Meeting Bus Emissions Standards—A Perspective

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Concern for the urban environment has resulted in strict particulates emissions requirements for bus diesel engines beginning in 1991. Similar standards become applicable to on-highway truck engines in 1994. Current technological developments suggest that bus heavy-duty diesel engines manufactured in 1991 are unlikely to meet the standards. Combustion of methanol and natural gas in internal combustion engines results in low particulates emissions and may present an opportunity to meet these limits. In this paper the characteristics of these fuels relative to diesel and technologies for alternate fuel engines are discussed, and emissions and performance trade-offs are highlighted. The criteria such engines must meet to gain customer acceptance are also developed.

Heavy-duty diesel engines predominate in the commercial transportation sector because of their excellent performance with regard to fuel economy, reliability, and durability. The Environmental Protection Agency (EPA) has promulgated emissions standards for heavy-duty diesel engines including bus and truck applications (Table 1). Diesel fuel consumed by transit buses is a small part of total diesel fuel consumed by heavy-duty engines in the transportation sector. However, concern for the urban environment and public visibility have been used as a rationale for much stricter particulates requirements for 1991 bus engines. The same strict requirements apply to heavy-duty truck engines in 1994.

TABLE 1 EPA HEAVY-DUTY DIESEL EMISSIONS REGULATIONS

Emissions (g/bhp-hr)	1988	1990	1991	1994
Hydrocarbons	1.3	1.3	1.3	1.3
Carbon monoxide	15.5	15.5	15.5	15.5
Oxides of nitrogen	10.7	6.0	5.0	—[a]
Particulates	0.6	0.6	0.25 (0.10 bus)	0.10

[a]Not yet promulgated.

In the regulatory environment described, manufacturers of diesel engines are faced with the challenge of practically eliminating particulates in bus exhaust. Alternate fuels may offer an opportunity to meet these requirements. Furthermore, the development of alternatives to hydrocarbon fuels also offers strategic benefits. These include energy security and economic advantages of using indigenous fuels. Technologies for burning alternate fuels in heavy-duty engines cleanly and efficiently may offer access to overseas markets where such fuels may be preferred.

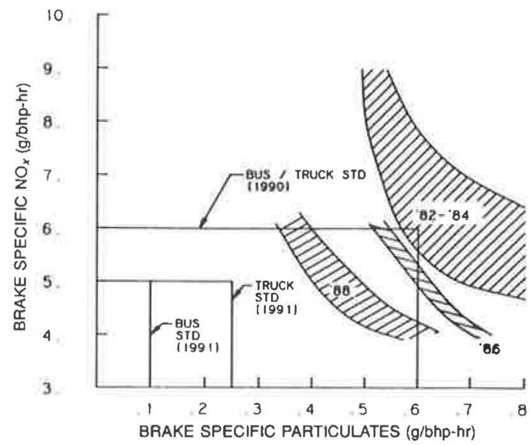

FIGURE 1 NO_x-particulate trade-off.

Evaluated here are potential alternate fuels, engine technologies, and emissions prospects for heavy-duty engines. Also highlighted are the criteria or parameters against which these engines should be judged for acceptance.

DIESEL ENGINE EMISSIONS TRADE-OFF

Diesel engine nitrogen oxides (NO_x) and particulate emissions follow a classic trade-off curve (Figure 1). Significant progress has been made in the 1980s in shifting this relationship so that lower particulates are emitted for a given NO_x. As combustion-generated particulates emissions are lowered, the contribution by lubricating oil and fuel contaminants (e.g., fuel sulfur) becomes a significant portion of the exhaust particulates. To meet the EPA requirement of 0.1 g/bhp-hr particulates (including deterioration factor, production tolerance variability, selective enforcement, etc.), the design target has to be lower than 0.1 g/bhp-hr. Current technological developments suggest that this may not be feasible if diesel fuel is used in the engine.

Technologies for aftertreatment of particulates are being developed. These require collection of particulates in a trap and their controlled oxidation or regeneration. The reliability and durability of trap systems have yet to be demonstrated. These systems also increase engine costs and add a fuel consumption penalty. Trap technologies may not be feasible for 1991 buses.

CHARACTERISTICS OF ALTERNATE FUELS

Some alternate fuels exhibit particulate emissions characteristics that make them attractive for use in heavy-duty engines.

