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FUEL UTILIZATION OF ARTICULATED VEHICLES: EFFECT OF POWERTRAIN CHOICE

by

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Ownership of the Transport Research Laboratory was transferred from the Department of Transport to a subsidiary of the Transport Research Foundation on 1st April 1996.

FUEL UTILIZATION OF ARTICULATED VEHICLES: EFFECT OF POWERTRAIN CHOICE

ABSTRACT

Computer simulation techniques have been used to evaluate the effect of powertrain choice on the fuel utilization (fuel consumption per tonne-km of payload) of heavy articulated vehicles. Powertrain parameters which were investigated included engine capacity and aspiration, engine torque-speed characteristics and final drive ratio. Fuel utilization was shown to improve as engine capacity was reduced. An improvement of 2.5 per cent per litre reduction of engine capacity was obtained for vehicles of 32–40 tonne gross weight. In practice most of the fuel consumption benefits associated with the choice of an optimum size engine can be obtained by modifying the characteristics of high capacity turbocharged engines in combination with a change in final drive ratio so that the engine will operate at lower speed and higher torque whilst producing the same power output as a smaller capacity turbocharged engine. Most heavy duty diesel engines, which are part of optimised powertrains of articulated vehicles, operate at average engine efficiencies within 10 per cent of the best peak engine efficiency available in 1978 products. The scope for further improvement is therefore limited.

1. INTRODUCTION

During the last three decades the brake specific fuel consumption of heavy duty diesel engines has been improved substantially. Improvements of 15–35 per cent have been reported in some instances[1,2,3]. As the figures in Table 1A show, almost 50 per cent of engines installed in articulated vehicles in 1978 had minimum specific fuel consumption within 5 per cent of the best value attained at that time. Similarly, the weight of engines has also been reduced, but the figures in Table 1B show that there remains a wide variation in installed specific weights. To what extent these trends will continue or be limited by emission regulations and limits of diesel engine technology is a matter for conjecture[3,4]. However, engine operating efficiency can also be improved by selecting a powertrain which is well suited to the transport task to be performed. Engine operating efficiency and thence fuel consumption is affected by the choice of engine capacity and aspiration, engine torque-speed characteristics, final drive ratio and choice of gearbox ratio.

Computer simulation techniques[5,7] which make it possible to evaluate the effect of vehicle design on fuel consumption and performance have been used already to demonstrate the sensitivity of fuel consumption to variation in gross vehicle weight[6]. This report gives an account of a further computer study aimed at examining the influence of powertrain choice on fuel consumption. Practical considerations such as the gradability and drivability of powertrains for a wide range of duties is beyond the scope of this investigation. Also the influence of gearbox ratios is not examined in detail in this study.

TABLE 1A

Fuel consumption of engines installed in 32–44 tonne gross weight articulated vehicles

Specific fuel consumption (g/kWh)	198–207	208–217	218–227	228+	Average 207
Per cent of population	43	34	16	7	

TABLE 1B

Weight of engines installed in 32–44 tonne gross weight articulated vehicles

Specific weight (kg/kW)	3.1–4.0	4.1–5.0	5.1–6.0	6.1–7.0	Average 5.0
Per cent of population	9	45	29	17	

2. METHOD OF EVALUATION AND DATA BASE

The vehicles considered in the present study belong to the 32.5 to 36 tonne gross weight category on four axles and the 36 to 40 tonne category on five axles. For each vehicle the unladen weight and carrying capacity was based on a 2-axle tractor and either a 2 or 3-axle platform skeletal trailer. Powertrain characteristics are detailed in Table 2, they were based on a supposed family of engines derived from the 12.2 litre Rolls Royce Eagle Mark III, and included naturally aspirated, turbocharged and charge cooled versions. Fuel maps for these are shown in Figure 1. Limited use was made of engine data from other engine manufacturers. Aerodynamic drag and tyre rolling resistance were based on former work[5].

TABLE 2

Specification of powertrains based on the Rolls Royce Eagle Mark III*
12.2 litre 6 cylinder in-line engine (130 mm bore, 152 mm stroke)

Engine	Aspiration	Naturally aspirated	Turbocharged	Turbocharged and charge cooled
	Max net output (kW) at 2100 rpm	157	229	244
	Max net torque (Nm) at 1500 rpm	821	1177	1296
	Minimum specific fuel consumption (g/kWh)	222	207	202
	Net weight (kg)	1092	1143	1137
Transmission	Type	Single drive 9-speed		
	Gear ratios	8.77, 5.85, 4.29, 3.20, 2.37, 1.83, 1.34, 1.00, 0.74		
	Maximum geared speeds (km/h)	Varied between 90 and 120 km/h		

* Scaled and economy tuned versions were also considered (see Figure 1 and Figure 5).

In general, the operation of a vehicle is simulated on the computer over a cycle typical of operating experience for long haul articulated vehicles. The fuel consumption is calculated for urban roads, all purpose rural roads, and motorways from simulated trips over selected test routes[5]. Trips at different vehicle weights (unladen weight plus payload weight) are simulated. The result of these runs is a set of fuel consumption versus vehicle weight curves for operation over each of the different types of road. Then, weighting factors are applied to the fuel consumption data to obtain an average fuel consumption, based on the annual kilometres travelled over each type of road and the distance run at different payload weights. Average fuel consumption divided by average payload then determines the fuel utilization for each vehicle type. Results were obtained at an average load factor of 53 per cent and over a typical mix of roads, 23 per cent urban, 42 per cent rural trunk and 35 per cent motorway.

The program used for calculating fuel consumption is able to allow for changes in engine bore, stroke and number of cylinders. The scaling laws were based on the principle of mechanical similitude[8], which assumes that the performance of any one of a series of geometrically similar engines with the same maximum piston speed can be represented by a single performance map, assuming that the generalised engine parameters of brake mean effective pressure, brake specific power output and brake specific fuel consumption are independent of cylinder size. For the purpose of this study engines were scaled at constant bore to stroke ratio; allowance was made for the change in unladen weight due to scaling the engine (100 kg/l).

