW POINT TO PILOT CENTER

	ROUTE ONE	ROUTE TWO	ROUTE THREE	ROUTE FOUR	TOTAL ROUTE
GCW OR GVW (LBS)	73000.	73000.	73000.	73000.	
CRUISE SPEED (MPH)	55	55	55	55	
WIND SPEED (MPH)	9	9	9	9	
WIND DIRECTION (DEG)	219	219	219	219	
TEMPERATURE (DEG F)	51	51	51	51	

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	ROUTE ONE	ROUTE TWO	ROUTE THREE	ROUTE FOUR	TOTAL ROUTE
DISTANCE (MILES)	64.6	71.3	86.9	37.3	260.1
DRIVING TIME(HRS)	1.41	1.62	1.88	1.16	6.07
IDLE TIME(MIN-SEC)	1-44	6-47	1-53	3-57	14-22
AVERAGE SPEED(MPH)	45.8	44.0	46.2	32.2	42.8
FUEL USED (GAL)	13.7	14.8	18.7	7.7	55.0
FUEL MILEAGE(MPG)	4.70	4.80	4.64	4.82	4.73
TIME AT FULL THROTTLE(PCT)	15.2	32.2	36.7	14.3	26.2
AVG ENGINE SPEED (REVS/MILE)	2001	2056	2029	2635	2116
ENG LOAD FACTOR(PCT)	47	44	48	32	43
TOTAL GEAR SHIFTS	109	139	184	240	672
TIME ON BRAKES(MIN)	3.2	3.1	6.3	7.4	20.0

EQUIVALENT TCA-450
VEHICLE MISSION SIMULATION

VEHICLE PERFORMANCE REPORT FOR DOE VEHICLE TESTS   PAGE NO -- 6
DATE - SEP 17, 180
VMS USER - J. L. HOEHNE   SIMULATION NO - 006   SERIAL NO --21299

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SIMULATION SUMMARY

ROUTE 1 - PILOT CENTER TO CEMENTVILLE
ROUTE 2 - CEMENTVILLE TO TRUCKSTOP AT I71
ROUTE 3 - TRUCKSTOP AT I71 TO NEW POINT
ROUTE 4 - NEW POINT TO PILOT CENTER

	ROUTE ONE	ROUTE TWO	ROUTE THREE	ROUTE FOUR	TOTAL ROUTE
GCW OR GVW (LBS)	73000.	73000.	73000.	73000.	
CRUISE SPEED (MPH)	55	55	55	55	
WIND SPEED (MPH)	9	9	9	9	
WIND DIRECTION (DEG)	219	219	219	219	
TEMPERATURE (DEG F)	51	51	51	51	

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	ROUTE ONE	ROUTE TWO	ROUTE THREE	ROUTE FOUR	TOTAL ROUTE
DISTANCE (MILES)	64.6	71.3	86.9	37.3	260.1
DRIVING TIME(HRS)	1.41	1.60	1.85	1.16	6.01
IDLE TIME(MIN-SEC)	1-44	6-47	1-53	3-57	14-22
AVERAGE SPEED(MPH)	45.9	44.7	47.0	32.2	43.3
FUEL USED (GAL)	12.7	13.6	17.1	7.1	50.4
FUEL MILEAGE(MPG)	5.08	5.26	5.09	5.28	5.16
TIME AT FULL THROTTLE(PCT)	8.4	20.4	22.1	9.9	16.1
AVG ENGINE SPEED (REVS/MILE)	1961	1972	1915	2455	2019
ENG LOAD FACTOR(PCT)	41	39	42	28	38
TOTAL GEAR SHIFTS	100	74	122	241	537
TIME ON BRAKES(MIN)	4.0	3.7	7.1	8.4	23.2

B. METRIC CONVERSION TABLE

CONVERSION FACTORS FOR SI (METRIC) UNITS

Quantity	Conversion	Factor	
Length	in to m	2.540	E-02
	mi to km	1.609	E+00
Area	in^2 to m^2	6.451	E-04
Volume	in^3 to m^3	1.638	E-05
	gal to l	3.785	E+00
Velocity	mi/hr to km/hr	1.609	E+00
Torque	lbf-ft to N-M	1.356	E+00
Pressure	lbf/in^2 to Pa	6.895	E+03
Power	hp to w	7.457	E+02
Mass	lb to kg	4.536	E-01
Temperature	°f to °c	$t_c = (t_f - 32)/1.8$	
Fuel Consumption	lb/bhp-hr to g/kwh	6.083	E+02
	mi/gal to km/l	4.251	E-01
Emissions	gm/bhp-hr to g/kwh	1.341	E+00