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These include natural gas, methanol, and propane. Natural gas is a primary fuel that is not tied to a petroleum base. Methanol can be derived from various feedstocks including natural gas, coal, and biomass. Major production of methanol currently uses natural gas as the feedstock, and its current oversupply is due to the abundance of this resource material. Propane is essentially produced by refining and cleaning up natural gas. Its longer-term availability is therefore limited.

Various characteristics of these fuels (energy density, combustion efficiency, safety, and infrastructure) are compared with those of diesel fuel in Table 2. Where possible, quantitative comparison is shown (e.g., energy density and thermal efficiency). The qualitative comparison uses an indicator of 1 if the parameter is similar to diesel; >1 if the parameter is better than diesel, and <1 if it is inferior to diesel. The table highlights differences in the characteristics of alternative fuels with respect to diesel fuel.

TABLE 2 FUEL CHARACTERISTICS

Characteristic	Diesel	Methanol	Natural Gas	Propane
Energy density	1	0.5	0.35 CNG 0.65 LNG	0.8
Combustion efficiency	1	1	0.83	0.83
Safety	1	<1	<1	<1
Toxicity	1	<1	1	
Infrastructure	1	<1	<1	<1

NOTE: Diesel equivalent = 1; better than diesel = >1; worse than diesel = <1; CNG = compressed natural gas; LNG = liquefied natural gas.

Energy Density

Energy density of methanol is about one-half that of diesel fuel. Either twice the fuel volume needs to be carried on board for equivalent range or the vehicle needs to be refueled more often. Because methanol is a liquid, this does not present a major issue. Natural gas has very low energy density and needs to be carried in a highly compressed state (2,500 to 3,000 psi) or as a liquid in cryogenic tanks (LNG). As compressed fuel, its energy density is about one-third of that of diesel for the same fuel tank volume. In the liquefied state, the range is about two-thirds of the diesel fuel range. On-board storage and refueling of natural gas require significant additional tank size and longer refill times. Propane exhibits energy density about 0.8 that of diesel fuel. Because it is a liquid, refueling logistics would be similar to those for diesel fuel.

Combustion Efficiency

The efficiency of methanol heavy-duty engines is similar to that of diesel engines because the principle of operation [direct injection (DI) of fuel, high compression ratio, and unthrottled] is preserved. The natural gas and propane engines in this analysis are a conversion of the diesel engine to spark ignition (SI) so their efficiency is lower than that of the DI methanol engine for which the fuel and air are mixed externally in the intake system and carburated. A spark plug (in place of a fuel injector) ignites the fuel. Intake restriction or throttling is used to control power output of SI engines. Throttling losses and necessary lower compression ratios contribute to a lower engine efficiency compared with diesel.

Safety

Methanol flame is invisible because of the lack of carbon in its combustion. Therefore methanol-related fires may be difficult to detect. Also, methanol is miscible with water, and any leak from storage tanks may disperse into and contaminate groundwater. Natural gas is lighter than air so any leaks are likely to disperse upward. Propane is heavier than air and can be hazardous if leaked in enclosed spaces.

Toxicity

Methanol is known to be toxic if ingested. It can be absorbed through the skin and may be ingested because it has a pleasant taste, as does ethanol, in contrast with diesel fuel. Propane and natural gas do not show any known toxicity.

Infrastructure

This may be defined as the ability to readily deliver fuel with existing distribution systems. Methanol and natural gas both suffer from a lack of infrastructure. Methanol can be transported; however, large-volume availability and storage systems do not exist.

Natural gas may be available in most urban areas, but the required compressor stations for vehicle fueling do not exist. Propane is available in most places and may be delivered reasonably easily compared with methanol and natural gas. It may be suggested that propane fuel exhibits better infrastructure than do the other alternatives to diesel fuel.

ALTERNATE FUEL ENGINE TECHNOLOGIES

In recent years, various engine developments have been reported to adapt heavy-duty diesel engines to burn methanol or gaseous fuels (*1–6*). The rationale for and results of developments at the Cummins Engine Company using some of these alternate fuels are described, and a current technologies perspective on the use of these fuels is offered.

Engine Technologies

Methanol Fuel

Methanol fuel has very low ignition qualities as indicated by its cetane number. Technical options for methanol engines include

- Direct injection,
- Engine modifications
  - –Ignition aids (glow plugs, spark plugs) and
  - –Pilot diesel,
- Fuel modification (ignition improvers), and
- Carburation and external mixture preparation.