3. ENGINE CAPACITY AND ASPIRATION

The effect of engine capacity and aspiration was investigated for 32.5, 35, 38 and 40 tonne articulated vehicles.

3.1 *Variation of fuel utilization with engine capacity*

The effect of engine capacity and aspiration on fuel utilization is shown in Figure 2 for a 32.5 tonne articulated vehicle. Typically, for a turbocharged engine the fuel utilization improves 2.5 per cent for each one litre reduction in engine capacity. Around 0.5 per cent of this is due to the increase in vehicle carrying capacity, 0.5 per cent is due to the change in engine operating efficiency and the remainder is due to the trade-off between performance and fuel consumption. For each 2.5 per cent improvement in fuel utilization there is a corresponding 2 per cent reduction in average journey speed. These results were obtained for the route and load conditions given in Section 2. The variation of performance with operating power-to-weight ratio is illustrated in Figure 3. Lower journey speed and more frequent gear changes over the same duty cycle result from limiting the power available to the driver. The dependence of fuel utilization on (turbocharged) engine capacity at various gross vehicle weights is shown in Figure 4. The optimum choice of engine capacity depends upon the minimum acceptable power-to-weight ratio[9].

3.2 *Effect of aspiration at fixed engine capacity*

Although the brake specific fuel consumption of the naturally aspirated engine shown in Figure 1, can be improved through turbocharging and charge cooling by around 10 per cent, the fuel consumption for a 32.5 tonne articulated vehicle given in Table 3 suffers slightly , largely due to a trade-off between performance and fuel consumption.

TABLE 3

Effect of turbocharging and charge cooling on the fuel consumption of a 32.5 tonne design gross weight articulated vehicle with a 12.2 litre engine

Engine	Naturally aspirated	Turbocharged	Turbocharged with charge cooling
Power-to-weight (kW/tonne)	4.8	7.1	7.5
Fuel consumption, unladen (litres/100 km)	34.4	34.9	35.6
Fuel consumption, fully laden (litres/100 km)	53.9	54.5	55.2
Fuel consumption for average payload (litres/100 km)	44.8	45.3	46.0
Average fuel utilization (litres/100 tonne-km)	3.98	4.03	4.09
Relative fuel utilization index	100.0	101.3	102.8

3.3 *Effect of aspiration at fixed power-to-weight ratio*

As shown in Table 4, the basic improvement in engine efficiency due to turbocharging and charge cooling can be converted into a corresponding fuel consumption improvement, provided that the engine capacity is adjusted to meet a constant power-to-weight ratio requirement. Fuel utilization is then improved by 12 per cent; the 10 per cent improvement in fuel consumption being augmented by the increased payload capacity allowed by the reduction in engine weight.

TABLE 4

Effect of turbocharging and charge cooling on the fuel consumption of a 32.5 tonne design gross weight articulated vehicle at 5 kW/tonne power-to-weight ratio

Engine	Naturally aspirated	Turbocharged	Turbocharged with charge cooling
Engine capacity (litres)	12.9	7.4	6.9
Unladen weight (tonnes)	11.3	10.8	10.7
Fuel consumption, unladen (litres/100 km)	35.2	31.1	31.6
Fuel consumption, fully laden (litres/100 km)	54.8	50.1	50.2
Average payload (tonnes)	11.2	11.5	11.6
Fuel consumption for average payload (litres/100 km)	45.6	41.1	41.4
Average fuel utilization (litres/100 tonne-km)	4.06	3.57	3.57
Relative fuel utilization index	100.0	87.9	87.9

The information in Table 4 is extended to Table 5 to cover a range of vehicles all with engines designed to provide a power-to-weight ratio of 5 kW per tonne.

TABLE 5

Estimated fuel consumption for articulated vehicles at 5 kW/tonne design power-to-weight ratio

Engine aspiration	Naturally aspirated		Turbocharged				Turbocharged with charge cooling			
Design gross weight (tonnes)	32.5	35	32.5	35	38	40	32.5	35	38	40
Engine capacity (litres)	12.9	14.3	7.4	8.3	9.3	10.0	6.9	7.7	8.7	9.3
Fuel consumption for average load (litres/100 km)	45.6	48.1	41.1	42.9	45.6	47.2	41.1	43.1	46.2	47.3
Average fuel utilization (litres/100 tonne-km)	4.06	3.87	3.57	3.37	3.30	3.19	3.57	3.37	3.30	3.17

4. ENGINE CHARACTERISTICS AND FINAL DRIVE RATIO

In practice it may often be difficult to choose an optimum size engine for a vehicle, but fortunately there are other ways to improve fuel consumption through powertrain design. For example, a large engine may be derated and governed at a lower speed with an appropriate change in the back axle ratio. Referring to Figure 5 the standard engine rating gives a power-to-weight ratio substantially above the requirement for a 32.5 tonne gross weight articulated vehicle. The engine may be derated by lowering the fuel pump delivery rate and thus reducing vehicle performance. To improve the usable range of engine speed, the torque-rise can be increased by boosting the turbocharger and fuel delivery system in the middle range of engine speed. Alternatively, the governed speed of a standard engine can be reduced in combination with a more modest amount of derating to bring the engine operating range into a more efficient region and maintain good drivability. When the governed speed is reduced, it is necessary to change the final drive ratio to obtain the same maximum vehicle speed. In fact, the engine can often be brought into a more efficient operating range by gearing the vehicle such that maximum road speed, which may be restricted by the use of a suitable road speed governor, is attained at less than maximum engine speed. All these measures were investigated for 32.5 tonne and 38 tonne gross weight articulated combinations.

The effect of engine characteristics and final drive ratio on fuel consumption is shown in Figure 5 for a fully laden 32.5 tonne gross weight articulated combination operating over 60 per cent motorway and 40 per cent trunk roads. From this illustration it is clear that there are substantial gains to be had by adjusting the specifications of engine and back axle. To show the effectiveness of optimising powertrain characteristics rather than choosing the smallest possible engine, a 38 tonne vehicle with a 12.2 litre turbocharged engine tuned to give the same performance as a smaller 9.3 litre engine was investigated. The maximum power output of the larger engine was reduced by 20 per cent, its governed speed was reduced by 10 per cent and its back axle ratio was chosen to give 108 rather than 100 km/h top speed. Selecting the smaller engine or economy tuning of the larger engine each improved fuel consumption by 8 per cent. The larger engine operated at a higher torque to produce the same power output as the smaller engine.

There are other important effects concealed within the overall figures given above. For example the effect of a reduction in governed speed of 10 per cent varies with the type of road. Over urban roads, improvements in fuel consumption of 3 per cent can be expected, whereas over motorways at higher operating speeds, around 6 per cent is possible. Similarly, the effect of a change in back axle ratio is most marked for vehicles running on motorways, as shown in Figure 6, whereas rural road fuel consumption increases with geared speed at 115 km/h. This is due to progressive reduction in the use of top gear at the 64 km/h (40 mile/h) cruising speed. Empty running allows greater use of top gear and there is more chance to benefit from a change in final drive ratio, as shown in Figure 7. In general the greatest improvement in fuel consumption through increasing geared speed was observed for engines with high torque output at low engine speed as shown in Figure 8; this is because these engines make it possible to operate more of the time close to the maximum engine efficiency.

A good measure of the scope for powertrain optimisation is engine operating efficiency averaged over a chosen duty cycle. Figure 9 shows that for each of the powertrains considered average specific fuel consumption on motorway and trunk road operation is close to the best obtainable for that engine; and in most cases the average engine operating efficiency is within 10 per cent of the best peak engine efficiency attainable on currently available engines.

5. FACTORS INFLUENCING POWERTRAIN CHOICE

It has been shown that optimum fuel utilization at similar road performance can be achieved through the choice of a small highly rated engine or the choice of an engine of around 30 per cent higher capacity, operating at lower piston speed, higher torque and the same rated power output to give the same BHP/tonne. Therefore the choice is more likely to be influenced by overall vehicle operating costs through differences in engine weight, differences in first cost and any differences in reliability and durability.

The advantages of a small highly rated engine are somewhat offset by durability considerations. Since inertial stresses increase as the square of piston speed[8], the larger derated engine will be less subject to these effects. For all types of wear, engines with large cylinders and large bearings have an advantage over engines in which these parts are small. Also the larger derated engine will operate at lower brake mean effective pressure. Thus on all these accounts, the larger engine will tend to be more durable and reliable than the small highly rated engine. Quantitative assessment of these factors and their influence on overall vehicle operating costs has not been included in the analysis presented in this report.

6. CONCLUSIONS

1. For the vehicles considered in this study, fuel utilization improved as engine capacity was reduced, at 2.5 per cent per litre for a 32–40 tonne gross weight articulated vehicle. The rate of improvement is due to a trade-off between performance and fuel consumption (1.5 per cent), an improvement in engine operating efficiency (0.5 per cent) and an increase in vehicle carrying capacity (0.5 per cent). Charge cooled turbocharged engines of capacity around 7 litres at 32.5 tonne gross weight and 9 litres at 38 tonne gross weight give the best fuel utilization results at a fixed maximum power-to-weight of 5 kW/tonne.

2. In practice most of the fuel consumption benefits associated with the choice of a small engine can be obtained by modifying the characteristics of relatively high capacity turbocharged engines of over 12 litres in combination with a change in final drive ratio, so that these engines will operate at lower speed and higher torque whilst producing the same power output as a smaller engine. This can nearly match the improvement in fuel consumption obtainable from reduction in engine capacity.

3. The choice between a small highly rated engine and a larger derated engine is likely to be influenced by overall operating costs through differences in engine weight, differences in first costs and the likely differences in reliability and durability. Quantitative assessment of these factors and their influence on overall operating costs has not been included in this analysis.

4. Fuel consumption improved as maximum geared speed, but not maximum road speed, was increased. Articulated vehicles covering high motorway mileages could benefit from geared speeds in excess of maximum cruising speeds. This is particularly applicable to final drives which operate behind engines with high torque output in the middle range of engine speeds. On such vehicles limitation of maximum road speed would be necessary.

5. Most heavy duty diesel engines, which are part of optimised powertrains of 32/38 tonne articulated vehicles, operate at average engine efficiencies within 10 per cent of the best engine efficiency available in 1978 products. Thus further improvements in heavy duty diesel engine operating efficiency will depend more upon the development of more efficient engines than upon powertrain matching.