Gaseous Fuel

Natural gas does not exhibit compression ignition qualities (cetane rating) suitable for diesel engines. Its high octane rating makes it most suitable for a spark ignition engine. Technical options for natural gas engines include

- Spark ignition—carburation and external mixture preparation,
- Dual fuel—pilot diesel injection and gas through the intake system, and
- Direct injection of natural gas—ignition aids in combustion chamber.

Dual-fuel technologies add the complexity of carrying two fuel systems on board but, more important, have not demonstrated a potential to meet the low particulates requirements. Direct injection of natural gas is at the concept evaluation stage and is not yet a technology available for consideration.

The spark ignition technical option for heavy-duty engines is the same as for automobile engines; the fuel and air are mixed in the intake system and ignition is with a spark plug in the cumbustion chamber. Spark ignition engines operate at a lower compression ratio than do diesel engines because of knock limitations. Intake restriction or throttling is a means of controlling the output of SI engines. These differences in design and operation (i.e., lower compression ratio and throttling losses) contribute to the lower efficiency of SI engines.

TECHNICAL APPROACH AND RESULTS

Ongoing technology evaluation programs for methanol and natural gas engines are described in this section. The base engine modified for this work is a Cummins L10 (10-liter swept volume) engine that is used and well accepted in transit bus applications.

The objective of the work reported here has been to demonstrate a methanol engine with minimum engine change and develop a performance and emissions data base. The base diesel engine selected for this work is currently used in both bus and truck applications. The strategy adapted was that of modifying fuel properties, such as ignition and combustion characteristics, to make them similar to those of diesel fuel. Ignition as well as lubrication additives are added to methanol fuel. The engine modifications were limited to injection system changes to deliver larger fuel quantities and material changes for methanol fuel compatibility. Specifically, changes were made to the fuel pump, cam, and injectors. Because of the lower energy density of methanol fuel, nearly twice the volume of methanol fuel needs to be injected to develop power similar to that of a diesel engine.

The results for this prototype engine are shown in Figures 2–7 in which the performance and emissions of the engine are

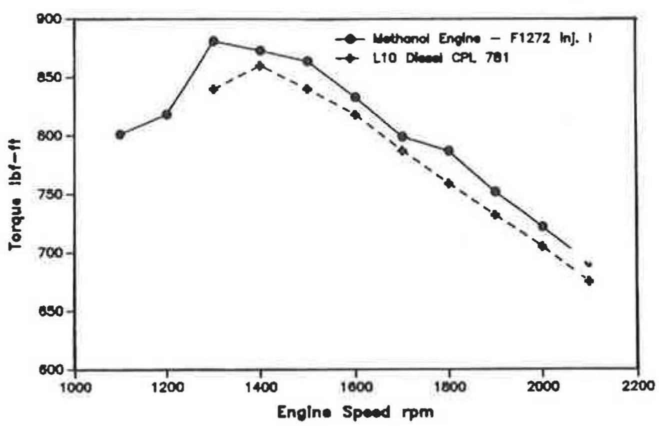

FIGURE 2 L10 methanol torque curve.

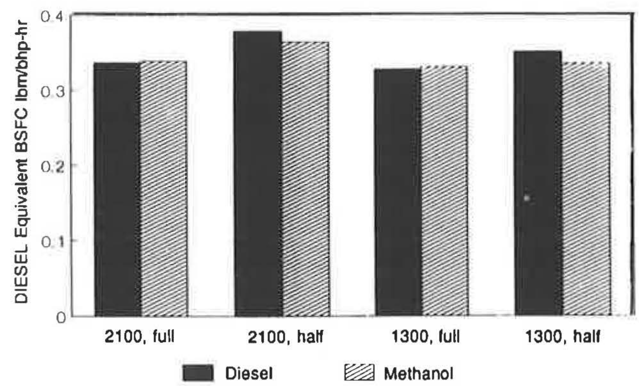

FIGURE 3 Diesel-equivalent BSFC comparison.

compared with those of the base diesel engine. The torque developed with the methanol engine is similar to that of the base diesel engine (Figure 2). There is a potential to develop higher torque at lower speeds than is practical with diesel engines because of smoke concerns. Brake specific fuel consumption (BSFC) (Figure 3) for methanol and diesel engines is identical under key performance conditions (rated and peak torque speeds/loads). The cylinder pressure developed with the methanol engine is similar to that of the base turbocharged diesel engine (Figure 4).