7. ACKNOWLEDGEMENTS

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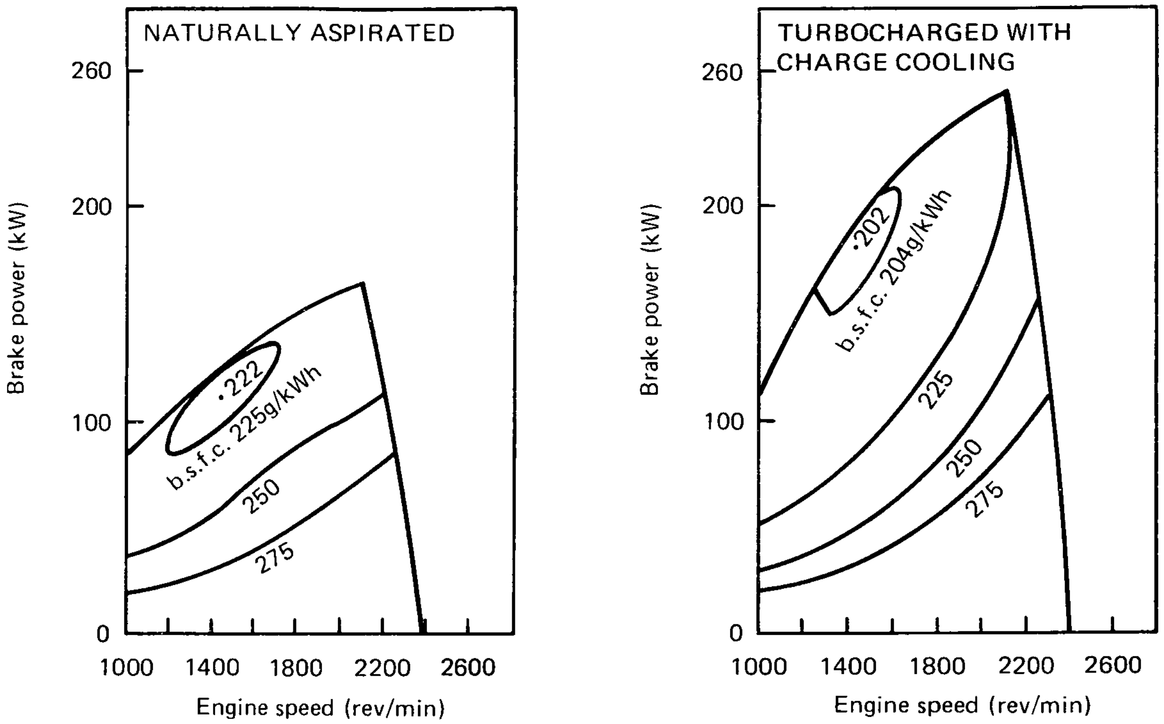
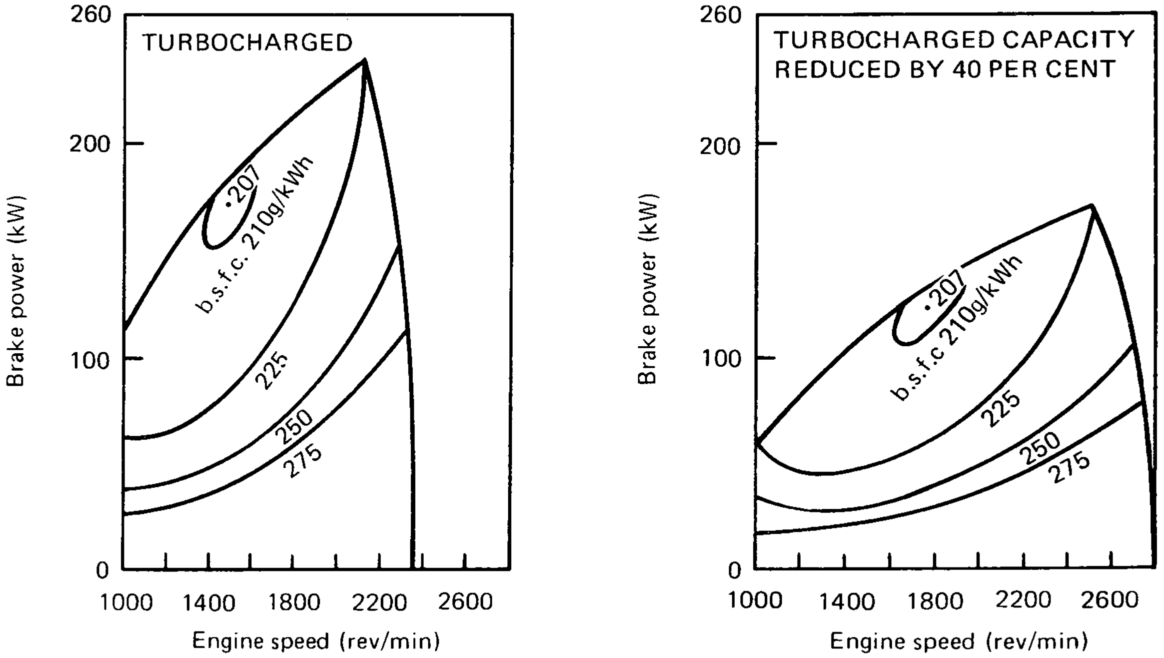


MAP OF EAGLE MARK III 220

MAP OF EAGLE MARK III 340



MAP OF EAGLE MARK III 320

MAP OF SCALED VERSION OF
EAGLE MARK III 320

Fig. 1 FUEL MAPS OF EAGLE MARK III ENGINES

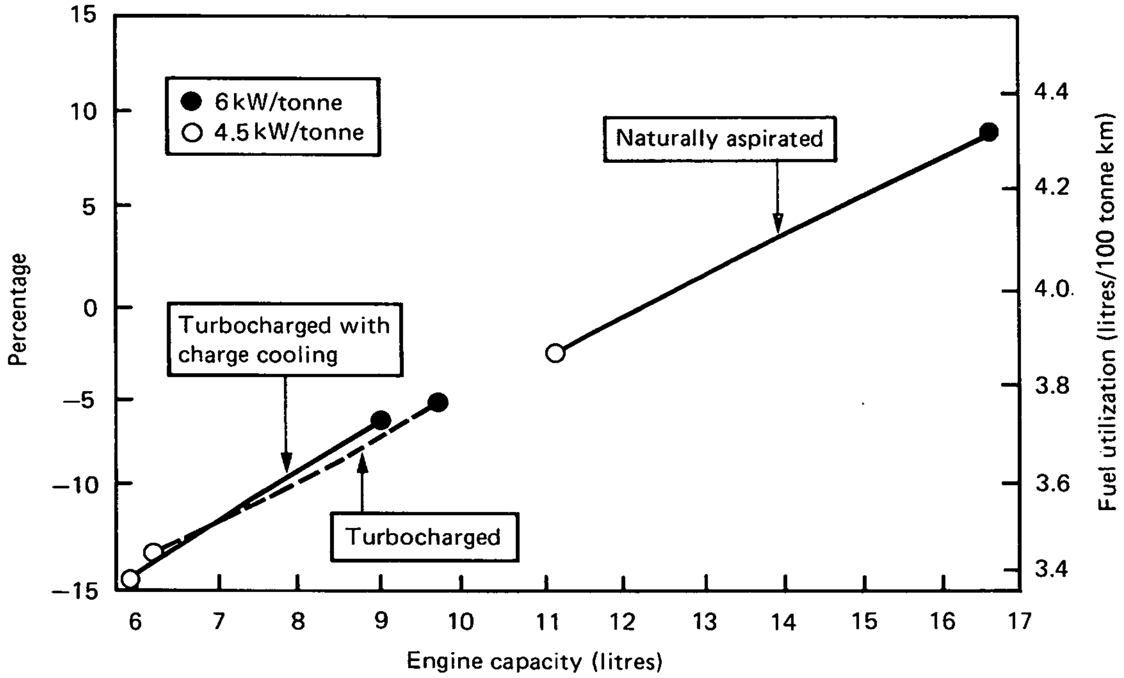


Fig. 2 EFFECT OF CHANGE IN ENGINE CAPACITY AND ASPIRATION ON FUEL UTILIZATION FOR A 32.5 tonne ARTICULATED VEHICLE