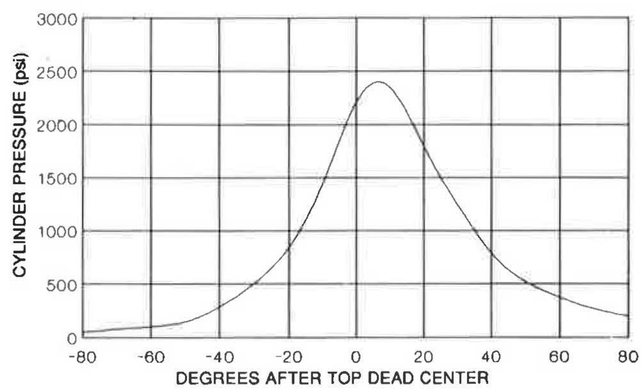

FIGURE 4 Cylinder pressure (5 percent Avocet, 1,300 rpm, 970 ft-lb).

Limited emissions data on a steady-state basis have been gathered for this engine. Figure 5 shows the NO_x emissions at 1,300 and 2,100 rpm for the methanol engine and base diesel engine. A point worth making is that the nitric oxide emissions are a function of ignition timing (residence time of combustion products at high temperature). The two engines compared here are not at the same injection timing because of differences in their injection characteristics. Nitric oxide emissions of the methanol engine will increase when the injection timing is advanced to be similar to that of the diesel engine.

Figure 6 shows unburned fuel emissions from the two engines. The hydrocarbons from the methanol engine have not been corrected for Flame Ionization Detector sensitivity differences between hydrocarbon and methanol fuels. The increase in unburned fuel emissions is due to the combination of mismatched injector cups in the methanol engine and long injection duration of the cam used to demonstrate concept feasibility. It is expected that further developments including an

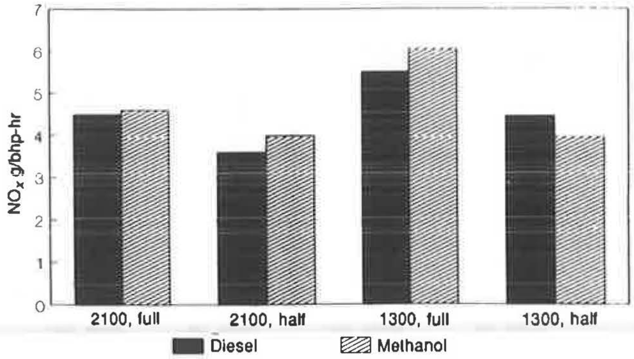

FIGURE 5 Comparison of NO_x emissions.

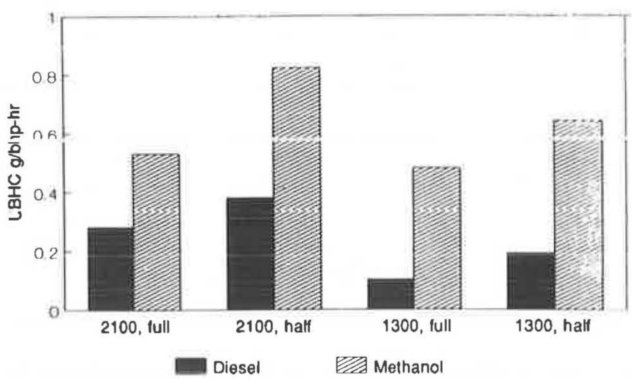

FIGURE 6 Comparison of unburned fuel.

optimized injection system (cam, injector, and injection characteristics) will overcome most of the deterioration observed in these results.

Figure 7 shows a comparison of particulates from diesel and methanol engines developing the same power. Particulates from the methanol engine are 5 to 10 times lower than from the diesel engine, which clearly demonstrates the rationale for considering methanol fuel for heavy-duty engines. Combustion of methanol contributes greater amounts of aldehydes to the exhaust than does diesel fuel. The qualitative data suggest that to be the case. Aldehydes are not regulated at present, but the focus of manufacturers of methanol engines has got to be on lowering this constituent below diesel levels. In the technical concept described previously, the in-cylinder temperatures are such that aldehydes may be oxidized further in the combustion space to a level below that of diesel emissions.