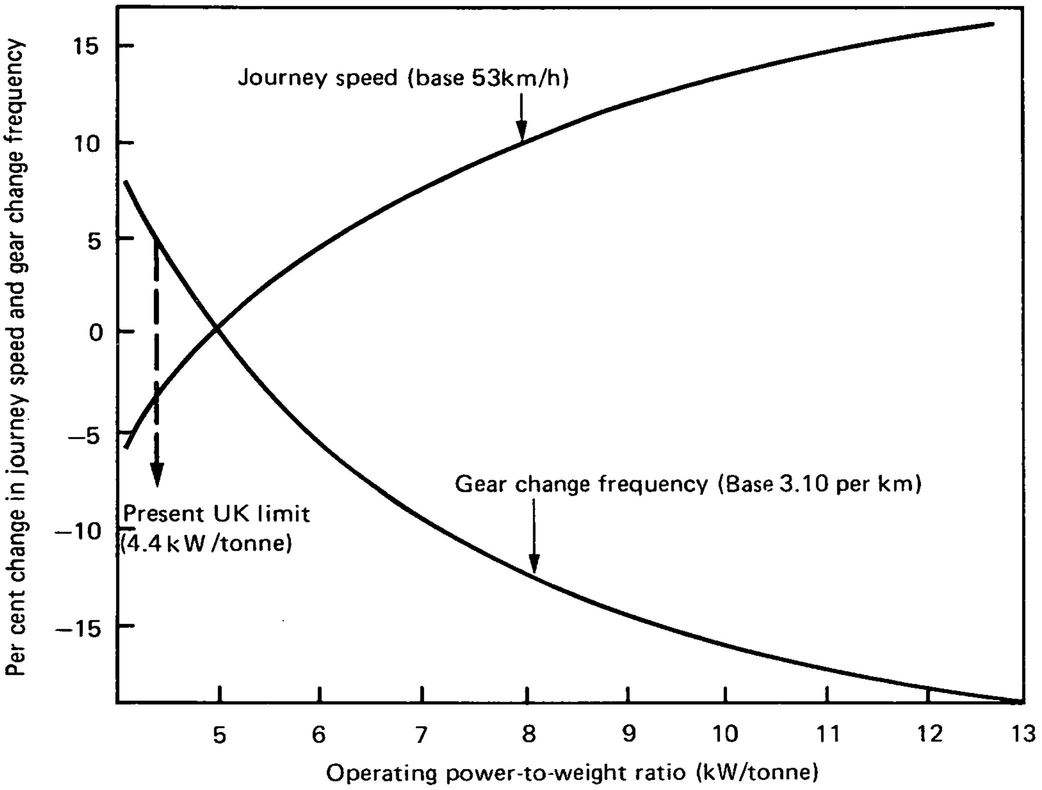


Fig. 3 EFFECT OF OPERATING POWER-TO-WEIGHT RATIO ON JOURNEY SPEED AND GEAR CHANGE FREQUENCY

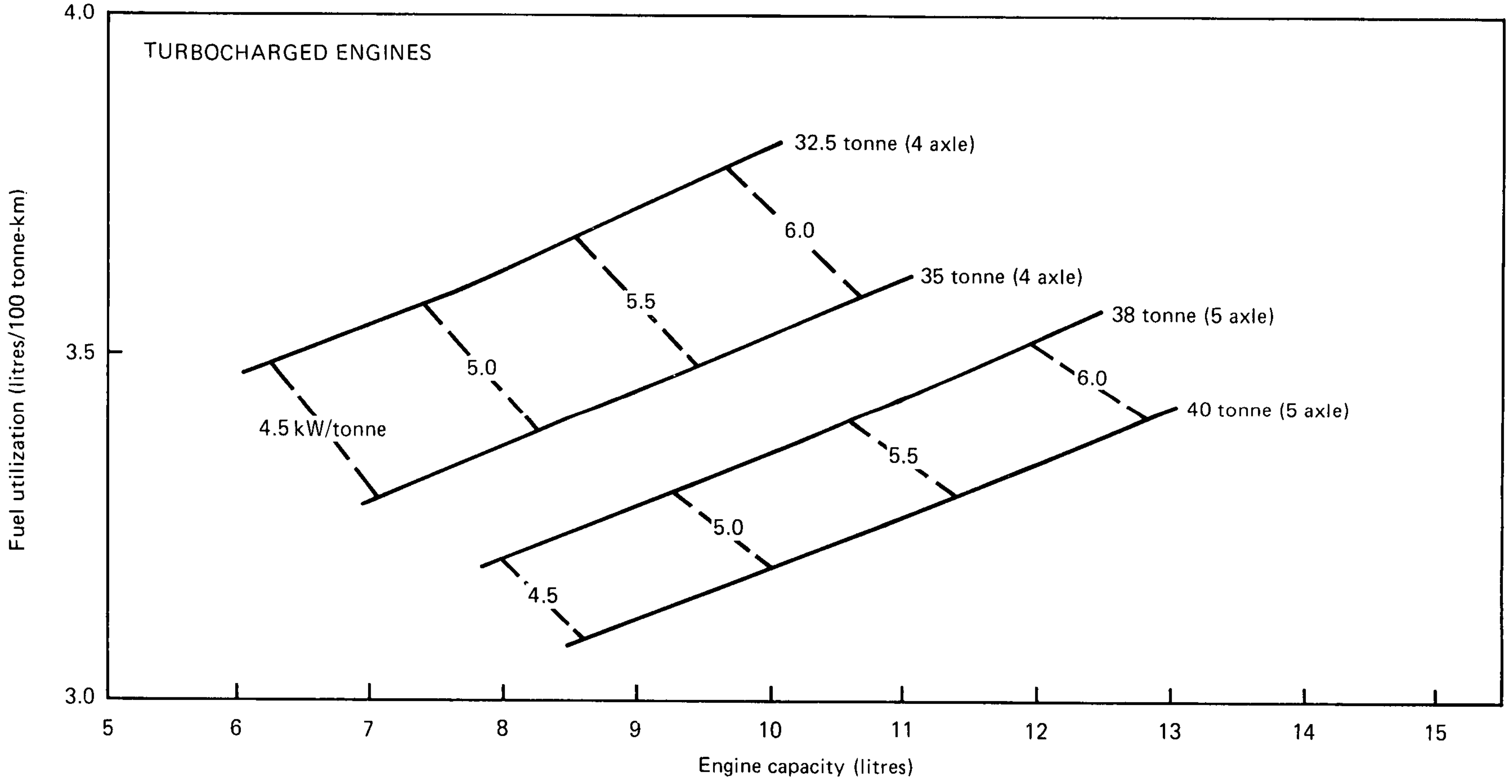


Fig. 4 DEPENDENCE OF FUEL UTILIZATION ON ENGINE CAPACITY AT VARIOUS GROSS VEHICLE WEIGHTS

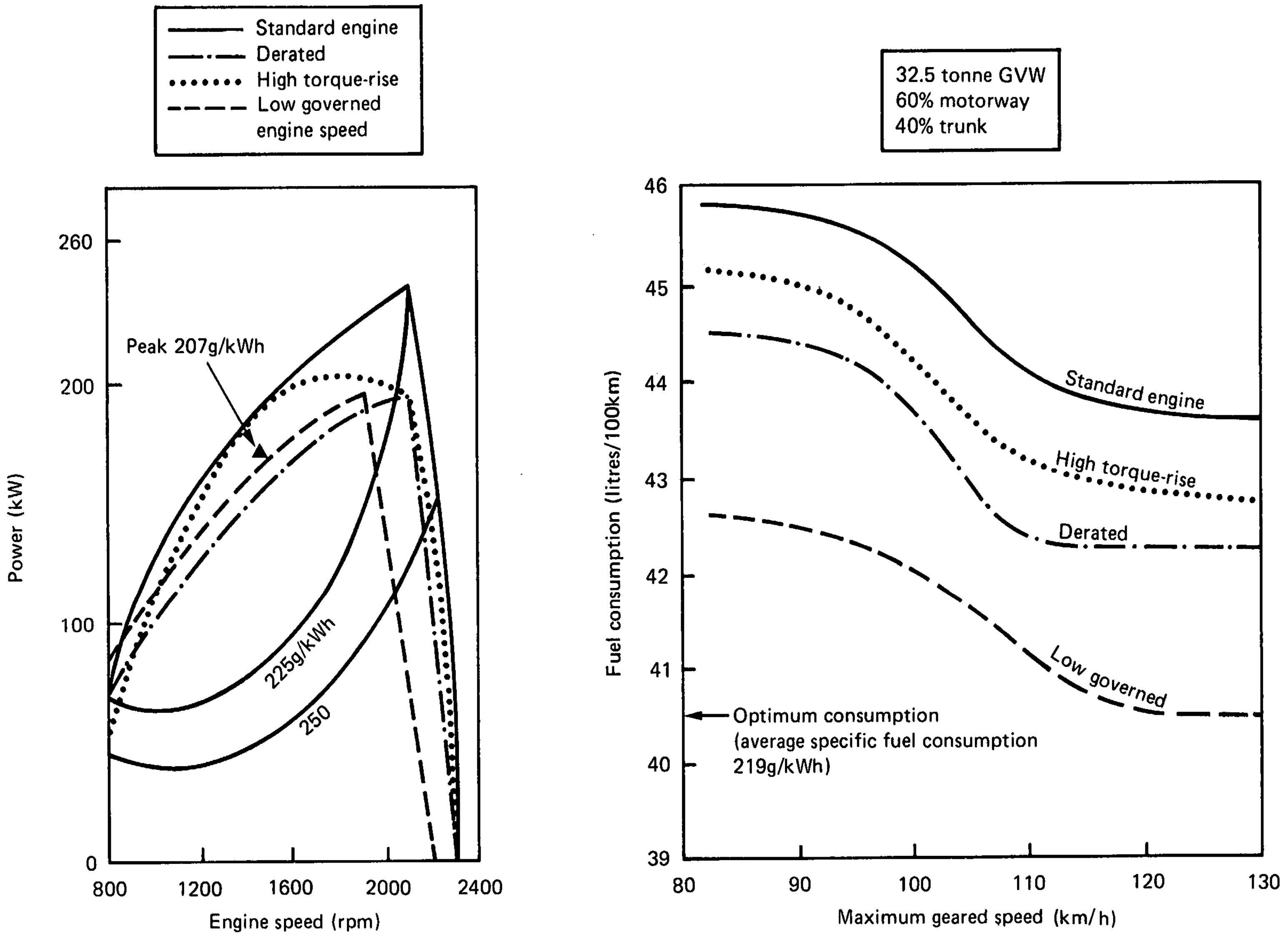


Fig. 5 THE FUEL CONSUMPTION OF ECONOMY TUNED VERSIONS OF A 12.2 litre TURBOCHARGED ENGINE

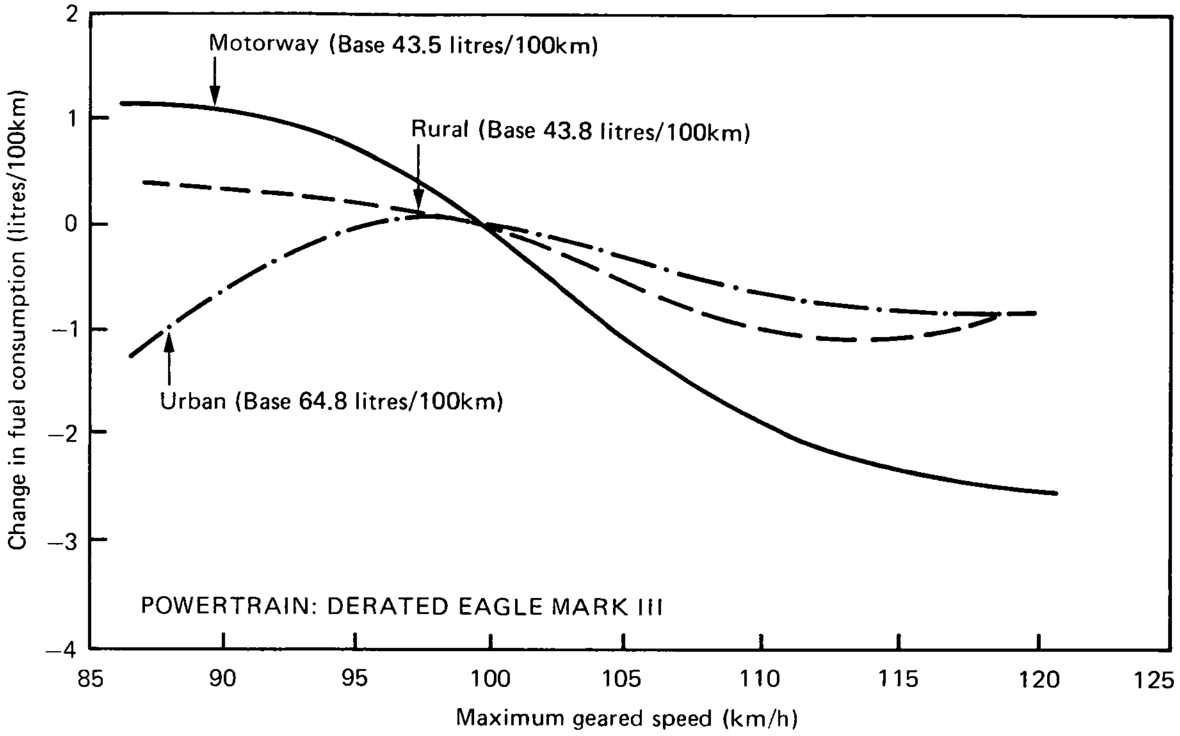


Fig. 6 EFFECT OF FINAL DRIVE RATIO CHANGES ON FUEL CONSUMPTION OVER DIFFERENT TYPES OF ROADS

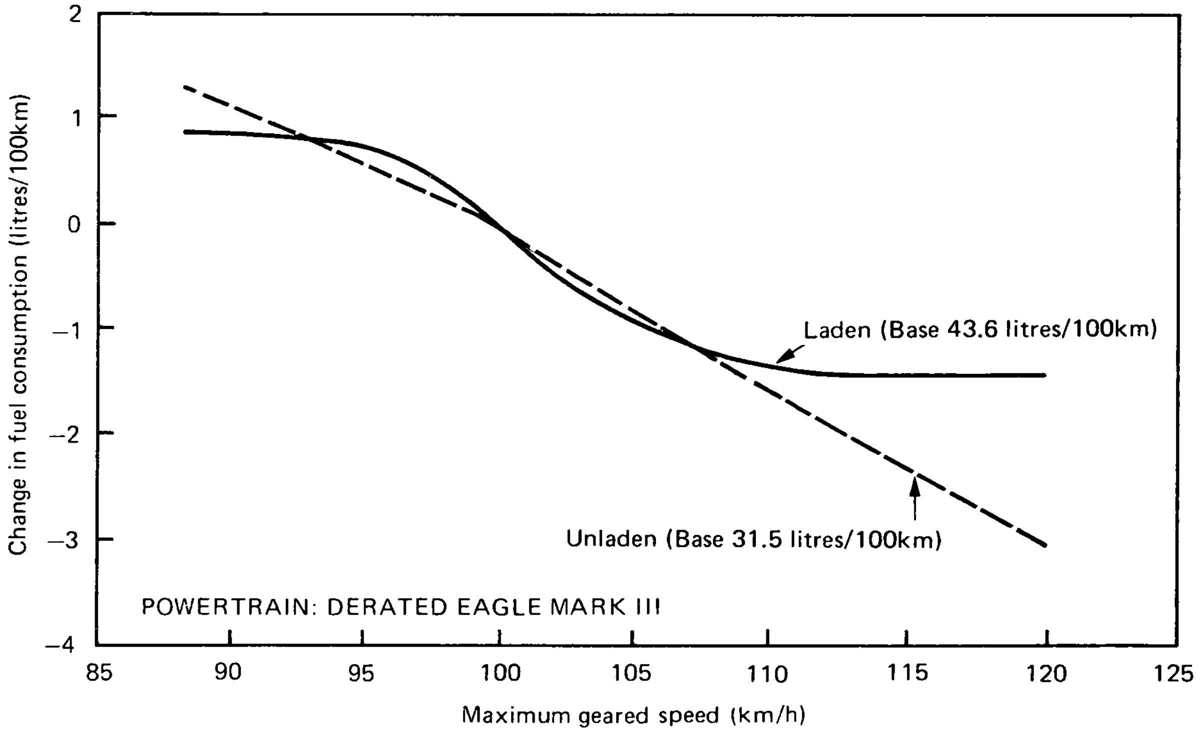


Fig. 7 EFFECT OF FINAL DRIVE RATIO CHANGES ON FUEL CONSUMPTION OF FULLY LADEN AND EMPTY 32.5 tonne GROSS WEIGHT ARTICULATED VEHICLES