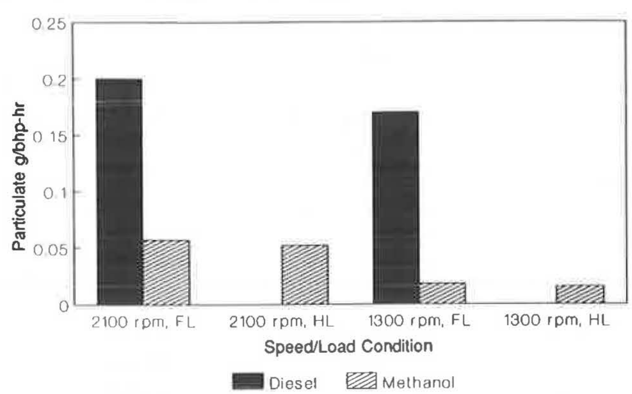

FIGURE 7 Particulate comparison.

Natural Gas Engine

An L10 engine has been modified to burn gaseous fuels (both natural gas and propane). Some of the critical engine components such as valve and valve seat materials have been modified to be compatible with higher (than diesel) combustion temperatures. Also, turbo machinery has been engineered that will optimize fuel economy for the bus operating cycle. These projects are in an early stage of development. Combustion and emissions data from these engines have not yet been developed for comparison with the methanol engine. However, on the basis of work reported elsewhere (7), the following qualitative evaluation can be made of natural gas engine emissions.

The homogeneous charge operates with fuel-air mixtures that are richer than those used for diesel fuel. As a consequence, these engines tend to emit much more NO_x in the exhaust. A comparative analysis of natural gas and propane engine emissions (Table 3) indicates that spark-ignited gas engines produce particulates an order of magnitude lower than similar diesel engines. The NO_x emissions of gas engines increase by a factor of two in these naturally aspirated engines. The HC and CO emissions are not much different. These data indicate that the NO_x needs to be controlled to acceptable levels, which may be feasible by employing lean-burn concepts—operating the engines at an air-to-fuel ratio that is leaner than chemically correct mixtures.

TABLE 3 COMPARATIVE ALTERNATE FUELS EMISSIONS DATA FOR EXPERIMENTAL BUS DRIVING CYCLE

Engine (fuel)	Particulates	HC	NO_x	CO
6V71 (diesel)	0.17	1.36	10.8	1.92
IVECO (diesel)	0.21	0.99	9.2	2.01
IVECO (propane)	0.015	1.17	19.2	2.07
IVECO (natural gas)	0.028	1.6	17.1	1.27
IVECO (optimized natural gas)		3.0	14.5	1.75

NOTE: Units are g/bhp-hr.

PERSPECTIVE ON ALTERNATE FUEL ENGINE TECHNOLOGY

A perspective on engine technologies is given in Table 4, including various performance characteristics and status of current diesel, methanol, and gas engines. The major issue with diesel engines is exhaust particulates. Methanol engines present the added issue of aldehydes in the exhaust. The reliability and durability of these engines are as yet unknown. It is anticipated that these engines will cost considerably more than current diesel engines. Gas-fueled engines are cleaner combustion engines except for their higher NO_x emissions. These engines also have inferior fuel consumption, specific output, and cost compared with modern diesel engines.

To gain wider customer acceptability, alternate fuel products need to meet diesel-like performance (reliability, durability) and cost standards.

TABLE 4 PERSPECTIVE ON CURRENT ENGINE TECHNOLOGY

Characteristic	Diesel	Methanol	Natural Gas
Reliability (unscheduled downtime)	Excellent	?	High
Durability (life to overhaul)	Long	?	?
Specific output	High	High	Mid
Fuel economy	High	High	Mid
Cost	Low	High	High
Emissions			
NO_x	Mid to low	Low	High
Particulates	Mid	Low	Low
Aldehydes	Low	High	Low

SUMMARY

Technological developments for methanol and natural gas engines are ongoing. Each of these technologies presents issues that need to be carefully evaluated, and trade-offs need to be developed. Fuel availability, life-cycle cost, maintenance, operator acceptance, and legislative requirements are the most appropriate criteria against which to judge alternate fuel engines.

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