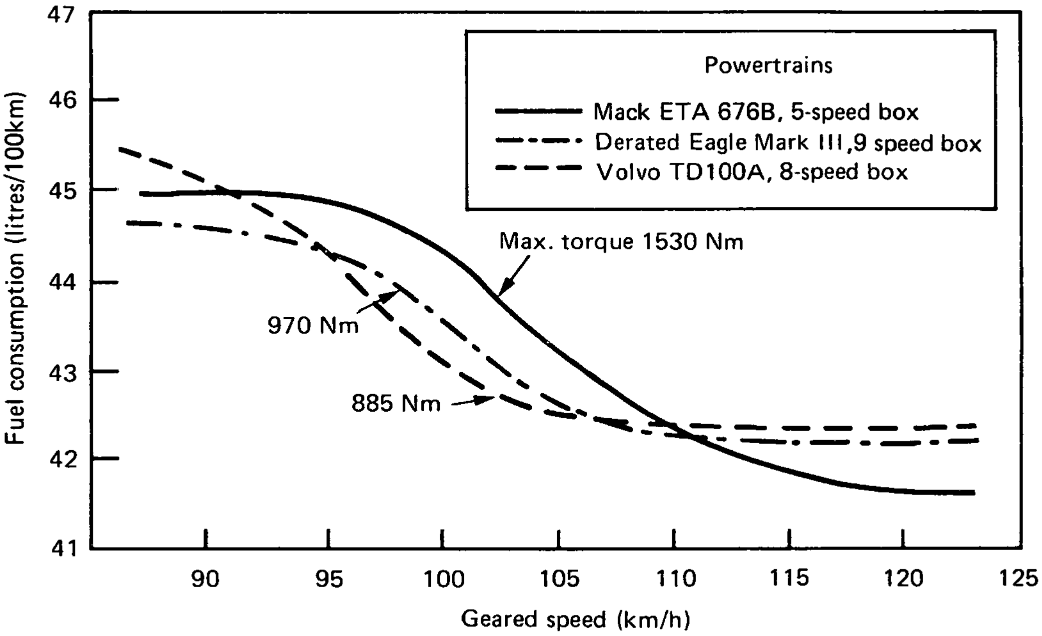


Fig. 8 EFFECT OF FINAL DRIVE RATIO CHANGES ON FUEL CONSUMPTION OF A FULLY LADEN 32.5 tonne GROSS WEIGHT VEHICLE WITH EACH OF THREE DIFFERENT ENGINES

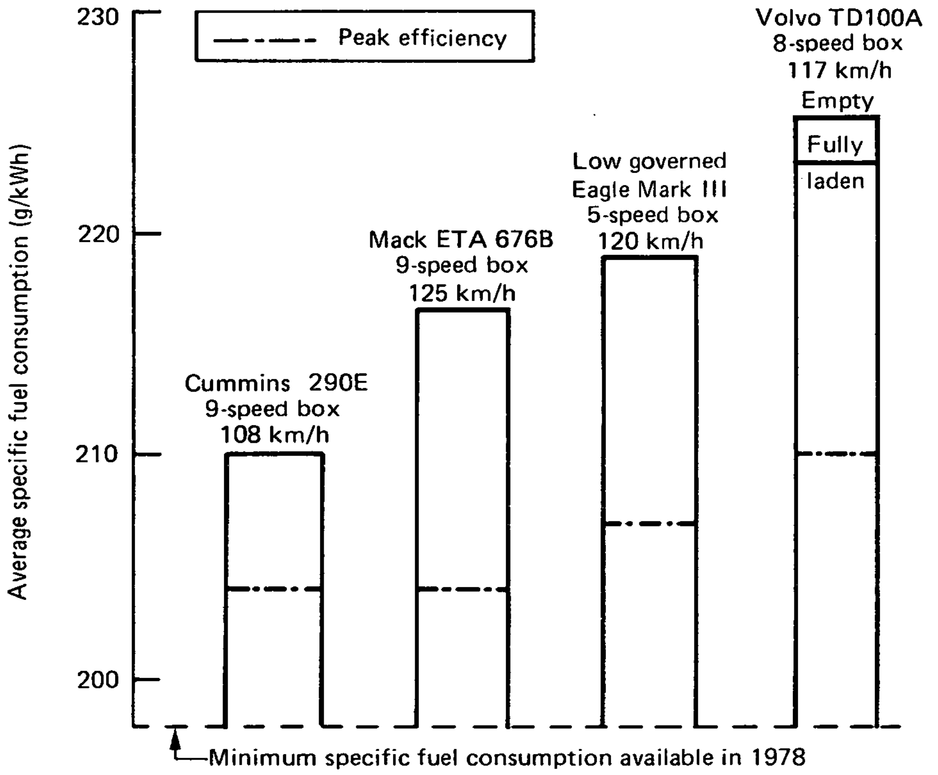


Fig. 9 ESTIMATED SPECIFIC FUEL CONSUMPTION OF HEAVY DUTY DIESEL ENGINES INSTALLED IN 32.5 tonne GROSS WEIGHT ARTICULATED VEHICLES OPERATED OVER A MOTORWAY/RURAL TRUNK DUTY CYCLE

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